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Preface

We are pleased to present the one of two Proceedings of the NEW HORIZONS 2025 - X International Scientific Conference of Transport and Communications, held in hybrid format in Dobož, Republic of Srpska, Bosnia and Herzegovina, from November 5–8, 2025. This year marks a special milestone - the 20th anniversary of the conference series - organized biennially by the Faculty of Transport and Traffic Engineering, University of East Sarajevo. Over the past two decades, New Horizons has grown into a recognized regional platform for interdisciplinary exchange, fostering innovation and collaboration across transport, communications, and related fields.

Modern transport and communication systems face increasing complexity, driven by technological advancement, sustainability imperatives, and global integration. This conference embraces a systems-oriented approach, addressing the design, optimization, and resilience of multimodal networks, digital infrastructure, and intelligent systems. Key topics span road, rail, maritime, and postal transport, logistics and supply chain management, ICT and telecommunication networks, transport of dangerous goods, and operations research in transport.

In this edition of our Proceedings, we are proud to present a diverse and insightful collection of scholarly papers. This edition includes a total of 42 papers¹ contributed by authors from many countries. The papers span a wide array of topics, reflecting the multifaceted nature of artificial intelligence applications, digital twins, smart solutions in transport systems and logistics, the digital economy and business, societal transformation, and more.

The conference featured keynote lectures from leading experts in connected vehicle communications, structural digital twins, and personalized mobility solutions, underscoring the event's commitment to cutting-edge discourse. Each submission underwent a rigorous peer review process to ensure the highest standards of academic quality. Our peer review system employed a single-blind method, where each paper

¹ Total of 92 papers has been accepted and presented at conference. Selected papers (50) from the 10th International Conference of Transport and Communications, will be published in Lecture Notes in Intelligent Transportation and Infrastructure, Springer.

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was evaluated by at least two reviewers, comprising both program committee members and external experts, to provide a thorough and fair assessment. We believe that this collection not only showcases cutting-edge research but also contributes to a deeper understanding of the diverse perspectives and methodologies within these dynamic fields.

We extend our sincere gratitude to all authors, reviewers, and institutional partners who contributed to the success of New Horizons 2025. Their work enriches the scientific community and offers valuable insights for researchers, practitioners, and policymakers navigating the evolving landscape of transport and communications.

Željko Stević
Miroslav Kostadinović

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Road Transport and Traffic

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Determining Service and Waiting Times at Ticket Counters at the Bus Terminal in Novi Sad

Milja Simeunović , Nenad Saulić , Pavle Pitka , Zoran Papić 

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Abstract. Ticket counters are one of the basic elements of a passenger building, where the highest intensity of use occurs. Earlier methods of service, i.e. issuing tickets, differed significantly from modern ones, which include the use of computers, the Internet, and other technologies. The existing research in the domestic literature refers to the period of several decades, so it was expected that many of the values valid at that time would have changed in the meantime. For the purpose of this paper, a study was conducted to determine the waiting time of users in queues and the service time at ticket counters. After obtaining the research results, a comparison was made with the values from the existing literature.

Keywords: Waiting Time, Service Time, Bus Terminal.

1 Introduction

There are many carriers that provide intercity bus transportation in Serbia. The underdevelopment of other modes of transportation in our country contributes to the high volume of passenger traffic on roads. Railway traffic is underdeveloped because little has been invested in this mode of transportation for decades, except for the Novi Sad–Belgrade route. Consequently, the number of passengers transported by rail is negligible. River transport for passengers was never developed in Serbia. These factors have contributed to the development of bus traffic as the primary means of passenger transportation to most destinations.

To adequately transport passengers, it is necessary to organize passenger terminals. From the perspective of both the carrier and the user, the formation of passenger terminals is significant since all the necessary services for the trip are available there. Depending on the size of the city, terminals are formed with basic facilities and accompanying amenities that satisfy users' transportation needs. One of the basic elements necessary for the functioning of passenger terminals is ticket counters. Since ticket counters are the area of the terminal with the highest user density, special attention should be paid to determining the number of counters and their placement. An insufficient number of ticket counters leads to overcrowding and customer dissatisfaction. Conversely, an oversized number of ticket counters leads to increased operating

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costs of passenger terminals. To determine the optimal number of ticket counters, certain data must be collected, such as the number of users and service time. New technologies applied in the operation of bus terminals can significantly affect queuing and service times. Today, most passenger terminals offer ticket sales through websites and mobile applications, as well as self-service terminals, all of which can reduce waiting times.

In our country, there is very limited literature on passenger terminals, and all of the research that has been carried out is decades old. Since ticket-related technology has changed and improved significantly, it is expected that the legalities adopted at that time, which refer to passenger behavior and passenger terminal capacity, have changed partially or completely.

This paper presents research related to the time it takes to serve users at ticket counters, as well as the waiting time of service, that is the time of users waiting in queue. The research results were compared with the data used in the existing literature.

2 Literature review

User satisfaction is greatly affected by the waiting time in the queue [1, 2]. Therefore, it is crucial to implement measures that increase the efficiency of service provision at ticket counters. Efficiency is important because even when users choose the shortest queue, it does not guarantee the shortest wait time for service [3]. Thus, it is crucial to conduct analyses to determine the factors influencing waiting and customer service times at ticket counters. A review of the available literature reveals that little research has been conducted on bus terminals. Most studies have been conducted at airport terminals and relate to passenger flow. However, these studies mainly refer to passenger flow through airport terminals, which are significantly different from other passenger terminals in terms of organization. Conversely, research conducted at railway terminals related to waiting times at ticket counters can be compared with similar research at bus terminals.

Research by Bulková et al. has shown that introducing a common system of waiting in lines is one of the most significant measures affecting the improvement of service provision [1]. Many researchers in this field address routing problems to improve the organization of transportation systems [4]. Kabalan et al. developed a model that optimizes passenger movement through the terminal, directly reducing congestion and improving customer service [5]. Stolletz developed a model to estimate waiting times at airport counters [6]. Halim and Sufahani believe that satisfying users requires using the theory of waiting to allocate resources as efficiently and effectively as possible to meet demand [2]. Other researchers also support applying queuing theory to estimate expected customer waiting time and queue length [7–9]. Almech and Roanes-Lozano modeled queuing in front of train station counters that sell different types of tickets. The goal of the modeling was to determine the optimal user distribution to minimize waiting time [10].

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All of the aforementioned models are important for optimizing the operation of the observed system and for the users themselves. In a poorly organized system, passengers wait much longer for service. Inefficient counter services can also cause delays for passengers [11]. Therefore, improving the service system at the passenger terminal is significant and directly increases the level of service provided to users.

3 Research methodology

The "MAS Novi Sad" bus terminal in Novi Sad was chosen as the research location. This passenger terminal is located in the northern part of the city at the beginning of one of its most important and busiest roads, the Bulevar oslobođenja street (see Fig. 1). It is also located right next to the train terminal. The bus terminal's position relative to the city, the existing traffic network, and the projected network of public city passenger transport lines affect the terminal's high level of accessibility.



Fig. 1. "MAS Novi Sad" bus terminal location.

The research was conducted on May 15, 2019, within the passenger building at the ticket counters. Two peak periods were included in the research: the first from 8:20 a.m. to 9:50 a.m. and the second from 2:20 p.m. to 5:20 p.m.

Nine of the total number of counters located in the passenger building are intended for the sale of intercity transportation tickets. In front of the ticket counter in the pas-

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senger building hall, queues form. If users estimate that the wait time at another counter is shorter, they move there. Between the ticket seller and the passenger is a glass partition with an opening at the bottom through which information, tickets, and money are exchanged. The ticket holder enters the necessary data, such as the route, date, time, and ticket type. Then, he or she issues a printed ticket. Of the nine existing ticketing counters, the survey covered six counters due to the limited range of the camera used to record, which was placed on the floor of the passenger building. For research purposes, two Samsung and Sony cameras were used alternately, and the camera's position is shown in Figure 2.



Fig. 2. Recording position

The recordings made during the research were transferred to a computer, where they were processed using the BS Player video playback program. This program is ideal for processing this type of data because it displays the time in hours, minutes, and seconds, and it allows for quick and precise pausing and resuming of the recording. The data were processed according to the following principle: when the client arrived, the time at which the passenger entered the queue was recorded (t_1). Then, the moment the passenger reached the ticket counter (t_2) and the time the passenger was served (t_3) were determined. When there was no waiting queue, passengers approached the ticket counter immediately, so only their arrival time was recorded on the service channel. Passengers sometimes moved from one queue to another, so special attention was paid to this to record the total time spent waiting for service, regardless of how many queues the passenger had been in previously. All established times

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were then entered into Microsoft Excel. The waiting time for passengers in the queue is obtained by determining the difference between t_2 and t_1 , and the service time is obtained by determining the difference between t_3 and t_2 .

4 Research results

A total of 854 users were recorded during the research. The results were processed individually for each counter, as well as for each research period. The waiting time and service time for each passenger were obtained. Based on these times, the average waiting and service times were calculated. Note that counter 5 was not operational during the first period (8:20 a.m. to 9:50 a.m.), so no results could be obtained for it. Counter 10 was operational for only a few minutes, during which three users were served. The remaining four counters operated with occasional short breaks that did not significantly impact the results.

Based on the obtained service times, the service capacity (μ), expressed in passengers per hour, was determined for each counter, as well as the average for all counters, based on the following expression:

$$\mu = \frac{3600}{t_s} \text{ pass/h} \quad (1)$$

Where is:

- t_s service time, expressed in seconds.

Table 1 shows the average waiting and service times for each counter during the first time period. It is also shown in Fig. 3 and Fig. 4.

Table 1. The results obtained from the research in the first period.

Number of counters	Number of passengers	Average waiting time [sec]	Standard Deviation	Conf. Level (95%)	Average service time [sec]	Standard Deviation	Conf. Level (95%)	μ [pass/h]
Counter 5	0	–	–	–	–	–	–	–
Counter 6	65	27	0.027	0.007	47	0.025	0.006	77
Counter 7	47	14	0.014	0.004	48	0.018	0.005	75
Counter 8	40	20	0.019	0.006	46	0.020	0.006	78
Counter 9	44	32	0.025	0.008	40	0.019	0.006	90
Counter 10	3	45	0.038	0.095	54	0.034	0.084	67
Average	40	27.6			47			77

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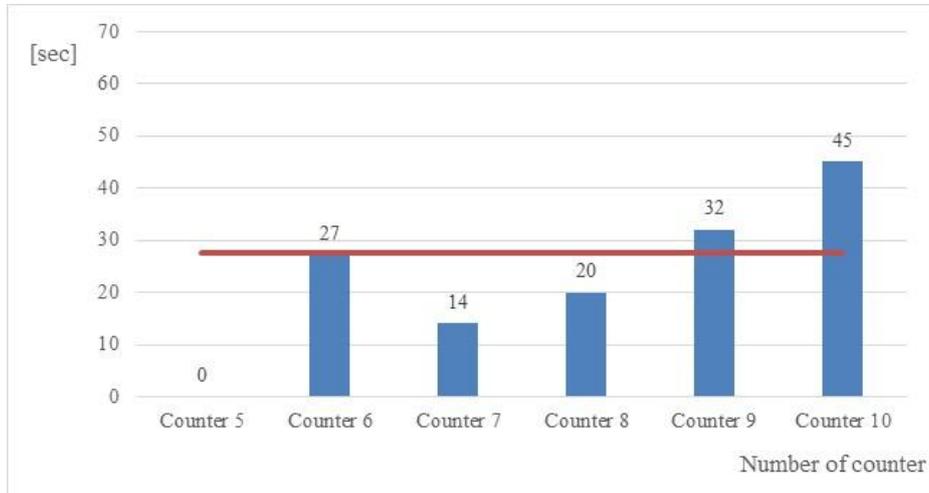


Fig. 3. Average waiting time per counter and total average waiting time, during the first research period.

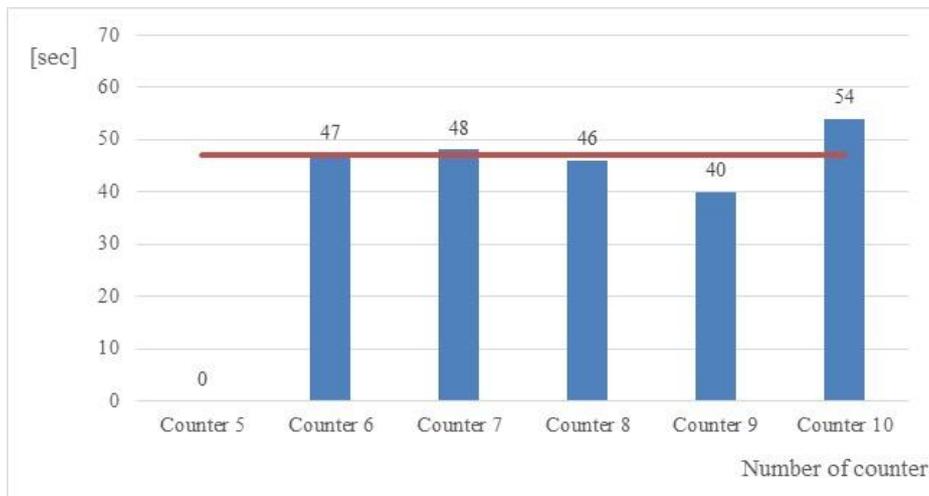


Fig. 4. Average service time per counter and total average service time, during the first research period.

The average waiting time for one passenger varies from 14 to 45 seconds. The results show that counter 10 had an extremely high average waiting time of 45 seconds compared to the other counters. One possible explanation is that only three clients appeared at counter 10 during the first period, one of whom spent one minute and 47 seconds in the queue, which significantly affected the result obtained at this counter. In addition, the reliability of this value is low, as indicated by the very high standard

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deviation (0.038) and a wide 95% confidence interval (0.095). Considering the average waiting time of 27.6 seconds at all counters, it can be concluded that passengers generally spend very little time waiting in the queue, and these are acceptable waiting times. For most other counters, the standard deviations are in the range of 0.014–0.027 with relatively narrow confidence intervals (0.004–0.008), which suggests stable and consistent results across the majority of service channels.

The service time observed at the counters and obtained through research ranges from 40 to 54 seconds. The variations in service time at the counters are small, indicating that each ticket holder needs approximately the same amount of time to receive service. This is supported by low standard deviations, ranging from 0.018 to 0.034, and narrow 95% confidence intervals (0.005–0.006 for most counters), which indicate that the process of issuing tickets is highly standardized. The average service time at all counters is 47 seconds.

Generally, an average service capacity of 77 users per hour is obtained when all counters within the first research period are taken into account. The relatively low variability in both waiting and service times, confirmed by the standard deviation and confidence interval values, demonstrates that the system functions reliably despite the uneven distribution of passengers across counters.

Table 2 shows the average waiting times and service times for each counter during the second time period. It is also shown in Fig. 5 and Fig. 6.

Table 2. The results obtained from the research in the second period.

Number of counters	Number of passengers	Average waiting time [sec]	Standard Deviation	Conf. Level (95%)	Average service time [sec]	Standard Deviation	Conf. Level (95%)	μ [pass/h]
Counter 5	88	40	0.030	0.006	61	0.033	0.007	59
Counter 6	128	24	0.021	0.004	40	0.018	0.003	90
Counter 7	109	22	0.021	0.004	45	0.030	0.006	80
Counter 8	152	22	0.021	0.003	36	0.014	0.002	100
Counter 9	113	20	0.0003	5.57E-05	33	0.0003	4.71E-04	90
Counter 10	54	20	0.022	0.006	59	0.059	0.016	109
Average	109	24.7			45.7			88

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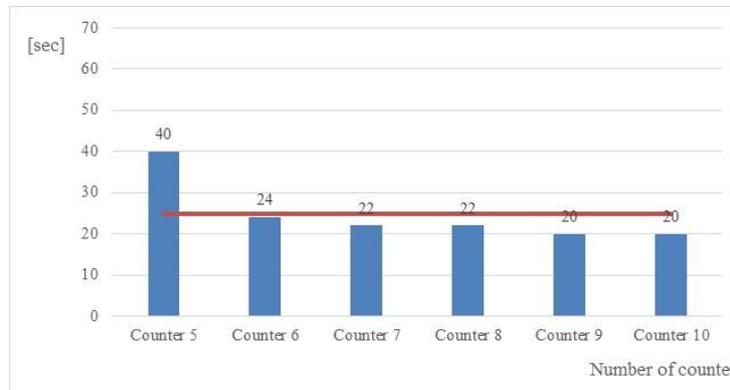


Fig. 5. Average waiting time per counter and total average waiting time, during the first research period.

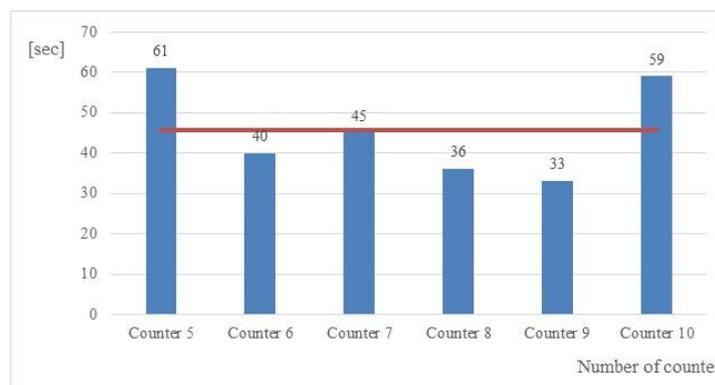


Fig. 6. Average waiting time per counter and total average waiting time, during the first research period.

The average waiting time for one passenger, as observed at each counter, ranges from 20 to 40 seconds. The total average waiting time is 24.7 seconds. The majority of counters recorded relatively low standard deviations for waiting times (0.021–0.030), with narrow 95% confidence intervals (0.003–0.006), which indicates a high level of reliability of these results. The only exception is counter 5, where the standard deviation is slightly higher (0.030) and the confidence interval wider (0.006), reflecting greater variability in waiting times. The average service time per counter ranges from 33 to 61 seconds. The total average service time observed for all counters is 45.7 seconds. Here, too, the results are relatively stable: most counters show standard deviations between 0.014 and 0.033 with confidence intervals of 0.002–0.007, confirming the uniformity of the ticketing process. However, counter 10 stands out with a much higher standard deviation of 0.059 and a wide 95% confidence interval (0.016), suggesting greater inconsistency in service duration at this counter.

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Table 3. Two-way ANOVA.

Factor	df	F	p-value
Period (AM/PM)	1	4.86	0.0277
Counter (6 different counters)	5	14.28	<0.0001
Interaction (period x counter)	5	1.05	0.381
Residual	1695	–	–

Table 4. Tukey HSD post-hoc test counter.

Group 1	Group 2	Meandiff	p-adj	Lower	Upper	Reject
Counter 10	Counter 5	10.723	0.1249	-1.5197	22.9657	False
Counter 10	Counter 6	-5.7607	0.6768	-16.8607	5.3393	False
Counter 10	Counter 7	-6.6405	0.557	-18.0367	4.7557	False
Counter 10	Counter 8	-9.7485	0.1234	-20.8551	1.3581	False
Counter 10	Counter 9	-10.5828	0.0863	-21.979	0.8133	False
Counter 5	Counter 6	-16.4837	0.0	-25.5863	-7.3811	True
Counter 5	Counter 7	-17.3635	0.0	-26.825	-7.9021	True
Counter 5	Counter 8	-20.4715	0.0	-29.5821	-11.3609	True
Counter 5	Counter 9	-21.3058	0.0	-30.7673	-11.8444	True
Counter 6	Counter 7	-0.8798	0.9996	-8.8074	7.0478	False
Counter 6	Counter 8	-3.9878	0.6541	-11.4931	3.5175	False
Counter 6	Counter 9	-4.8221	0.5084	-12.7497	3.1055	False
Counter 7	Counter 8	-3.108	0.8744	-11.0448	4.8288	False
Counter 7	Counter 9	-3.9423	0.7574	-12.2795	4.3949	False
Counter 8	Counter 9	-0.8343	0.9997	-8.7711	7.1025	False

Table 5. Tukey HSD post-hoc test period.

Group 1	Group 2	Meandiff	p-adj	Lower	Upper	Reject
AM	PM	0.9422	0.6567	-3.2145	5.0989	False

The results of the two-way ANOVA revealed that the Period (morning/afternoon) and Counter factors significantly impacted waiting time. However, the interaction between these two factors was not statistically significant. This means that the effects of period and counter occur independently of each other. A more detailed post hoc analysis using the Tukey HSD method revealed that significant differences in waiting time primarily occurred between counter 5 and counters 6, 7, 8, and 9. However, the differences between the other counters were not statistically significant. Regarding the period factor, the average waiting times in the morning and afternoon did not differ significantly, though the initial ANOVA test indicated a period effect. These findings suggest that the load distribution among the counters is uneven, particularly at Counter 5, though changing the time of day does not lead to significant systematic differences in average waiting time.

5 Discussion

The research shows that the values obtained for waiting and service times are favorable for bus terminal users in Novi Sad. Research during the two peak periods shows that the average research time does not exceed one minute, and the average waiting time is 30 seconds. Comparing the results of the first and second research periods reveals that the counters have an average service capacity of 88 users per hour during the second period, significantly higher than during the first period. The average waiting time and service time show minimal differences between the observed periods. Since workers at all counters use the same technology, variations between counters can be attributed to worker dexterity and the diversity of user requests.

For the entire research period and a total of 854 users, the average waiting time for service was 26 seconds, while the average service time was 46.3 seconds.

A review of the literature revealed that researchers most often focused on optimizing waiting lines where waiting times in the queue or system were specified in literary units. Research conducted by Bulková et al. shows that the average waiting time in the existing system is 105.5 seconds [1]. Noordin et al. determined through research at an urban train station that the average waiting time in the morning is less than one minute [11]. Halim and Sufahani conducted research at two bus terminals. Using the theory of waiting lines, they calculated the average waiting time of passengers in the system. For the first terminal, they calculated an average waiting time of 39.44 minutes per passenger, and for the second terminal, they calculated an average waiting time of 41.25 minutes per passenger. These long waiting times are explained by the fact that these terminals serve a large number of transport lines and receive an extremely large number of passengers. Patel et al. recorded the service time for 41 passengers and determined that it varies between 54 and 78 seconds per passenger. The mean value for all passengers observed on weekdays is one minute and six seconds.

Researches in the literature [12, 13] conducted at faculties in the Republic of Serbia determined the waiting time of users in the queue about fifty years ago. The research involved measuring waiting times and conducting user surveys. The survey included 1,035 respondents, and the results quantified their subjective impressions of short, moderate, and long waiting times at ticket counters. The results obtained based on their answers are shown in Table 6.

Table 6. Waiting time in the queue [12, 13].

Impression of the waiting time	Real waiting time	Percentage of users [%]
Short	4 min and 25 sec	57
Moderate	7 min and 13 sec	25
Long	18 min and 38 sec	18

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Based on the obtained data, it was concluded that the acceptable waiting time is between four and seven minutes. If the average value is taken with sufficient reliability based on the research conducted, the adopted waiting time for service is five minutes.

It is very important to predict the user's waiting time in the system because passengers base their arrival time at the terminal on this prediction. Passengers need to be able to estimate how long they will spend in the system so they do not miss their departure [14].

By comparing the values obtained from the research at the bus terminal in Novi Sad with those from other studies, it was concluded that the waiting time in the queue most closely aligns with the values obtained by Noordin et al. In general, a literature review found that the aforementioned waiting times for service are longer compared to the times obtained by the research in this paper. Since waiting time is a factor in determining the number of ticket counters, the data from existing domestic literature is deemed outdated and irrelevant to modern work technologies.

6 Conclusion

Based on the research conducted at the Novi Sad bus terminal, it was concluded that the average waiting time for service during the entire research period was 26 seconds. Specifically, it was 27.6 seconds during the first research period (from 08:20 to 09:50) and 24.7 seconds during the second research period (from 14:20 to 17:20).

A drastic difference in these values can be observed by comparing the data on the average waiting time for service in the waiting queue obtained from the research at the MAS Novi Sad bus terminal with the research data from the existing literature. The waiting time obtained by the current research is much less than five minutes, which the domestic literature states as an acceptable waiting time. Compared to other research, lower values of waiting and service time were observed in relation to foreign literature. To determine the differences between the values obtained in this study and those in the literature, it is necessary to understand the conditions under which other researchers conducted their studies. It is assumed that the differences compared to the research presented in literature 12 and 13 are due to the fact that the MAS Novi Sad bus station has modern equipment for issuing tickets. This equipment shortens service time and reduces waiting time to a minimum. Previously, ticket agents wrote and issued tickets manually or used technologies that required a significantly longer time to print tickets. Certain studies show that applying various modern systems and online ticket sales can significantly increase ticket sales efficiency and reduce waiting time [15, 16]. At the MAS Novi Sad bus terminal, however, tickets are still sold exclusively at the counters. The introduction of online sales, sales through mobile applications, and self-service would further reduce waiting times.

Additional research is certainly necessary to obtain more reliable data. This research should cover a longer period of time and a larger number of bus terminals. Conducting research at only one terminal, where it was impossible to record all the counters in the passenger building, limits the reliability of the results.

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Impact of urban planning documentation on traffic safety

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Abstract. The aim of this paper is to highlight and emphasize the importance of urban planning documentation and urban planning processes in relation to traffic safety. To analyze this issue, various parameters were observed and categorized into three groups: general parameters, traffic safety parameters, and urban planning documentation parameters. The results indicate that urban planning documentation significantly influences traffic safety. Recognizing and establishing this correlation can and should play a key role in directing traffic safety improvement efforts toward the development of high-quality urban planning documentation. This paper continues research initiated in 2019, while the presented results cover the period from 2011 to 2023.

Keywords: Urban documentation, traffic safety.

1 Introduction

Long-term monitoring of traffic safety and urban planning conditions in the Republic of Serbia has revealed a notable lack of research and action aimed at structuring the relationship between urban planning and traffic safety. The goal of this paper is to raise awareness and interest within the professional community regarding this issue, thereby creating favorable conditions for further study and improvement of urban planning documentation in Serbia. Enhancing urban planning documentation by involving transportation engineering professionals should not only improve the quality of planning documents but also contribute to improvements in traffic safety.

To explore the relationship between urban planning and traffic safety, an initial data collection was carried out in both fields. For the purpose of evaluating urban planning documentation in terms of its quality, an analysis was conducted using publicly available documents from official websites of local self-governments. The focus was placed on whether a certified traffic engineer participated in the preparation of each urban plan. For traffic safety analysis, publicly available data were also collected and processed to calculate specific parameters. Upon completion of the individual analyses, a comparative assessment was conducted to explore the interrelationship between urban planning and traffic safety.

The baseline for assessing urban planning documentation is represented by publicly available documents collected in 2011. The data used for analyzing traffic safety spans the period from 2011 to 2023. Due to the large volume of collected data

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and the limitations in presenting detailed comparisons, the results are shown through percentage-based comparisons between the observed regions. All values are expressed relative to a reference value for clarity.

2 Methodology and Data Framework

To analyze the correlation between urban planning documentation and traffic safety, a methodological framework was adopted, which included the following steps:

- Definition of the study area and segmentation into characteristic spatial units,
- Collection of data for determining baseline and general parameters,
- Collection of data for assessing the initial state and quality of urban planning documentation,
- Collection of data for evaluating the initial state and trends in traffic safety,
- Separate analysis of the collected data,
- Comparative presentation and analysis of the obtained results.

The territory of the Republic of Serbia was observed based on the official statistical nomenclature (NUTS 1), topography, driver habits, attitudes, and behaviors, as well as spatial and urban characteristics and data availability. The entire territory was divided into two statistical units: Serbia – North and Serbia – South (hereinafter referred to as "North" and "South"). For the purposes of this study, the "North" region includes only the local self-government units (LGUs) within the Autonomous Province of Vojvodina, excluding Belgrade, while the "South" region includes all remaining LGUs, excluding the Autonomous Province of Kosovo and Metohija. The Belgrade region was excluded from analysis due to its unique urban and traffic characteristics, and the Kosovo and Metohija region due to data unavailability.

This regional division is also justified in terms of terrain type—flat in the North versus hilly and mountainous in the South—as well as differences in driving habits and behaviors.

After defining the study area and regional division, data were collected and analyzed for 45 LGUs in the North and 102 LGUs in the South, totaling 147 local self-government units in total.

The regional grouping of LGUs enabled the collection and analysis of general statistical data, including population size, number of registered vehicles, total road network length, etc.

The planning documents representing the initial state of urban planning documentation were obtained from official LGU websites, with a focus on documents available in 2011. From each LGU, one urban plan was selected—either a general urban plan or a detailed regulation plan. Priority was given to plans that addressed traffic issues; if such plans were unavailable, general urban or general regulation plans were used instead. The main quality criterion was whether a certified transportation engineer participated in the planning process.

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This approach was partly dictated by limitations in accessing full urban planning documentation for each LGU at the time of data collection. Furthermore, a comprehensive analysis of all available plans for all LGUs would have required significantly more time and personnel. Nonetheless, this selected approach is deemed satisfactory for the scope of this research, as LGUs that involved transportation engineers in the preparation of their urban documentation generally demonstrated greater awareness of traffic issues, as well as higher expertise and a more responsible attitude toward both urban development and traffic safety.

Traffic safety documentation analyzed in this study was also obtained from publicly available sources, specifically the website of the Traffic Safety Agency of the Republic of Serbia, covering the period from 2011 to 2023 [1]. This dataset enabled the calculation and analysis of several traffic safety indicators, including collective risk, accident risk rate, vehicle-to-accident ratio, average traffic flow density, and the number of fatalities per passenger car unit (PCU).

3 Results

Data collection and processing were carried out across 147 local self-government units (LGUs), of which 45 are located in the Northern region and 102 in the Southern region. Due to the large volume of data and in order to present the results more effectively, all findings are expressed through a comparative ratio between the North and South regions [2]. All results are presented and analyzed relative to an adopted reference value representing the ratio between the two regions.

3.1 Results of General Parameter Analysis

The analysis of general parameters showed that the North and South regions are approximately equal in terms of the number of LGUs and total population. However, other parameters deviate from the reference value, particularly population density (number of inhabitants per km²) and road network length. These deviations indicate a significantly higher population density in the Northern region compared to the average value, whereas the road network length is notably shorter.

Based on the analysis of these parameters, it can be concluded that the Northern region is characterized by less favorable conditions for traffic flow and infrastructure development.

A graphical representation of the obtained results is shown in Figure 1.

3.2 Results of Urban Planning Documentation Analysis

The analysis of urban planning documentation reveals significant deviations from the average (reference) value. Ultimately, the results indicate a more favorable situation in the Northern region—specifically, a higher number of LGUs in this region have

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urban planning documentation that involved the participation of certified traffic engineers in its development.

A graphical representation of the results is shown in Figure 2.

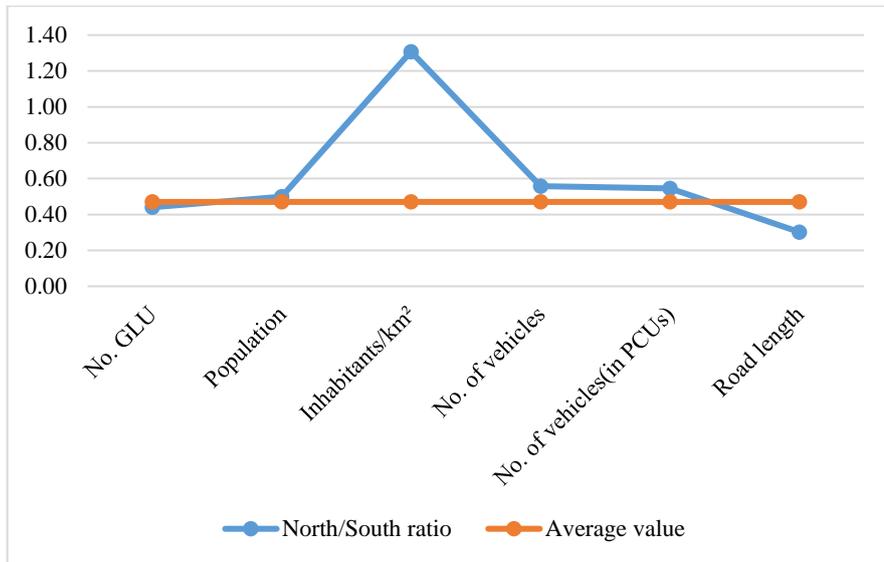


Fig. 1. Presentation of obtained values and mutual relationship of the observed Regions regarding general parameters.

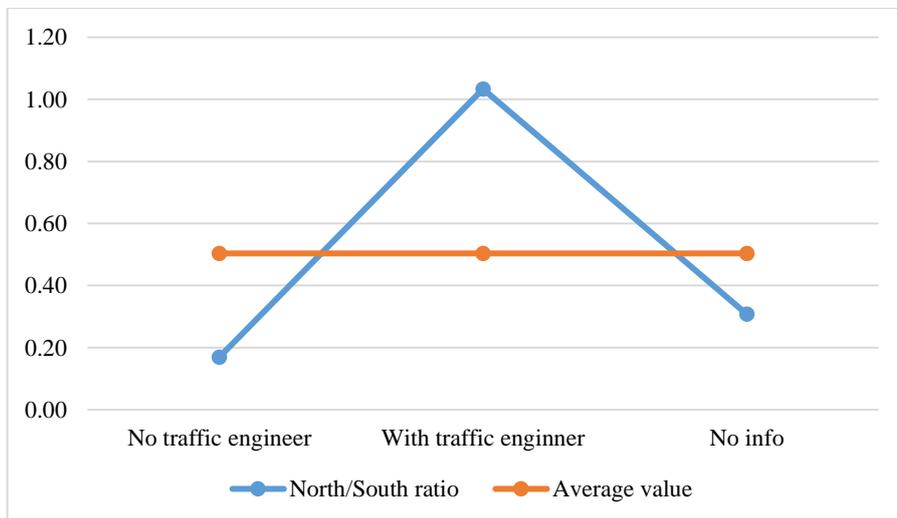


Fig. 2. Presentation of obtained values and mutual relationship of the observed Regions regarding urban planning documentation.

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3.3 Results of Traffic Safety Analysis

The collected data, used as primary indicators of traffic safety, were calculated using adapted formulas as follows:

- **Collective Risk:**

$$KRd = \frac{(SNPOGn + SNTTPn)}{Ld} \quad (1)$$

Where:

KRd — collective risk,

SNPOGn — total number of traffic accidents with fatalities on the entire road network during the observed period,

SNTTPn — total number of traffic accidents with seriously injured persons on the entire road network during the observed period,

Ld — length of the road network in the region.

- **Accident Risk Rate (Degree of accident risk):**

$$SO = \frac{Nnezgoda * 10^6}{Q * L} \quad (2)$$

Where:

SO — accident risk rate,

Nnezgoda — total number of recorded traffic accidents,

Q — number of registered vehicles,

L — length of the road network.

- **Dependence of the Number of Traffic Accidents on the Number of Vehicles:**

$$Nsn = a * Q^b \quad (3)$$

Where:

Nsn — number of traffic accidents,

Q — number of registered vehicles,

a, b — coefficients.

- The data for the number of casualties, fatalities, traffic accidents, and derived parameters were obtained and calculated from official documents and statistics of the Traffic Safety Agency of the Republic of Serbia for the observed period.

Regarding the traffic safety analysis results, it is evident that parameters related solely to the number of traffic accidents are close to the reference value, while all other parameters significantly deviate. Based on the analysis, it can be concluded that the Northern region presents considerably less favorable conditions for safe traffic flow.

The graphical representation of traffic safety analysis results is shown in Figure 3.

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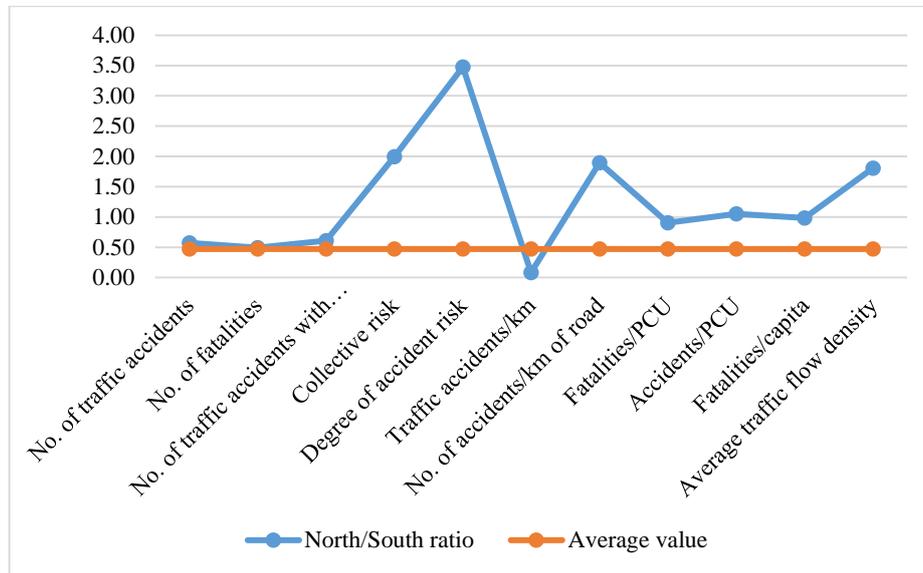


Fig. 3. Presentation of obtained values and mutual relationship of the observed Regions regarding traffic safety analysis.

4 Discussion

The values of all parameters are presented in ascending order in the graph shown in Figure 4.

The obtained results can be categorized based on their deviation from the adopted reference value located in zone "0", which includes the basic values: number of local self-government units (LGUUs), number of fatalities, and population size. The graph shows that the values are distributed into seven zones ranging from -2 to 4.

Zones -1 and -2 highlight parameters with higher percentage values in the Southern region. Zone "-1" includes parameters such as road network length and the number of LGUUs that have not publicly disclosed urban planning documentation, i.e., those for which no information is available. Zone "-2" contains parameters indicating the dependency between the number of traffic accidents and the number of vehicles, as well as the number of LGUUs that have urban planning documentation prepared without the engagement of traffic engineers. These values point to unfavorable conditions in the Southern region, reflected by parameters labeled "Without traffic engineers" and "Without information," indicating lower quality urban planning documentation. On the other hand, road length as a parameter shows a relatively better condition in the Southern region, suggesting a higher percentage of constructed road kilometers compared to the Northern region.

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Parameters within zone "0" fall within the reference range ($\pm 10\%$) and include basic indicators such as the number of LGUUs, population, registered vehicles, and the number of traffic accidents.

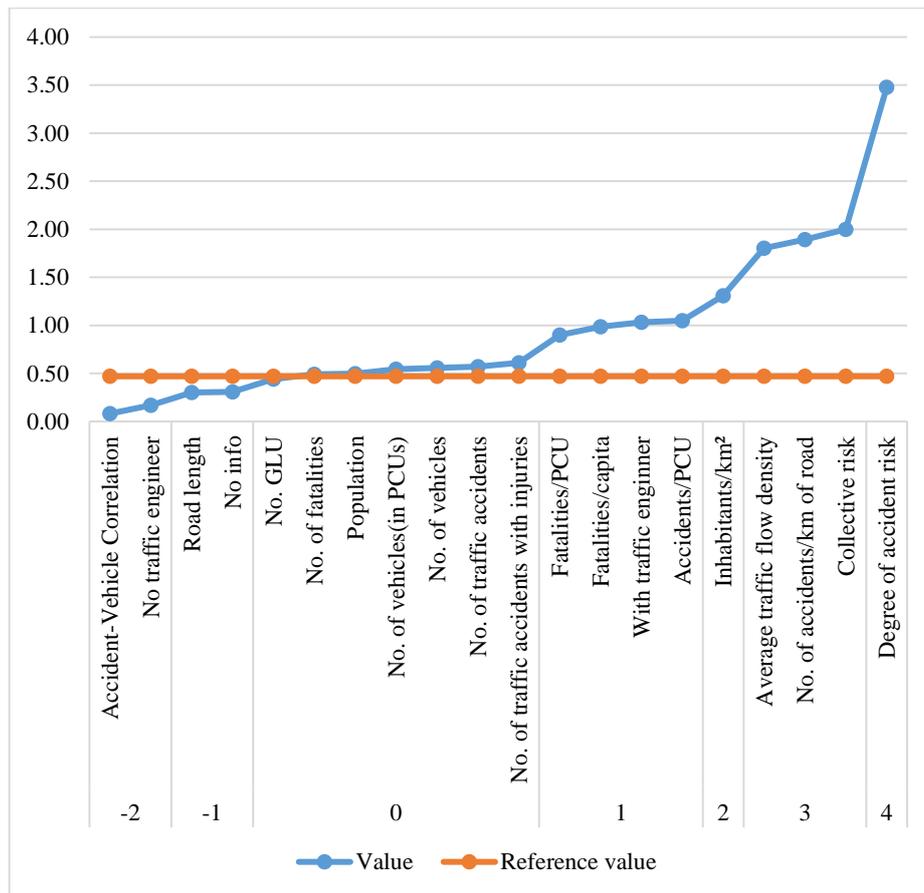


Fig. 4. Comparative presentation of obtained parameter values of the observed Regions.

Parameters in zones 1 through 4 indicate higher percentage values in the Northern region. Zone "1" includes parameters showing a higher number of fatalities, the number of traffic accidents normalized per passenger car unit, and a higher fatality rate relative to population, all pointing to less favorable traffic safety conditions in the Northern region. However, this zone also contains a positive parameter for the Northern region— a higher percentage of LGUUs with urban planning documentation prepared by certified traffic engineers.

Zone "2" consists solely of the parameter representing population density per square kilometer, clearly indicating a higher population density in the Northern re-

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gion. From a traffic safety perspective, higher population density negatively impacts traffic safety, positioning the Northern region at a disadvantage.

Parameters in zone "3" refer to average traffic flow density, the number of traffic accidents per kilometer of road, and collective risk. Increased traffic density and higher collective risk further emphasize the unfavorable and riskier traffic conditions in the Northern region.

Zone "4" comprises the parameter representing the degree of hazard for the occurrence of traffic accidents, which is markedly high in the Northern region, signifying the most critical traffic safety situation there.

Analysis of parameters by zones has led to grouping them into three categories:

- The first group includes parameters reflecting the traffic conditions in the Northern region, indicating significantly less favorable safety conditions. This includes the parameter below the reference line— a lower percentage of constructed road network in the Northern region—and parameters above the reference line, such as higher vehicle numbers, population density, traffic flow density, collective risk, and especially the degree of hazard, which significantly deviates from the reference.
- The second group includes parameters within the reference range, i.e., zone "0," encompassing the number of fatalities, total traffic accidents, and accidents involving bodily injuries.
- The third group pertains to urban planning documentation parameters. Considerable differences exist between parameters labeled "Without traffic engineers" and "With traffic engineers," indicating better quality documentation in the Northern region.

Overall, although the Northern region shows more unfavorable conditions for safe traffic flow, the number of traffic accidents remains within or close to the reference values. This suggests that the quality of urban planning documentation plays a crucial role in traffic safety and that higher-quality documentation in the Northern region may mitigate the adverse effects of less favorable conditions.

In conclusion, the urban planning documentation parameter is a significant indicator of traffic safety quality. Lack of engagement of certified traffic engineers and poor-quality urban documentation generally lead to poorly designed traffic spaces, resulting in unsafe traffic conditions and increased accident rates.

5 Conclusion

The greatest challenge in determining the interdependence between urban planning documentation and traffic safety lies in the size and diversity of the studied areas. While data collection and processing related to traffic safety are facilitated by the availability of public data, obtaining data on urban planning documentation is much more complex and requires detailed individual analysis of each LGUU.

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Complete systematization and analysis of urban planning documentation, including quality assessment, degree of implementation, and expert involvement, would enable more precise and comprehensive conclusions.

The lack of scientific and professional literature on this topic [3,4], alongside the need for multidisciplinary engagement and financial resources, represents additional barriers to deeper analysis.

Despite these limitations, the results indicate a significant impact of urban planning documentation on traffic safety. It is necessary to expand this research by involving more experts and institutional approaches to systematically address this important issue.

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Analysis of the Impact of Road Network Noise on Animal Populations, Ecological Consequences, and Protective Measures

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Abstract. Noise is one of the most significant environmental risks, according to data from the World Health Organization, and thus represents an important field of research. In line with this fact, this paper presents an analysis of the impact of road network noise, with the aim of reducing ecological risk and mitigating negative effects on animal populations. Results of experimental research in the United States confirm a considerable reduction (37.5%) in the overall bird population in noisy road environments, as well as the complete avoidance of such locations by certain species (*Bombycilla cedrorum* and *Setophaga petechia*), demonstrating that road network noise is a key driver of negative ecological consequences for animal populations. The trend of decreasing population density near noisy roads is evident in most bird species. For example, *Sitta canadensis* showed an 86% decrease in occupancy near noisy roads, *Turdus migratorius* 77%, *Regulus calendula* 33%, and *Pipilo maculatus* 17%. Furthermore, the number of males at bird mating sites exposed to traffic noise is 73% lower compared to quiet locations. Studies conducted in the Netherlands also revealed a reduced bird density near roads, with lower occupancy found in areas where traffic noise exceeds 50 dB(A), and for some species even at 40 dB(A). A significantly lower presence of several large mammal species has also been documented in habitats near roads. In order to mitigate these adverse effects and consequences on health, communication, reproduction, and more, protective measures have been proposed, aimed at achieving an optimal level of protection for vulnerable populations.

Keywords: Traffic noise, road network, animals, ecological consequences, protection.

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1 Introduction

The purpose of this paper is to present a multidisciplinary study on the noise impact on fauna during road construction and operation, aiming to reduce noise and mitigate negative ecological effects as much as possible. This represents the main goal of the research, considering that noise is becoming an increasingly significant factor threatening animal and other populations, with numerous ecological consequences.

According to the most commonly used definition, noise is any unwanted sound. It shares the same physical characteristics as sound but differs in that it causes disturbance, harm, and various adverse effects on the health of both humans and animals [1].

Traffic and road networks have a very positive impact on the integration of people and essential goods, but they also significantly alter ecological communities and the acoustic environment by generating and emitting noise. Road construction typically involves the use of heavy machinery. Additionally, bridge and tunnel construction often requires pile driving and blasting. Road traffic noise is generally of lower intensity than construction noise but tends to be continuous and long-term. Noise caused by moving motor vehicles can spread on either side of the road, significantly altering the environment, leading to reduced animal populations and degradation of natural habitats. In parts of Europe and America with a high density of road networks, there has been a significant reduction in the habitats of species sensitive to noise. Noise emitted from road networks causes a range of ecological effects, making it crucial to consider these during the planning and design of new roads, as well as when implementing noise control measures.

By using available scientific data from the researched area in parts of Europe, America, and elsewhere, and by applying appropriate research methods, this study has produced significant results and findings. This research's outcomes are highly important for the optimal design of road infrastructure and the implementation of appropriate technical and other protective measures, as well as for the development of monitoring plans aimed at periodically reviewing and improving measures for the protection of endangered populations.

2 Methods

This study employed multi-criteria methods of analysis and synthesis, including the comparative method. Relevant and available data from scientific and professional studies were used, including those from the United States (USA) [2, 3], the Netherlands [4–6], Denmark [7], Serbia [1, 8], and other countries.

In the structure of the subject work, the method of analyzing the presence of the most significant bird species in the vicinity of a noisy road was primarily applied, along with a comparison of their presence at minimal levels of traffic noise and the synthesis of data. Additionally, methods of analysis, comparison, and synthesis of available scientific data were used in defining the ecological consequences of noise from the road network on animal populations and measures for their protection. The

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application of all the aforementioned methods in the research generated significant results and conclusions for this work.

3 Analysis, Results, and Discussion

3.1 Analysis of the Noise Impact on Bird Occupancy Near Noisy Roads

According to an experimental study conducted in the USA [2], the presence, i.e., occupancy, of birds was analyzed near a quiet road (with a noise level of 37 dB(A)) and a noisy road (with a traffic noise level of 57 dB(A)), within a 50-meter radius from the road. This was done by comparing and synthesizing relevant data (approximate bird counts), as presented in Tables 1–3. The analysis included the following most significant bird species: *Turdus migratorius*–1, *Regulus calendula*–2, *Pipilo maculatus*–3, *Sitta canadensis*–4, *Vireo cassinii*–5, *Piranga ludoviciana*–6, *Spizella passerina*–7, *Poecile gambeli*–8, *Bombycilla cedrorum*–9, *Setophaga petechia*–10, *Empidonax oberholseri*–11, and *Setophaga townsendi*–12.

Table 1 shows the average number of 12 key bird species present in the environment near the experimental quiet road, while Table 2 presents the average number of the same bird species in the environment near the experimental noisy road, in the USA.

Table 1. Average number of the most significant bird species present near the quiet road [2].

Parameter	Bird species											
	1	2	3	4	5	6	7	8	9	10	11	12
Average number of birds present [-]	850	300	300	350	90	130	80	70	43	45	58	33

Table 2. Average number of the most significant bird species present near the noisy road [2].

Parameter	Bird species											
	1	2	3	4	5	6	7	8	9	10	11	12
Average number of birds present [-]	200	200	250	50	50	80	30	30	0	0	2	10

In accordance with the results of the data analysis presented in Tables 1 and 2, an average of 850 *Turdus migratorius* birds were present along or near the quiet road at a noise level of 37 dB(A), but their presence decreased by 77% (to 200 birds) with an increase in traffic noise to 57 dB(A).

A decrease in presence is also evident in other listed bird species, although the number of individuals per species decreased differently. For example, 300 *Regulus calendula* birds present along or near the quiet road decreased by 33% (to 200 individuals) under noisy traffic conditions; 300 *Pipilo maculatus* birds decreased by 17% (to 250 individuals); 350 *Sitta canadensis* birds decreased by 86% (to 50 individuals);

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etc. - representing a significant reduction. The trend of decreasing density of the mentioned animal population near noisy roads is evident in other bird species as well, with certain variations.

Table 3 presents the average number of all birds present in the vicinity of the experimental road in the USA, at different levels of traffic noise.

Table 3. Average number of all birds present in the environment of the experimental road at specific noise levels [2].

Parameter	Values	
Traffic noise level [dB(A)]	37	57
Average number of all present birds [-]	4000	2500

Analysis of the data from Table 3 shows that the total number of bird species present in the environment of the quiet road decreased by 37.5% during the noisy period. The negative impact of road noise on birds and other animal populations leads to their avoidance of the road and its surroundings, as well as other ecological consequences. A significant reduction in the number of birds along and near the noisy road, as well as the complete avoidance of these locations by two bird species (*Bombycilla cedrorum* and *Setophaga petechia*), proves that road network noise is the main driver of ecological consequences on the animal population.

The results of the previous experimental research [2] in the USA confirm the conclusions of studies [4–6] in the Netherlands, which found reduced bird density near noisy roads and demonstrated that bird populations decline in areas where traffic noise exceeds 50 dB(A), even 40 dB(A) when it comes to forest birds. In countries with dense networks of roads of various categories, especially highways, such as the Netherlands and other developed countries, traffic noise represents a significant threat to animal populations, particularly birds, leading to a reduction in population density.

The obtained analysis results show that traffic noise can seriously affect bird abundance. Furthermore, it is highly likely that other negative effects of the road network will amplify the noise effects on numerous populations.

3.2 Ecological Consequences of Road Network Noise on Animal Populations in Surrounding Habitats

Many animal species, such as birds, mammals, fish, frogs, insects, and others, communicate using sound, which serves multiple functions. However, noise emitted from the road network very often disrupts this communication and important interactions between animals, which can have significant ecological consequences. In traffic noise-affected areas, the following ecological consequences often occur: difficulties in attracting mates, reduced reproductive success, decreases in population numbers and species diversity, changes in the composition of ecological communities, and more [9, 10].

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Due to road traffic noise, some animal species call or sing differently, but these changes are not sufficient to restore all lost communication [11]. Acoustic disturbances generated by noise from the road network can increase animals' vulnerability to various predators and reduce success in foraging for animals that use sound to locate their prey.

Results of conducted researches [12] prove that some animal species, such as bats, avoid foraging near noisy highways.

Noise from road construction and reconstruction, as well as road traffic noise, can cause physiological stress [13] and frighten animals in the road environment. As a consequence, animals often temporarily or permanently move away from areas affected by noise. Permanent avoidance of noise-affected areas along roads leads to a lasting reduction in available habitats for various noise-sensitive species. In regions with a dense road network, such as parts of Europe and North America, this reduction can be very significant [14].

An experimental study on the bird *Tetrao urogallus* (Western Capercaillie) in North America [3] found that males of this species avoid lekking (calling) sites located near noisy roads. According to this study, the number of males was 73% lower at breeding sites exposed to traffic noise (accompanied by increased stress levels in the birds) compared to quiet sites.

Research results [15] demonstrate a lower presence of several large mammal species (elephant, zebra, etc.) in habitats near roads.

Noise emitted during the construction and operation of various categories of roads often causes hearing loss in animals. High noise levels can damage the cochlea in the inner ear, leading to increases in hearing thresholds and hearing injuries in animals [13]. Such hearing damage may result from prolonged exposure to high noise levels or from a single extreme noise event. Related to this, the conclusion of the conducted research [16] is that continuous noise above 93 dB(A) emitted from roads can cause an increase in hearing thresholds in birds, while impulsive noise above 125 dB(A) can cause permanent hearing damage.

Acoustic internal injuries to fish are most often caused by noise during road construction (noise from pile driving of support posts into the substrate, etc.) in aquatic habitats.

3.3 Protection Measures for Populations Endangered by Noise Emitted from the Road Network

Due to various potential dangers and ecological impacts, it is necessary to plan and design protective and mitigating measures against the negative effects of noise emitted from roads, both on humans and animal populations. This is especially important in areas with endangered species populations where high noise levels from road construction or traffic are expected. Noise mitigation from the road network often requires significant financial investments, so it is essential to consider and analyze necessary measures during the design phase, i.e., before road construction. Necessary

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expert preparation must include the collection of ecological data on various animal population activities in habitats that will be affected by road-emitted noise.

Findings based on numerous studies [17] in several European and world countries indicate that a significant reduction of traffic noise produced by the contact of vehicle tires with the road surface can be achieved by using porous or draining asphalt in the surface layer of the road. Noise from motor vehicles traveling on roads can be reduced by structural improvements to the engine, exhaust system, tires, and other components.

Protective measures vary depending on the type of noise, road, expected traffic volume, and types of habitats that may be affected by the noise.

Sound barriers have been used for decades to protect people from high levels of road traffic noise but are less frequently used solely for the protection of animals. These barriers are built from various solid materials (concrete, earth, wood, steel, glass, etc.) and can reach heights of 5 meters or more above ground level. Such protective structures are very effective. Depending on the category and type of noise protection construction, their effectiveness (Table 4) in reducing noise levels can be up to 11 dB(A) or more.

Table 4. Classification of noise protection constructions [8].

Category	Type of construction	Noise reduction [dB(A)]
A1	Reflective	up to 4
A2	Absorptive	from 4 to 8
A3	Highly absorptive	from 8 to 11
A4	Super absorptive	over 11

In addition to their relatively high efficiency, sound barriers have a drawback as they prevent the movement of many animals (mammals, reptiles, amphibians, and invertebrates).

Birds in flight may collide with the mentioned barriers made of transparent materials unless these barriers are patterned or painted to make them more visible. A sound barrier with silhouettes of birds of prey (Figure 1), besides reducing noise from the highway, also reduces the risk of bird collisions.

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Fig. 1. Photographic appearance of a sound barrier with silhouettes of birds of prey [18].

Figure 2 is a photographic representation of a sound barrier with horizontal bright-colored stripes, which, besides reducing noise from the highway, also serves a safety function (repelling birds and reducing the risk of collisions with the barrier).



Fig. 2. Photographic representation of a sound barrier with horizontal stripes [19].

On busy and noisy roads where, solid sound barriers are installed, many animals are prevented from crossing. To address these drawbacks of solid sound barriers, other types of barriers are being developed. Significant solutions include green sound barriers, as shown in Figure 3, or barriers that have a small opening (for the passage of animals). However, the effectiveness of most such barriers in reducing noise emitted from roads is less than that of solid barriers.

As a special type of sound barrier, Figure 4 shows a photographic appearance of a sound tube designed to reduce road noise in Melbourne (Australia) while preserving the aesthetic appearance of the surrounding area.

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Fig. 3. Green sound barrier [20].



Fig. 4. Sound tube [21].

Within the protection measures set, important potential actions include reducing or stopping noise-generating activities during certain periods in locations where animals sensitive to noise are present.

When considering the impact in terrestrial habitats, such measures may include temporary halts in road construction, temporary road closures, or reducing vehicle speeds to lower traffic noise. Implementation of protective measures is considered and planned during the breeding season of particular animal species that communicate via sound (birds, frogs, etc.) [22–24]. However, these measures require reliable information about the distribution and breeding activities of these animals.

To reduce the impact of pile driving noise on animal populations (fish and mammals) during road construction in aquatic habitats, one important measure is the use of air bubble curtains (Figure 5).



Fig. 5. Air bubble curtain [25].

The mentioned curtain produces air bubbles, which are most often released at the bottom of the water and distributed throughout the water. Once they rise, the bubbles interrupt the propagation of waves and reduce noise, i.e., they function as a barrier.

Results from experimental research in Denmark [7] indicate that noise from pile driving were significantly reduced when the mentioned curtain was in use.

4 Conclusion

From the analysis of scientific data in this study, an important conclusion emerges: noise from road construction and road traffic often has significant ecological consequences for most animals in various habitats surrounding roads.

Experimental research results on the noise impact on bird populations along noisy roads in the USA confirm a significant reduction in the abundance of all studied bird species near noisy roads, amounting to 37.5%. For example, *Sitta canadensis* reduced its presence near noisy roads by 86%, *Turdus migratorius* by 77%, *Regulus calendula* by 33%, along with most other bird species. Some bird species (*Bombycilla cedrorum* and *Setophaga petechia*), included in the same study, completely avoid noisy locations. At bird breeding sites exposed to traffic noise, the number of males was 73% lower than at quiet sites. The conclusions of the experimental research in the USA align with research findings in the Netherlands, which demonstrated reduced bird density near noisy roads. According to those results, bird presence decreased in areas of the Netherlands where traffic noise exceeds 50 dB(A), even 40 dB(A) for noise-sensitive forest birds. Based on the analysis results, it is concluded that traffic noise can significantly affect bird population abundance. Furthermore, analysis results show reduced presence of several large mammal species in habitats adjacent to roads.

The analysis and synthesis of research results confirm that road network noise can very negatively impact animal populations and cause many consequences for them and other populations. An integral part of the conclusion is that the negative ecological consequences on animal populations, primarily driven by road noise, may include increased health stress, various behavioral changes, injuries, or death of animals. High noise levels emitted from roads often lead to hearing damage and increased hearing thresholds in animals. Related to these conclusions, it is proven that impulsive noise above 125 dB(A) generally causes permanent hearing damage in birds, while continuous noise above 93 dB(A) very often causes increased hearing thresholds. From the perspective of animal populations, ecological consequences may include reduced reproductive success and lower survival probabilities in habitats affected by noise from road networks.

Due to the ecological risk and numerous consequences of road network noise, implementation of appropriate protection measures for endangered animal populations is often necessary. These measures must be carefully considered, analyzed, and planned during the design and planning of road infrastructure. To achieve the best option for planning and implementing protective measures for different animal groups, further research is needed, which would significantly contribute to the field.

According to available data, it can generally be concluded that insufficient attention is currently given to the issue examined in this work, especially in developing countries.

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An Analysis of Novice Drivers' Unpredictable Behavior

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Abstract: Driver behavior is one of the key factors influencing traffic flow conditions at unsignalized intersections. Gap acceptance models at such intersections are based on the premise that drivers on minor approaches do not receive a signal but instead make independent decisions on when it is appropriate to enter the intersection. Although the actions involved in performing minor maneuvers are practically identical across drivers, the acceptance of time headways depends almost entirely on the driver's individual judgment. Given the specific characteristics that novice drivers represent within the traffic stream, their behavior was selected as the focus of this research. A comprehensive review of the available literature revealed that this is the first theoretical analysis addressing the influence of novice drivers on gap acceptance under real traffic conditions. For the study, 3,882 headways were measured, and after data selection, a database of 3,313 headways was compiled for further analysis. To analyze novice driver behavior, accepted and rejected headway curves were developed for minor maneuvers at three unsignalized intersections. These curves were generated separately for novice and experienced drivers to enable a comparative behavioral analysis. The results clearly indicate the unpredictability of novice drivers' behavior at unsignalized intersections in contrast to the more consistent behavior of experienced drivers.

Keywords: Novice drivers, unsignalized intersections, headway.

1 Introduction

Intersections regulated by traffic signs and general traffic rules are the most common type of intersections. These intersections are internationally known as unsignalized or priority intersections. According to [1], at unsignalized intersections, drivers are not controlled, meaning they must decide for themselves when it is safe to enter the intersection. A driver attempting to enter the intersection must yield the right of way to vehicles in the priority stream. Thus, every driver on the minor approach must assess which headway between vehicles in the major stream is long enough to safely per-

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form the desired maneuver. This process is known as the gap acceptance process, and it is expressed in seconds.

According to [2], headways between vehicles are defined in such a way that the time of passage of any vehicle that comes into direct conflict with the subject vehicle can be considered the beginning of the interval. In [3], headway is defined as the time interval between the arrival of one vehicle from the major stream at the intersection and the arrival of the next vehicle from the same stream. To further define the gap acceptance process, another term was introduced, the so-called lag. More precisely, lag represents the time from the moment a vehicle from the minor stream arrives at the stop line until the moment a vehicle from the major stream passes in front of the approach where the minor stream vehicle is waiting [2].

Previous studies have reported mixed findings regarding factors influencing gap acceptance. In [4], there was no significant effect of driver age, while in [5] and [6] age plays a role, with younger drivers being more aggressive and older drivers accepting larger headways. According to [7], younger drivers are more inclined to accept headways than older ones. Sangole et al. [8] further showed through a neuro-fuzzy model for two-wheelers that driver age is a key factor. From a safety perspective, Tupper et al. [9] emphasized that gap acceptance can contribute to accidents, particularly among young drivers. These inconsistencies highlight the need for further research to clarify how age and experience shape driver behavior in complex traffic situations, which is the main focus of this study.

The available research on novice drivers' gap acceptance has been conducted in simulator-based settings. Mitsopoulos-Rubens et al. [10] showed that novice drivers tend to accept more headways than experienced drivers, often within the "dilemma zone." Similarly, Scott et al. [11] found differences in visual information acquisition strategies, with young novice and older experienced drivers classified as higher-risk compared to young experienced drivers. More recently, Tian et al. [12] demonstrated that the original Rural Intersection Conflict Warning System (RICWS) reduced the likelihood of accepting critical headways among older and middle-aged drivers, but had little effect on novice drivers, likely due to their limited attention to or misunderstanding of the warning signs.

The studies by [10], [11], and [12] are the only available works directly related to the topic addressed in this paper. The scarcity of research on headways accepted by novice drivers, both globally and within our region, provided the main motivation for undertaking this study. Unlike previous works that rely on driving simulators, this research examines novice drivers' behavior in real traffic flow. The primary objective is to analyze their actual behavior in situations where they are unaware that their actions are being observed, with particular attention to their implications for traffic conditions and safety. The novelty of this paper lies in the fact that it may represent the first study to investigate such behavior under natural traffic conditions, thereby contributing to a better understanding of its impact on overall traffic performance.

2 Methodology

In order to determine the influence of the highest-risk group of drivers on the gap acceptance process, a comparative analysis of the behavior of novice drivers and experienced drivers was conducted within this study. During the data collection process, it was essential to ensure conditions of saturated traffic flow under daylight, without the presence of rain or snow, in order to isolate the predefined headways. According to [13], vehicles operated by novice drivers must be specially marked. These drivers were identified based on the letter "P" displayed on their vehicle [14].

A request was submitted to the Ministry of the Interior, Doboj Police Department, outlining the research plan and the need for their assistance in collecting all necessary and available data. Following a positive response, access was granted to review video recordings of intersections in the urban area of the city of Doboj.

The research was spatially focused on three unsignalized intersections located in the urban area of the city of Doboj, Republic of Srpska, Bosnia and Herzegovina. The observed intersections are situated at the following locations:

- The intersection of Sveti Sava Street, Miloš Obilić Street, King Aleksandar Street, and Vidovdanska Street (marked as I_1 in the paper);
- The intersection of Vasilije Ostroški Street and King Aleksandar Street (I_2);
- The intersection of Vojvoda Stepa Street and King Dragutin Street (I_3).

For the purpose of measuring headways, one of the most widely used techniques, the so-called photographic method, was applied. It is considered one of the most reliable methods for determining traffic flow parameters, as it does not influence driver behavior. This represents one of the main advantages of the research conducted in this study, as novice drivers did not alter their behavior and drove in a natural, routine manner.

In order to determine the value of accepted and rejected headways, it was first necessary to isolate individual time points. Two imaginary lines were drawn: one at the entry point into the center of the intersection (A), and the other at the location of the potential conflict between vehicles in the major stream and those on the minor approach (B) (Fig. 1).

To determine the length of the headway, two key time points are considered: T_1 as the beginning of the headway and T_2 as its end. In addition to accepted and rejected headways, accepted and rejected lags were also taken into account. The moment when the subject vehicle A stops at the entry point to the center of the intersection represents the first key time point T_1 , i.e. the beginning of the lag. The moment when vehicle C, coming from the major stream, reaches the imaginary line B marks the second key time point T_2 , i.e. the end of the lag. The lag is then calculated as the difference ($T_2 - T_1$). Based on the figures below, it can be concluded that the lag in this traffic situation was rejected.

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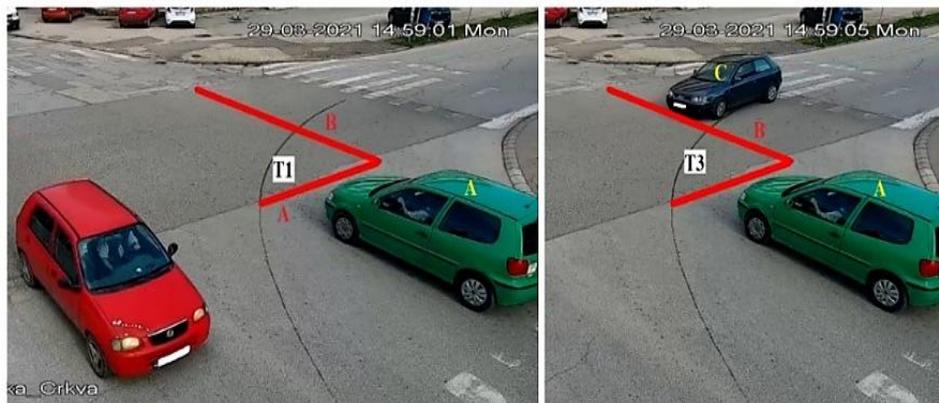


Fig. 1. Timestamps [15]

The moment when vehicle C from the major stream touches the imaginary line B represents the next key time point, T_3 , which is necessary for forming the next analyzed headway. The time point T_3 , as the beginning of the headway, simultaneously marks the end of the lag T_2 .

The moment when vehicle D from the major stream touches the imaginary line B, that is, when the front bumper of the vehicle in the major stream reaches line B, represents the next characteristic timestamp, labeled T_4 (Fig. 2). The headway is defined as the difference between these two timestamps ($T_4 - T_3$). Based on the following figure, it can be concluded that the headway was rejected, meaning it can be included in the analysis aimed at determining the values of both accepted and rejected headways.

The creation of the database involves repeating the previously described procedure, and for each calculated headway, it is verified whether the headway was accepted or rejected, depending on whether the subject vehicle A entered the center of the intersection during the observed interval. In the cases shown in the following figures, it is clear that the driver from the minor approach, who is also a novice driver, rejected one more headway before entering the center of the intersection. More precisely, the difference between timestamps T_5 and T_6 , i.e., the time headway between vehicles E and F, represents the accepted headway.

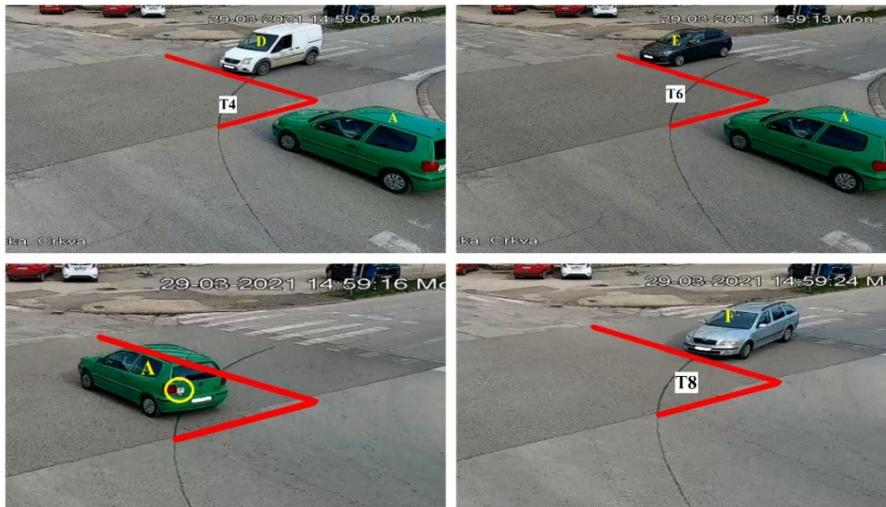


Fig. 2. Decision-Making Process for Gap Acceptance [15]

3 Research results

Using the photographic method, a database of 3,882 headways and lags was collected, from which a core dataset of 3,313 intervals was derived for analysis. The study assumes that the probability of headway acceptance increases with headway length and that this relationship differs across intersections and particularly between novice and experienced drivers. To test this, the percentage of accepted and rejected intervals was calculated for all intersections and turning maneuvers, except for the right turn from the minor approach at intersection I₁, where the limited number of intervals after filtering prevented reliable calculation.

3.1 Percentage values of accepted and rejected headways at the intersection I₁

Fig. 3 shows curves where the x-axis represents interval class values of 1 second and the y-axis the percentage of accepted and rejected intervals. For experienced drivers, almost all headways shorter than 4 seconds were rejected, and those longer than 10 seconds were accepted. In contrast, novice drivers exhibited inconsistent patterns, particularly in the 6-9 second range, where they sometimes rejected larger headways after accepting shorter ones. This irregularity suggests instability in their decision-making and reflects limited experience in assessing traffic risk.

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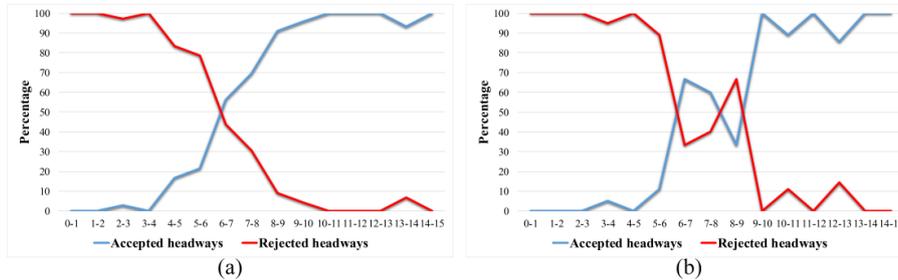


Fig. 3. Curves of accepted and rejected headways for through traffic on the minor street for experienced drivers (a) and novice drivers (b) at the intersection I₁

Fig. 4 shows the curves of accepted and rejected headways for left turns from the minor street. Among experienced drivers (Fig. 4a), the curve is relatively uniform, with all headways shorter than 6 seconds rejected, which is expected given that left turns are among the most demanding maneuvers. In contrast, novice drivers (Fig. 4b) display pronounced fluctuations, accepting even shorter headways than experienced drivers while at the same time rejecting longer, safer ones. This inconsistency suggests that novice drivers tend to underestimate risks associated with short headways and struggle to evaluate longer ones, increasing the likelihood of misjudgments during left turns.

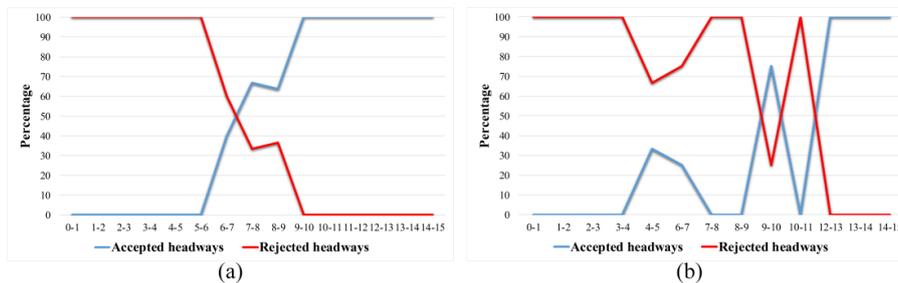


Fig. 4. Curves of accepted and rejected headways for left turn from minor street for experienced drivers (a) and novice drivers (b) at the intersection I₁

3.2 Percentage values of accepted and rejected headways at the intersection I₂

For intersection I₂, Fig. 5 shows the curves of accepted and rejected headways for right turns from the minor street. Among experienced drivers (Fig. 5a), the pattern is consistent, i.e. all headways shorter than 5 seconds were rejected, those longer than 8 seconds were accepted, and acceptance gradually increased within the 5-8 second range. Novice drivers (Fig. 5b), however, displayed less uniform behavior, though with fewer irregularities than at the previous intersection. Notably, in the 6-8 second range, the percentage of accepted and rejected headways was equal, indicating indecision and a lack of clear judgment. These observations imply that novice drivers face difficulties in evaluating borderline headways, which may reduce the

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predictability of their behavior and elevate the risk of conflicts in turning maneuvers at unsignalized intersections.

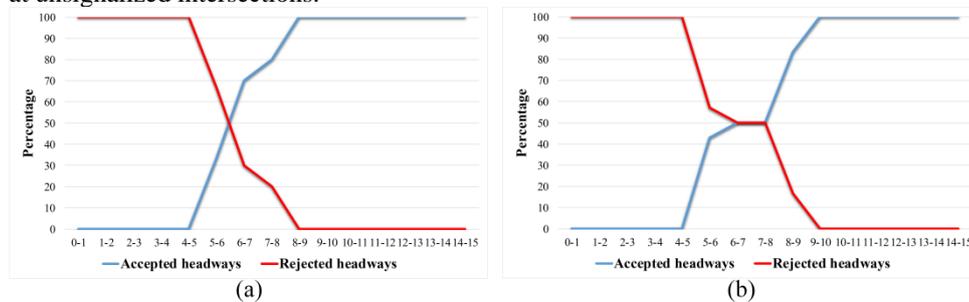


Fig. 5. Curves of accepted and rejected headways for right turn from minor street for experienced drivers (a) and novice drivers (b) at the intersection I₂

Fig. 6 shows the headway acceptance curves for left turns from the minor approach. Among experienced drivers (Fig. 6a), the curve is relatively uniform, with only minor deviations in the 9-11 second range. In contrast, novice drivers (Fig. 6b) exhibit more irregular behavior. While all headways shorter than 4 seconds were rejected, significant fluctuations appear from 12 seconds onward, as some drivers rejected even very large headways (12-15 seconds). These findings imply that novice drivers not only struggle with borderline headways but may also misjudge evidently safe ones, reflecting insufficient risk assessment skills.

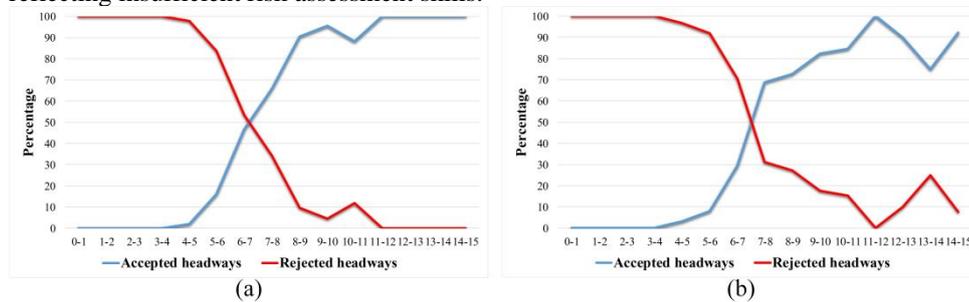


Fig. 6. Curves of accepted and rejected headways for left turn from minor street for experienced drivers (a) and novice drivers (b) at the intersection I₂

3.3 Percentage values of accepted and rejected headways at the intersection I₃

As shown in Fig. 7, the headway acceptance curves for left turns from the minor approach again reveal clear differences between experienced and novice drivers. Experienced drivers (Fig. 7a) show a largely uniform pattern, rejecting all headways shorter than 4 seconds, with only minor deviations where some longer headways (13-14 seconds) were rejected. In contrast, novice drivers (Fig. 7b) display pronounced variability, including the rejection of very long headways, even up to 16-17 seconds. These results imply that while experienced drivers generally apply consistent

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judgment, novice drivers demonstrate instability and a tendency to misjudge even clearly safe headways.

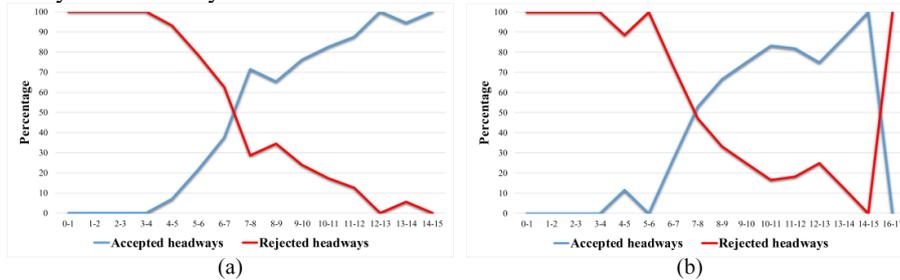


Fig. 7. Curves of accepted and rejected headways for left turn from minor street for experienced drivers (a) and novice drivers (b) at the intersection I₃

Fig. 8 shows the headway acceptance curves for right turns from the minor approach, where an atypical pattern emerges for experienced drivers (Fig. 8a), marked by irregularity due to the rejection of a headway in the 8-9 second class. In contrast, novice drivers (Fig. 8b) display their most uniform curve across all intersections, rejecting all headways shorter than 8 seconds and accepting those longer, while experienced drivers applied a lower threshold of 6 seconds. However, it cannot be ruled out that the relatively small sample of collected headways for this maneuver may have contributed to this result.

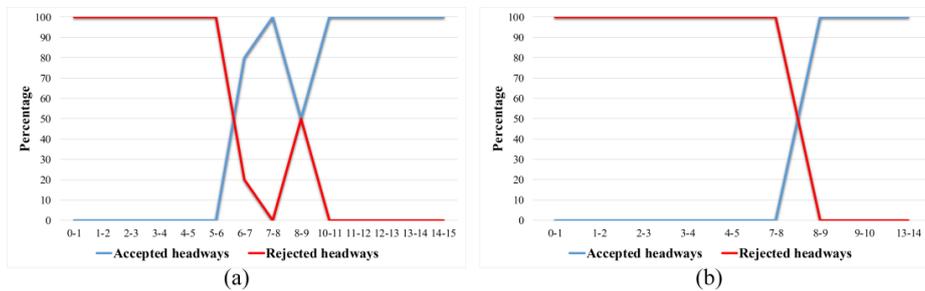


Fig. 8. Curves of accepted and rejected headways for right turn from minor street for experienced drivers (a) and novice drivers (b) at the intersection I₃

4 Conclusion

Novice drivers are consistently present in the traffic flow, indicating that their participation influences traffic conditions at unsignalized intersections. The decisions they make when estimating time headways in potentially conflicting traffic streams have a significant impact on traffic safety. Specifically, accepting headways shorter than the safe threshold leads to potentially hazardous traffic situations, while accepting headways longer than the critical threshold reduces the operational capacity of the inter-

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section. An important aspect to emphasize is that novice drivers are not a homogeneous group, as their behavior may also vary depending on their level of experience within the two-year period, during which they are required to display the "P" plate.

A review of the available literature revealed only three studies presenting results on novice drivers' headway acceptance behavior using driving simulators. However, to date, no research has been presented that investigates the influence of novice drivers on time headway values at priority intersections under real traffic conditions. Therefore, the key contribution of the present study lies in the results obtained through local, field-based measurements conducted under fully realistic traffic conditions.

The results of the study showed that the position and shape of the accepted and rejected headway curves vary depending on the specific intersection, the type of minor maneuver, and, most notably, the driver's level of experience. In the case of experienced drivers, each maneuver across the analyzed intersections exhibited a more or less consistent gradual increase in the percentage of accepted headways with increasing headway length. Thus, the general shape of the accepted and rejected headway curves for experienced drivers was fairly uniform and consistent. In contrast, novice drivers exhibited substantial variability in the headway acceptance process across nearly all minor maneuvers at all three analyzed intersections. The analysis revealed significant fluctuations in the acceptance of headways by novice drivers, resulting in headway acceptance curves characterized by irregularity and variability. These findings clearly point to the unpredictability of novice driver behavior at priority intersections compared to experienced drivers.

This research is limited by the number of intersections, maneuvers, and the relatively small dataset in some cases. Future studies should expand the analysis to larger datasets, a broader range of intersections and maneuvers, and novice driver subgroups with varying experience. Such efforts would enhance result reliability and support the development of measures to improve traffic flow efficiency and intersection capacity, while also contributing to targeted safety improvements at unsignalized intersections.

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Enhancing Traffic Planning Process by Incorporating Driver Experience: A Fuzzy-Logic Approach

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Abstract. Urban traffic planning typically depends on the estimation and/or empirical measurement of quantitative parameters such as traffic flow and delays. However, despite all known parameters, the procedure of traffic planning often overlooks drivers' experiences in traffic. Considering that drivers are participants in traffic as well as users of the road infrastructure, their experience-measured through the level of satisfaction can be a valuable supplementary metric parameter in procedures of planning and controlling traffic flows. This paper presents the application of a fuzzy logic system in evaluating driver satisfaction at a three-way intersection. Based on experimental results and expert knowledge, membership functions for the inputs - time of the day, delays, and traffic flow- were defined, along with the corresponding fuzzy rule base. The system's output quantifies the driver's level of satisfaction. Results highlight the potential for integration of fuzzy logic systems into procedures of traffic planning, where conventional performance measures may fail to capture user discomfort. By taking driver experiences into account, traffic planners can prioritize interventions - such as signal timing adjustments, intersection redesigns, and strategic rerouting - directly targeting the minimization of driver dissatisfaction. By placing user experience at the core of planning decisions, this method supports the development of responsive, user-centric urban mobility solutions.

Keywords: Traffic planning, Fuzzy Logic System, Driver Experience.

1 Introduction

Quantitative measurements such as traffic flow, delay, and capacity are traditionally based on the process of urban traffic planning in order to evaluate network performance and to guide infrastructure and operational decisions. Conventional metrics often fail to capture the experience of traffic participants, which is generally subjective. However, the satisfaction of traffic participants can be an important indicator of public acceptance of road and traffic measures. Perceived level of service and drivers' subjective assessments may be different compared to purely traffic-engineering

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measures. Due to the subjectivity of traffic participants, it is not easy to predict their satisfaction with the implemented measures [1]. Integrating driver perception and user-centered metrics into traffic planning has great importance. In [2], authors examined factors influencing the perceived value of travel time in European urban areas, highlighting that travel satisfaction is shaped not only by objective measures such as travel duration and congestion, but also by subjective aspects including comfort, predictability, and personal preferences. In addition, traffic conditions, road surface quality, and the surrounding driving environment affect driver stress levels [3].

The application of fuzzy logic in traffic engineering is present in developing fuzzy controllers for isolated and coordinated intersections, adaptive traffic-signal systems that use flow and queue information, and methods that incorporate human-centric criteria into level of service assessments [4, 5]. In [6], a fuzzy-logic system as an adaptive fuzzy-logic traffic control system (AFLTCS) is proposed for dealing with uncertainties and non-linearities in traffic, providing more responsive control strategies for traffic management. The application of a fuzzy controller to ensure precise determination of green signal duration is presented in [7]. Chala et al. presented a novel agent-based fuzzy traffic control system for multiple road intersections designed to operate in a decentralized manner, with each intersection having its own agent (fuzzy controller) functioning concurrently [8]. On the other hand, although some cities use traffic information systems to manage congestion, their effectiveness depends on drivers perceiving the system as useful and of adequate quality [9]. Due to the high uncertainty and variability inherent in real traffic conditions, understanding driver behaviour remains a complex problem that often requires the use of flexible and adaptive modelling techniques, such as fuzzy logic. Xiao et al. proposed a novel fuzzy deep attention network (FDAN) method to recognize driver behaviours [10]. Human behaviour assessment is important in critical applications such as driving or piloting tasks. In [11], the authors presented an experiment with fuzzy-logic-based models for approximating data representing human driver behaviour during a simple lane-changing task.

In this paper, the fuzzy logic approach for enhancing the traffic planning process by evaluating driver satisfaction is presented. The fuzzy logic system is designed for a three-way intersection, using both experimental data and expert knowledge to define membership functions and a rule base. Based on experimental results and expert knowledge, three inputs are defined – time of day, delays, and traffic flow, as well as an output - driver's level of satisfaction. The results showed how fuzzy logic approaches can complement conventional traffic performance measures and support user-centered planning interventions.

2 Problem description

The three-way traffic signalized intersection of Pantalejska Street is one of the most frequent three-way intersections in the city of Niš. This intersection connects the wider central area of the city, and is used by cars, light trucks, and public transport vehi-

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cles, i.e. buses. The problem that was observed at this intersection, due to both dependent and independent research, is the geometry of the southern way of this intersection (the southern way of Pantalejska Street). Width of the lanes on the southern way is especially challenging because of making left turns from the eastern to the southern way of Pantalejska Street during peak periods of the day. During these periods, it is necessary for the driver to "catch" a sufficiently large arc when making a left turn in order to safely make the turn, because the waiting lines on the southern way of Pantalejska Street are larger. While drivers on the eastern approach have to take a large arc in order to make the turn safely, longer queues are created on the southern approach because the traffic participants on that approach have a conditional arrow for right turns at the light signalling. However, in most cases, there is often a participant in the queue who intends to make a left turn at the intersection, which negatively affects the participants in traffic, because their waiting time to pass through the intersection increases, as well as the length of the queue. All of this greatly affects participants' level of satisfaction.

A problem that is also present at this intersection is the insufficient capacity of the intersection to "accept" a larger number of vehicles during the morning and afternoon peak hours. In addition, this intersection is used by citizens when going to and from work, attending school/faculty, as well as going to and from shopping, recreation, and private visits.

2.1 Description of the three-way intersection

The intersection of Knjaževačka and Pantalejska Streets is located in the wider central area and connects two larger urban areas, the so-called Durlan and Bulevar. The high frequency of traffic is caused by the relatively dense population in these areas, the presence of many public transport lines, as well as the close vicinity of various facilities (Fig. 1). There are several types of such facilities, including the textile factory "Benetton", the shopping center "Delta Planet", multi-story residential buildings, family houses, a couple of restaurants, an auto parts store, a paint and varnish store, a gas station, a self-service laundromat, "Niteks" ambulance, a kindergarten and the river Nišava.

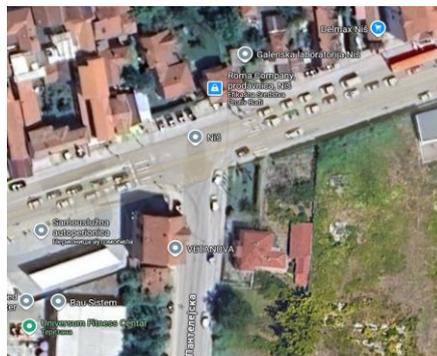


Fig. 1. Satellite view of the three-way intersection

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The intersection consists of three ways that are systematized and marked in relation to the cardinal directions (Fig. 2):

- The southern approach to Pantelejska Street (direction from the bridge on the Nišava river to the intersection), marked in white in Fig. 2;
- The Eastern approach to Pantalejska Street (direction from the factory "Benetton" to the self-service laundromat), marked in red in Fig. 2;
- The western approach to Pantalejska Street (direction from the self-service laundromat to the factory "Benetton"), marked in yellow in Fig. 2.



Fig. 2. Marked ways of three-way intersection

3 Fuzzy-Logic Approach for enhancing traffic planning process

The fuzzy system has become an important approach for dealing with uncertainty and nonlinearity, particularly in complex systems where accurate modeling is difficult [12]. It has been applied in areas such as autonomous driving, robotics, and image processing, as well as in inference-based applications. For instance, in autonomous vehicles, fuzzy logic is employed for path planning, obstacle avoidance, and multi-sensor data fusion, while in image processing, it is used for image enhancement and object recognition [13,14]. A fuzzy logic system (FLS) can be described as a nonlinear mapping of an input feature vector into a scalar output (in the case of vector outputs, this is decomposed into a set of independent multi-input/single-output systems) [15]. In general, an FLS transforms crisp inputs into crisp outputs, with the fuzzy inference process acting as an intermediate step. Its implementation in practical scenarios involves three main stages: fuzzification, fuzzy inference, and defuzzification. Fuzzification determines the degree to which input values belong to corresponding fuzzy sets. These membership values are then applied to the antecedents of fuzzy rules, and finally, defuzzification converts the fuzzy output produced by the inference engine into a crisp value.

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According to the defined problem, FLS is designed to estimate drivers' level of satisfaction based on inputs (Fig. 3). To determine the factors that influence driver satisfaction, a dependent survey of drivers at the intersection was conducted. Based on 107 answers, three factors were detected as influencing the drivers' level of satisfaction. Those factors are used as inputs of FLS: Time of Day, Delays, and Traffic Flow. The output of the FLS is the Drivers' Level of Satisfaction (SLevel). All variables and their membership functions were defined based on both dependent and independent research, as well as through interviews with experts in the field of Traffic Planning.

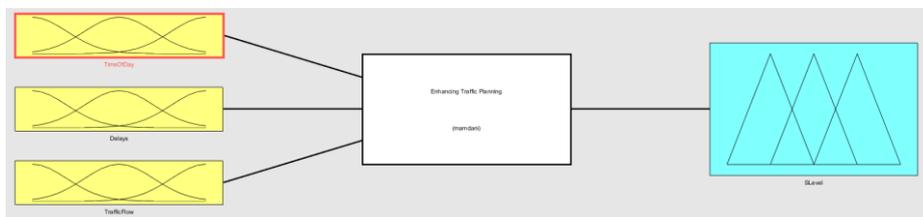


Fig. 3. FLS for estimating traffic participants' level of satisfaction

The input variable Time of Day is divided into five ranges: Morning (Morning), Morning Peak Load (MLoad), Noon (Noon), Afternoon Peak Load (NLoad) and Evening Period (Evn) (Fig. 4). The period from 12 a.m. to 7 a.m. (00:00-07:00) was taken as the morning, because most people are sleeping during that period, and there are only a few vehicles on the streets.

The Morning Peak Load includes the period from 6 a.m. to 11 a.m. (06:00-11:00), when people start commuting to go to work, school, or faculty and to run various errands such as shopping. The period from 10 a.m. to 2 p.m. (10:00-14:00) was taken as the Noon, when the number of vehicles decreases compared to the morning peak load, and this period is mostly used for personal activities. The Afternoon Peak Load from 1 p.m. to 7 p.m. (13:00-19:00) is the busiest part of the day in terms of traffic, because during this period, people change work shifts, school, and college. Additionally, during this period, private visits, shopping, and recreational activities are common. The time interval from 6 p.m. to 12 a.m. (18:00-24:00) is defined as the Evening Period. During this time, evening events take place and people return from afternoon shifts, while the number of vehicles in traffic gradually decreases.

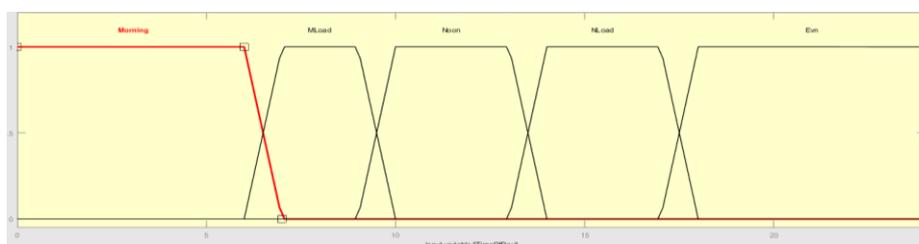


Fig. 4. Fuzzy membership functions of input Time of Day

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The second input Delays was divided into three ranges: Short, Medium, and Long (Fig. 5). Dependent research of drivers was conducted to gather responses regarding how acceptable the delay (waiting time) was for them to pass and leave the intersection. Based on research results, it was concluded that short delays range from 0 to 40 seconds, medium delays range from 30 to 70 seconds, and high delays are those exceeding 60 seconds.

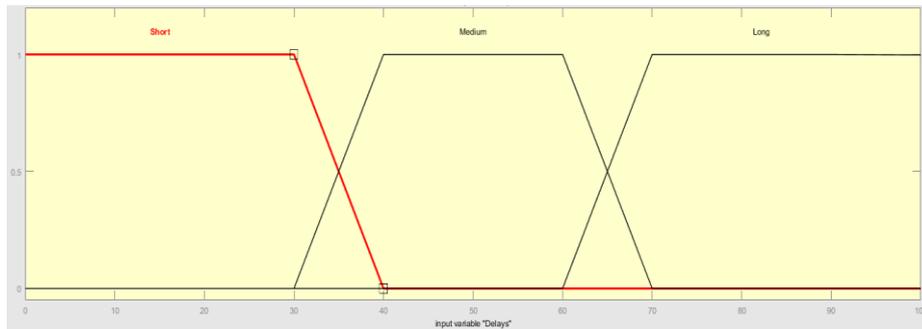


Fig. 5. Fuzzy membership functions of input Delays

The Traffic flow input is defined as the number of vehicles in the queue in front of the surveyed driver. For that input, the following classification is applied: LowT, MidT, and HighT (Fig. 6). For LowT, a value of 0 to 3 vehicles in the queue is considered, for MidT, a value of 2 to 6 vehicles, while for HighT, a value of 5 or more vehicles. This classification is justified by the observation that most traffic signal timing plans are designed to allow the passage of 4-6 vehicles during the green phase.

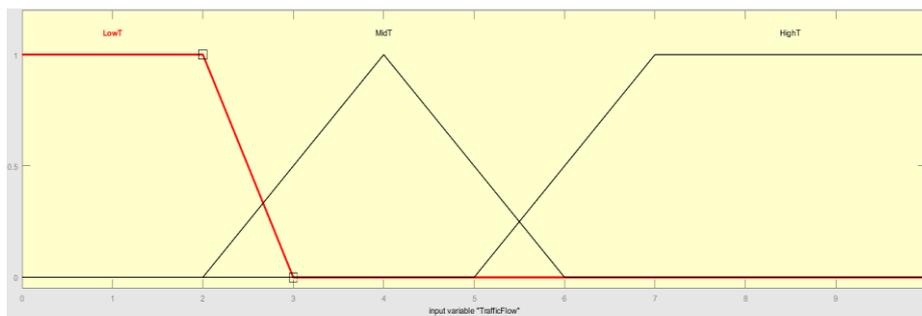


Fig. 6. Fuzzy membership functions of input Traffic flow

The output Drivers' level of satisfaction (SLevel) is divided into three categories: LowS, MidS, and HighS (Fig. 7). The range of LowS is 0–30%, while the ranges of MidS and HighS are 20–70% and 60–100%, respectively.

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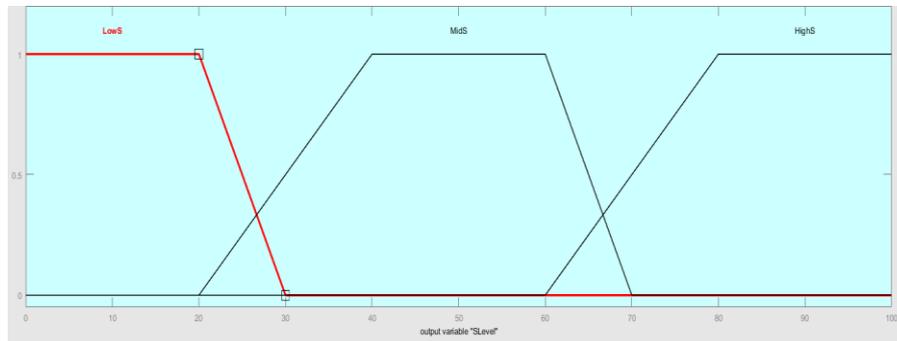


Fig. 7. Fuzzy membership functions of output Participants' level of satisfaction (SLevel)

Experts in the field of traffic planning were interviewed, and based on their knowledge and experience, fuzzy rules for the FLS were defined. Some of the fuzzy rules are given below:

If Time of Day is Morning and Delays is Low and Traffic Flow is Low then SLevel is High.

If Time of Day is Morning and Delays is High and Traffic Flow is High then SLevel is Low.

If Time of Day is MLoad and Delays is Low and Traffic Flow is Mid then SLevel is High.

If Time of Day is Noon and Delays is High and Traffic Flow is High then SLevel is Low.

If Time of Day is Evm and Delays is Mid and Traffic Flow is Low then SLevel is Mid.

4 Results and discussion

During the test of this approach, five characteristic cases were identified. The first case is when Time of Day is 6 a.m., Delays is 20 seconds, and Traffic Flow is 2. This can be represented as: 'What is drivers' level of satisfaction at 6 a.m., with delays of 20 seconds, and when 2 vehicles are in the queue in front of the surveyed driver?' By using the FLS, the driver's level of satisfaction is 84.7%, which corresponds to High (Fig. 8).

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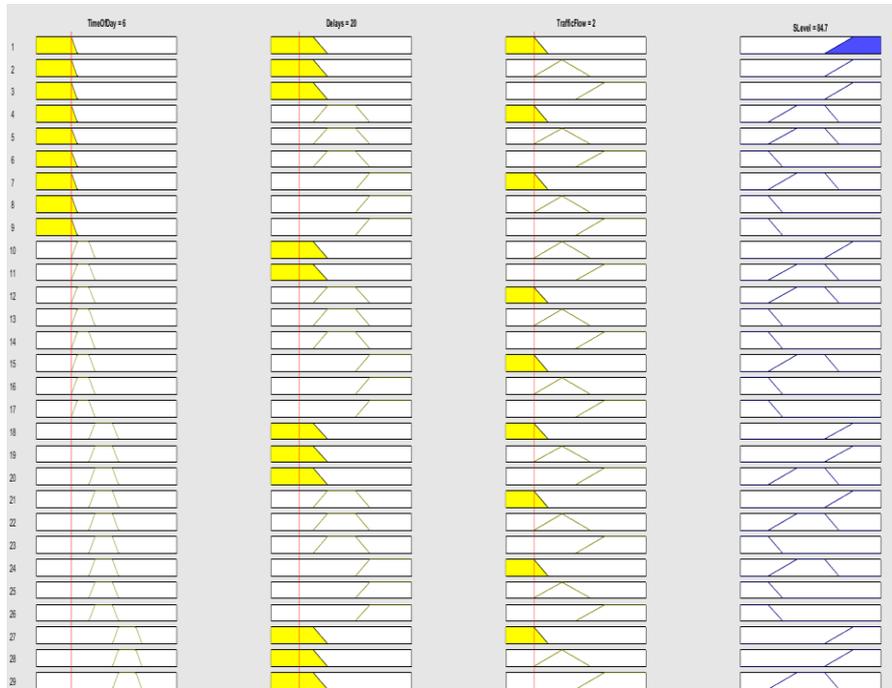


Fig. 8. Rule viewer for the first case

The inputs and outputs for the five identified characteristic cases are presented in Table 1.

Table 1. Inputs and outputs for the five identified characteristic cases

Time of Day	Delays [s]	Traffic Flow [No. of vehicles]	SLevel [%]
6	20	2	84.7
8	40	2	47.1
12	70	7	12.4
16	50	9	12.4
20	30	7	47.1

The results showed that the proposed FLS provides accurate and consistent outputs, closely matching the expected values. This indicates that the fuzzy logic approach is capable of effectively modeling the problem and handling variations in the input data. Moreover, the results confirm the reliability of the inference process with satisfactory precision.

5 Conclusion

This paper presents the potential of using fuzzy logic systems in enhancing urban traffic planning by incorporating subjective driver experience into performance evaluation. By designing a fuzzy logic system for a three-way intersection, using quantitative inputs such as Time of Day, Delay, and Traffic Flow, and an output representing drivers' satisfaction, the research demonstrates that fuzzy approaches can successfully model complex and non-linear relationships between traffic conditions and user perceptions. Testing process included five characteristic cases. Results showed that the fuzzy logic system is capable of distinguishing different traffic scenarios and predicting corresponding levels of driver satisfaction. Although subjective, drivers' experience can be an important factor that may enable planners to prioritize interventions, such as signal timing adjustments or intersection redesigns, that directly target improvements in perceived service quality.

This approach can be used at all signalized intersections, as well as on roundabouts, regardless of the number of ways. However, for other types of intersections (not signalized), the distribution of participant satisfaction is different, especially at roundabouts. Different rules, as well as different reasoning processes, lead to differences in the structure of FLS for different types of intersections. Nevertheless, fuzzy logic-based models offer a practical and adaptive method for urban traffic planning, providing predictive capability. According to that, this approach can be used to set traffic light timing plans, signal timing adjustments, lane reassignment, combine traffic directions, etc. Taking into account the experiences and expectations of traffic participants, these systems support the development of human-centered mobility solutions that can enhance both operational efficiency and public acceptance of traffic management measures. Future research will be oriented towards the validation of the presented approach through independent research on a larger sample at the presented intersection, as well as at other signalized intersections. In addition, further research may be directed toward the application of fuzzy logic approaches to all types of intersections to improve the accuracy and applicability of user-centered planning tools.

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Comparative Analysis of Traffic Flow at Intersections: A Case Study of Roundabout in the City of Niš

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Abstract. The procedure of traffic planning at intersections is a complex and long-term series of coordinated activities to yield effective and high-quality outcomes. In order to provide useful results, traffic planners must identify solutions that ensure planned traffic-flow capacities facilitate safe and unobstructed vehicle movement. The continual increase in motorized and non-motorized traffic volumes further exacerbates traffic planning procedures complexity. Furthermore, traffic flow capacity forecast activities on the target intersection as well as in intersections in close vicinity are essential to the comprehensive planning framework. In this paper, a case study of roundabouts' performance - traffic flow and delays during peak periods - is presented. In 2022, empirical measurements of these parameters by counting vehicles in a specific roundabout in the city of Niš, Serbia, were done. Based on these data, forecasts for traffic flow and delays were obtained by a simulation process for a two-year period. In order to validate simulation results, traffic flow and delays were measured for the same roundabout in 2024. Results of comparative analysis showed that the simulation projected traffic flow and delays within acceptable error margins.

Keywords: Traffic flow, delays, roundabout.

1 Introduction

With the development of industry and technological progress, the mass production of motor vehicles has been enabled, making their use widespread and adapted to the needs of the population [1]. Consequently, with the increasing number of vehicles on the roads, traffic congestion and frequent delays occur more intensively, disrupting continuity and reducing traffic flow capacity [2]. This increase in vehicles leads to a greater number of conflict points within the flow itself. Such problems generate additional challenges for planners and designers of surface intersection infrastructure, since the increased workload and growing complexity require the application of advanced analytical methods and decision-making that ensure functionality, safety, and sustainability of the system.

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Surface intersections are a type of intersection where the relationships among traffic participants are regulated on a shared roadway. In practice, they are both far more common because of traffic needs and for economic reasons, as well as simpler financing of their construction [1]. Surface intersections can be classified into three main groups: unsignalized, where traffic is regulated primarily by signs and right-of-way rules; roundabouts, which function on the principle of circular flow and allow smoother and safer traffic movement; and signalized, where vehicle and pedestrian movement is directed using traffic lights [3]. Recent studies emphasize the importance of adapting methodological frameworks to local conditions, as international standards are not always directly transferable to different urban environments [4], [5].

In this paper, a comparative analysis of the traffic flow at a selected roundabout in the City of Niš for the years 2022 and 2024 was conducted. The analysis included actual traffic flow values and forecast results, with the aim of determining the degree of deviation and assessing the accuracy of the applied methodology. The selection of the applied methodology was guided by the specific traffic conditions in the City of Niš, where the roundabout under study is exposed to high traffic demand and heterogeneous vehicle flows. This approach provides a reliable framework for evaluating capacity, delay, and level of service, which are key indicators for identifying practical traffic solutions. In this way, the reliability of the forecast and its practical applicability in future traffic flow planning were evaluated. The presented study not only addresses local traffic challenges but also contributes to the broader discussion on the transferability and applicability of traffic planning procedures in urban contexts.

2 Methodology

Research on traffic planning and intersection performance generally relies on several methodological approaches. The most widely applied are:

1. Empirical field measurements – direct vehicle counting and traffic flow observations, which provide baseline data on traffic volumes and delays [6];
2. Analytical procedures – standardized approaches such as those presented in the Highway Capacity Manual (HCM), which offer deterministic models for capacity and level of service evaluation [7];
3. Microscopic simulation models – software such as VISSIM, SIDRA or Aimsun, that replicate vehicle movements in detail and allow scenario testing under varying traffic conditions [8];
4. Data-driven approaches – using machine learning and big data analytics to predict traffic patterns and optimize control strategies [9].

In this study, the methodology combined empirical traffic counts with a simulation and validation process. During 2022, manual vehicle counting was conducted at the selected roundabout in the city of Niš, Serbia, covering peak traffic hours [6]. These

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empirical measurements served as the input for the simulation, i.e. forecasting process of traffic flow and delays over a two-year period. To validate the accuracy of the forecasting process, repeated field measurements were conducted at the same location in 2024 using the same methodology- manual vehicle counting, following good practices of forecasting validation [10].

This methodological framework was considered adequate for the study objectives for three main reasons. First, it ensures a direct link between observed traffic behavior and simulated outputs, reducing the risk of bias associated with purely model-based approaches. Second, it provides a cost-effective and practical tool for medium-sized cities, where advanced simulation platforms may not always be available. Finally, the empirical–simulation–validation connection strengthens the robustness of the results, allowing their application in future planning of similar intersections [9].

3 Characteristics of the analyzed intersection

In order to observe the characteristics of traffic flows and identify potential problems in the functioning of the urban network, a detailed analysis of one of the most significant intersections in the city was carried out. The analyzed intersection is located in the wider central zone of the city of Niš and represents the junction of Bulevar Ne-manjića and Vojvode Mišića Street (Fig. 1). Due to its location, which provides connections to several attractive and functionally important areas of the city, this intersection has a very high traffic flow and is considered to be one of the busiest in the urban area [1].



Fig. 1. An observed intersection [1]

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In the immediate vicinity of the observed intersection, there are multi-story residential blocks, the large Delta Planet shopping center, and the Health Center. Also, the Fire Department building and the Traffic Police building, a kindergarten, a gas station, as well as the Nišava River are near intersection [1].

For a more precise analysis and clearer understanding of functional characteristics, the approaches to the intersection were systematized and designated in relation to the cardinal directions:

- the southern approach represents Vojvode Mišića Street (direction from the Health Center toward the Delta Planet shopping center),
- the western approach is Bulevar Nemanjića (direction from the kindergarten toward the Delta Planet shopping center),
- the northern approach is Vojvode Mišića Street (direction from the Delta Planet shopping center toward the Health Center),
- The eastern approach represents the roadway connecting the Delta Planet shopping center and the kindergarten.

A satellite image of the observed roundabout is shown in Figure 2.



Fig. 2. Satellite image of the observed intersection with marked approaches [1]

Bulevar Nemanjića is one of the longest streets in Niš, with a total length of about 2.5 km. On its western side, it connects with Sedmi juli Street, while on its eastern side, it intersects with several side streets (Blagoja Parovića, Pariske Komune, Sremska, Branka Miljkovića), as well as with Vizantijski Bulevar, and finally con-

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nects to Bulevar dr Zorana Đinđića [1]. Vojvode Mišića Street, approximately 1.2 km long, stretches from the bridge over the Nišava River, north of the observed intersection, to Čair Park, located in the south. Their mutual crossing forms a four-arm roundabout, with two traffic lanes in circulation and at the approaches, except for the northern and southern approaches, where three lanes are formed, with the right-side lane functioning as a “by-pass” lane to facilitate traffic flow [1].

4 Traffic flow analysis

As a part of the research, a comparative analysis of the traffic flow at the roundabout of Bulevar Nemanjića and Vojvode Mišića Street was carried out for the years 2022 and 2024. The intersection was chosen because of its attractive location and high volume of motorized and non-motorized traffic, which often leads to congestion. In its surroundings are the Delta Planet shopping center with a large parking area, a kindergarten, the Health Center, and numerous residential blocks, all of which significantly affect the volume and structure of traffic flows [1]. Monitoring of traffic flow was conducted in order to obtain a reliable picture of the traffic situation at the intersection, which represents the basis for further calculations and finding the optimal solution for traffic regulation [1]. For the purpose of this research, aerial traffic monitoring was carried out using unmanned aerial vehicles (DJI Mavic 3 and DJI Mini 2). Through previous counting and observation at the roundabout, the peak period was determined to be between 16:00 and 18:00, during which monitoring was conducted [1]. Based on the collected data, the number of vehicles in all categories (bicycles, motorcycles, passenger cars, buses, light and medium trucks) was manually counted, while other categories were not present during the analyzed period. The results are presented for the years 2022 and 2024 in Table 1, showing the hourly distribution of traffic flows by approaches to the intersection, which allowed for observation of traffic intensity and the share of individual vehicle categories.

Table 1. Hourly distribution of the traffic flow for the year of 2022.

Time	The northern approach	The eastern approach	The southern approach	The western approach
	2022	2022	2022	2022
16:00-17:00	776	1220	616	620
17:00-18:00	809	952	731	923
Total	1585	2172	1347	1543

5 Traffic flow forecast

The field of traffic forecasting emerged in response to the rapid growth of traffic, driven by accelerated motorization and the widespread adoption of passenger cars in urban environments, which began to generate numerous challenges and necessitated

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more sophisticated methods for monitoring, analyzing, and managing traffic flows. The mid-20th century saw a significant advancement in computer technology, which greatly facilitated its application in traffic forecasting. Accurate forecasting is crucial for selecting future traffic project alternatives, as erroneous estimates may result in the construction of infrastructure with insufficient capacity or, conversely, over-dimensioned facilities whose utilization fails to justify the associated economic costs [1]. A distinction is made between current and forecasted traffic conditions. Existing traffic volumes, which can be measured directly, are used to implement immediate traffic management measures. In contrast, forecasted traffic volumes represent anticipated future traffic, for which it is essential to ensure adequate capacity within the urban road network and public transportation systems [1]. The general model for traffic forecasting is given by [11]:

$$V_i^n = V_{i_{BAZ}} * Fi^n$$

$$Fi^n = (i + e * RBDP^n\%)$$

where:

$V_{i_{BAZ}}$ – observed traffic flow for vehicle type (i) in the base year, obtained from field measurements,

Vin – traffic flow for vehicle type (i) in year (n) obtained through traffic forecasting;

Fin – growth factor of the traffic flow for vehicle type (i) over the period, i.e., in year (n);

$RBDP^n \%$ – average annual growth rate of the gross domestic product over the period, i.e., up to year (n);

n – number of years in the period.

e – elasticity factor.

For the purpose of determining traffic growth, data from the REBIS study [12] for Serbia were used. Only a single scenario was considered in the traffic forecast. The projection of future traffic was based on an annual growth rate of 4% in the first year, with a linear decrease in the growth rate to 0.5% by the fifth year. Table 2 below presents the forecasted traffic for the peak hour [1].

Table 2. Forecasted traffic flow for the peak hour

Year/Approach	2022 Base year	2023	2024	2025	2026
The northern approach	776	807	839	872	905
The eastern approach	1220	1269	1319	1370	1423
The southern approach	616	641	666	692	719
The western approach	620	645	670	696	723
Total vehicles/h	3232	3361	3494	3630	3770

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During the peak hour in 2022, a total of 3,232 vehicles were counted, while the forecast for the following five-year period predicted an increase to 3,494 vehicles in 2024, and 3,770 vehicles in 2026, in the same time interval.

In order to verify the forecast process, manual counting of vehicles was conducted in 2024, using the same methodology, roundabout, and time interval. The data collected show the total number of 3,374 vehicles in the peak hour of 2024 (Table 3). The earlier forecast for 2024 had predicted 3,494 vehicles (Table 2). The absolute deviation amounts to 120 vehicles, which represents 3.43% relative to the forecasted value and 3.56% relative to the actual value, an insignificant discrepancy.

Table 3. Hourly distribution of the traffic flow for the year of 2022 and 2024.

Time	The northern approach		The eastern approach		The southern approach		The western approach	
	2022	2024	2022	2024	2022	2024	2022	2024
16:00-17:00	776	833	1220	1151	616	654	620	736
17:00-18:00	809	763	952	1072	731	605	923	678
Total	1585	1596	2172	2223	1347	1259	1543	1414

To make a clearer insight into the intensity and distribution of the vehicle flow upon approaches to the intersection, traffic flows in the peak period for manually counting in 2022 and 2024, as well as forecasted in 2024, from 4 to 5 p.m., are shown graphically in Figure 3.

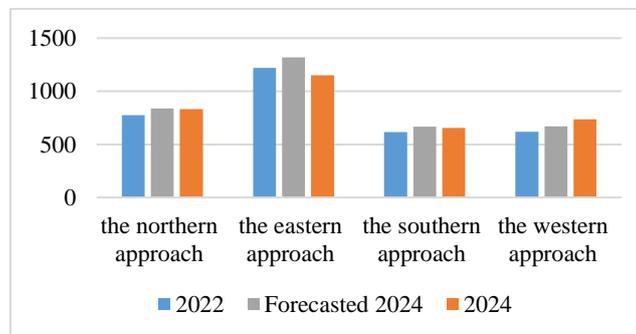


Fig. 3. Traffic flows in the peak period – in 2022, forecasted 2024 and 2024

6 Conclusion

Traffic forecasting represents a significant tool in the planning and improvement of transportation infrastructure, as it enables a better understanding of future needs and more efficient management of traffic flows. Roundabouts occupy a special place in such studies, being increasingly implemented due to their advantages in terms of safety and traffic throughput. The results of the analysis conducted confirm that traffic

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forecasting provides reliable and applicable outcomes. By comparing the results from the forecasting process of traffic flow in 2024 and those obtained by manually counting in 2024, a deviation of only 3.43% relative to the forecasted value was observed, which can be considered negligibly small. The data obtained demonstrates that the method is adaptable to various traffic conditions and that, despite inevitable traffic fluctuations, the estimates remain stable and realistic. It is particularly noteworthy that the results indicate a high degree of accuracy of the applied methodology, thereby confirming its usefulness for planning and further research.

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Investigation of Environmental Pollution Caused by Noise Generated from Transportation Operations in Tbilisi

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Abstract. Noise pollution generated by transportation systems continues to be a pressing issue in modern urban environments, reflecting broader shortcomings in current transportation planning and management. Tbilisi, the capital of Georgia, is no exception to this challenge. This study offers an in-depth examination of transportation-related noise pollution within Tbilisi, identifying its key sources and underlying causes. Particular attention is given to the technical condition and developmental status of the city's transport infrastructure and vehicle fleet, assessing their direct contribution to noise-related problems. The research also explores the broader context of European Union (EU) practices by analyzing relevant policies, regulatory frameworks, and technical standards aimed at mitigating transportation noise. A comparative evaluation is carried out between the legislative measures in Georgia and those established within the EU, highlighting gaps and opportunities for policy alignment. The study's findings provide a detailed assessment of existing conditions and pinpoint the critical factors influencing noise pollution levels in Tbilisi, offering guidance for more effective noise reduction strategies.

Keywords: Noise, Pollution, Transport, Decibel, Tbilisi.

1. Introduction

Environmental pollution remains a critical challenge in contemporary urban development, encompassing not only visible pollutants such as emissions and waste but also less tangible forms like noise. Among these, noise pollution has emerged as an increasingly significant public health and ecological concern, particularly in large cities where dense populations, congested traffic, and outdated infrastructure exacerbate its impact. Numerous studies and international reports highlight that urban noise primarily caused by transportation systems is not merely a nuisance but a substantial contributor to stress-related illnesses, hearing impairment, reduced cognitive performance, sleep disruption, and negative behavioral and reproductive effects in wildlife.

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In this context, the examination of transportation-related noise pollution becomes particularly relevant for cities undergoing rapid urban expansion and motorization, such as Tbilisi, the capital of Georgia. Tbilisi, characterized by its complex terrain, dense urban structure, and aging vehicle fleet, faces substantial challenges in mitigating environmental noise. The rise in vehicular numbers, increasing use of motorcycles and mopeds, and intensifying air traffic have collectively pushed ambient noise levels in many districts of the city to thresholds that far exceed internationally accepted standards.

Despite the urgency of the problem, noise pollution in Georgia remains an under-addressed issue from both policy and technical perspectives. Compared to the European Union (EU), where robust regulatory frameworks and noise abatement strategies are in place, Georgia's legal and institutional mechanisms appear inadequate and fragmented. This regulatory gap, combined with limited enforcement and outdated infrastructure, contributes to the growing severity of the problem. Moreover, the prevalence of modified vehicles - particularly those with altered exhaust systems or electronic control modules adds to the complexity, as such practices often result in excessive noise emissions that bypass official regulatory thresholds.

The motivation for this research stems from the observed lack of integrated noise management strategies in Tbilisi and the corresponding need to assess the real impact of transportation systems on urban acoustic environments. While some attention has been given to traffic flow optimization and pollution reduction, the specific issue of transportation-generated noise has not received proportionate academic or policymaking focus in Georgia. As urbanization continues and mobility demands increase, the necessity of understanding the primary sources and patterns of noise generation becomes paramount for planning future interventions.

The principal aim of this study is to investigate the environmental pollution caused by noise emanating from transportation operations in Tbilisi. The research is structured to:

- Identify and analyze the key sources of transportation-related noise in the city;
- Examine the technical and operational factors influencing these noise levels, including vehicle conditions and modifications;
- Compare Georgian regulatory standards with EU benchmarks to highlight discrepancies and areas for legislative improvement;
- Offer practical recommendations for policymakers, urban planners, and environmental authorities to mitigate the impacts of transport-related noise pollution.

By presenting evidence-based findings and insights, the study seeks to support the development of more effective strategies and regulations aimed at reducing urban noise levels and promoting healthier and more sustainable urban living in Tbilisi.

2. Materials and Methods

The purpose of this study is to assess transportation-related noise pollution in Tbilisi, identify its main sources, and compare national standards with EU regulations.

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Field measurements were conducted at various locations in Tbilisi, selected based on traffic intensity and flow type (homogeneous, mixed, modified vehicles). Certified Class 1 sound level meters were used to record noise levels (in dB) during day and night hours, following ISO and IEC standards. Simultaneously, traffic composition was observed, categorizing vehicles by type (light, heavy, motorcycles, modified).

Additional data were collected through visual inspections of road conditions and secondary analysis of the technical condition of the city's vehicle fleet. A legal review compared Georgian regulations - primarily Resolution No. 510 - with EU standards to identify regulatory gaps.

Collected data were processed using basic statistical tools to determine average and peak noise levels, and findings were visualized for clarity. This multi-method approach ensures a comprehensive view of noise pollution sources and influencing factors.

Within the framework of the study, a multifactor analysis method was used, which involves analyzing the existing situation and determining measures to eliminate the problem, based on identifying the main factors causing the problem. For this purpose, a full analysis of the current legislation in Georgia was carried out, and the main elements of the transport system of Tbilisi were examined-specifically, the main actors of the transport system, their role in ensuring urban mobility, the age and technological development level of the vehicle fleet and infrastructure.

Based on the analysis of legislative regulations and the current state of Tbilisi's transport system, further research activities were planned and implemented, including both field studies and methods for processing the collected data. For this purpose, the authors' group applied observation methods and statistical data processing methods.

3. Primary Causes of Environmental Pollution from Noise Generated by Transportation System Operations in Tbilisi

Noise represents one of the most significant sources of environmental pollution with a substantial negative impact on human health and animal adaptation to the environment, including information transmission, and other factors. Consequently, it currently poses an ecological threat to life on Earth. Noise levels are primarily measured in decibels (dB). For example, sound intensity during conversation ranges from 40-45 dB, in offices 50-60 dB, on streets 70-80 dB, while jet aircraft produce 180 dB. Humans can perceive vibrations from 0 to 170 dB. A sound level of 30 dB is considered comfortable for humans. In Georgia, the maximum permissible level in residential buildings is 55 dB during the day and 45 dB at night (from 11:00 PM to 8:00 AM). [1].

Urban environments are particularly sensitive to noise generated by transportation operations. Tbilisi is no exception in this regard. The composition of the city's transportation system and the intensity parameters of its use are noteworthy. In this context, the primary factors include high frequency of vehicle movement, narrow streets, and densely populated districts. These factors and the existence of a

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transportation system model where regulations are minimized provide a background for the sharp increase in noise caused by transportation operations, leading to long-term damage to urban ecosystems [2].

The elements of Tbilisi's transportation system do not differ from those of major cities worldwide. Tbilisi's vehicle fleet consists of M2 and M3 category motor vehicles, as well as private/commercial M1 category light vehicles and N1, N2, N3 category freight transport vehicles with corresponding infrastructure [3]. Throughout the city, we intensively encounter various types of motorcycles, mopeds, quadricycles, and two-wheeled electric scooters. It is important to note Tbilisi's underground electric transport (metro), approximately 90% of whose network is underground and therefore does not significantly affect noise pollution in the city's residential areas. Research revealed that the average speed of vehicular traffic in Tbilisi conditions is 30-45 km/h during most day/night periods, which determines the so-called structural noise resulting from engine operation and tire-road interaction. The level of this noise depends primarily on the vehicle's year of manufacture, the vehicle's technical condition, and natural-climatic conditions. It should be noted that street noise levels vary according to the intensity and characteristics (composition) of traffic flow.

The levels of so-called construction noise caused by the operation of motor vehicles and motorcycles/mopeds/quadricycles under various loads are determined by manufacturers in construction with legislative requirements in effect in the operational area. Therefore, the noise level generated by newly manufactured vehicles with zero mileage corresponds to permissible limits. Tbilisi's automotive fleet is predominantly represented by aging motor vehicles, whose internal combustion engine noise levels (according to European standards) should not exceed 74-75 dB (80 dB for N2 and N3 category freight transport vehicles and M3 category buses), according to manufacturer-specified norms (when moving at permitted speeds in urban conditions), while vehicles manufactured after 2016 produce engine noise levels of 68 dB. Regarding motorcycles/quadricycles/mopeds, their internal combustion engine noise levels should not exceed 83-85 dB, while post-2016 noise levels range from 73-77 dB.

As a result of prolonged operation, the technical condition of transport vehicles changes, specifically increasing the structural noise generated by vehicle operation [4]. Therefore, monitoring all parameters of the technical condition of the main units of land transport vehicles and eliminating identified malfunctions is extremely important. For example, the exhaust system for processed gases of internal combustion engines of land transport vehicles should be in proper working condition, and all components and units should be reliably secured to limit vibration levels.

Various locations throughout Tbilisi were selected as research objects under conditions of high and medium traffic intensity, specifically: homogeneous traffic flow movement at different speeds under permitted speed conditions; heterogeneous traffic flow movement with the involvement of motorcycles and mopeds; and heterogeneous traffic flow movement with the involvement of automobiles and motorcycles having modified exhaust systems.

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According to the results of research conducted in Tbilisi, in most cases, the manufacturer-specified so-called structural noise levels are maintained. However, depending on the traffic flow composition, there are sharp changes in this parameter, specifically concerning light automobiles and motorcycles whose exhaust systems for combustion gases have been modified according to consumer preferences. In the case of light automobiles, there is not only structural intervention but also modification of the engine's electronic control system software, which in certain cases changes the ignition advance angle of the internal combustion engine. As a result, a specific amount of the working mixture supplied to the engine cylinders burns directly in the exhaust system for processed gases (so-called "popcorn effect"), correspondingly increasing the generated sound level [5]. In these cases, noise levels in the space adjacent to the roadway reach 107-114 dB. The situation differs for motorcycles and mopeds. There exist motorcycle brands and models whose engine operation produces noise levels within the 95-110 dB range (e.g., American-manufactured Harley-Davidson, German BMW, and others), but in most cases there is an increase in noise levels due to modification of the exhaust system for processed gases [6]. The detailed results of research conducted throughout Tbilisi are presented in Diagram No. 1.

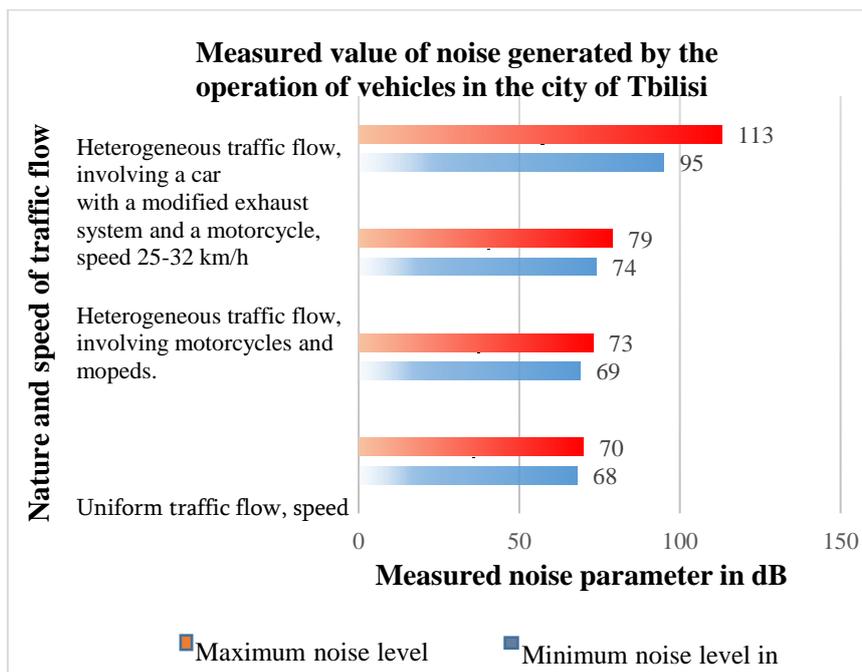


Fig. 1. Noise Levels Caused by Transportation Operations Recorded in Tbilisi

4. For the Field Study

Within the framework of research on noise caused by the operation of Tbilisi's above-ground transport system, several locations were selected for conducting field measurements. The study was carried out at the following sites: 14 Pekini Avenue, Zurab Zhvania Square, 69 M. Kostava Avenue, 23 A. Tsereteli Avenue, Kakheti Highway (six different points), 35 S. Tsintsadze Street, 5 I. Chavchavadze Avenue, P. Melikishvili Street, and others.

The data collection process was conducted according to pre-determined time parameters, specifically measuring noise levels generated by vehicle operation during peak hours and periods of relatively reduced traffic flow. Noise levels were recorded at a distance of 1.2–1.7 meters from the roadway, using a sound level meter placed on the sidewalk.

The research process was carried out in strict accordance with a regulated methodology, which involved positioning the sound level meter in such a way as to ensure the maximum accuracy in recording only the noise produced by the object under investigation, while excluding so-called accompanying or screened noise, such as sound reflections from building walls, which could create an echo effect.

The need for applying this method arose from the research objectives, which aimed to study noise generated by the operation of Tbilisi's above-ground transport system.

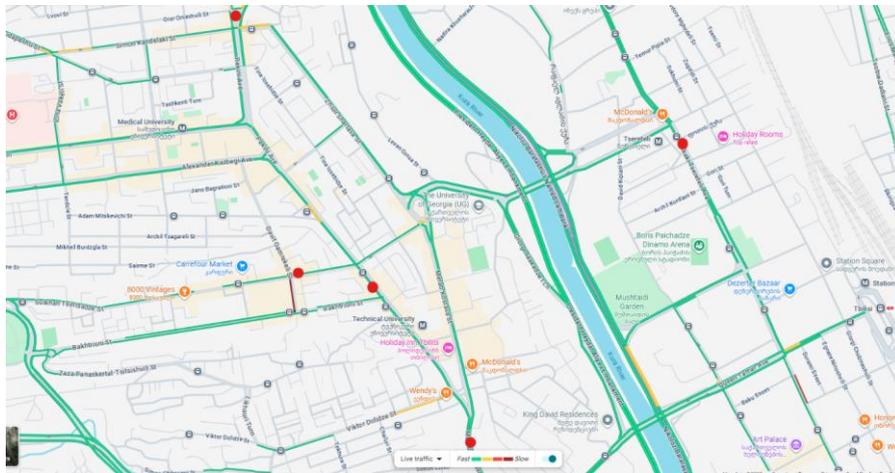


Fig. 2. Some of the locations used in the study

In Figure 2, the red dots indicate some of the locations where field measurements of noise generated by vehicle operation were carried out.

In the context of noise pollution in Tbilisi, Road usage is not the only source of transport-based noise pollution, the railway system requires separate mention, as it virtually bisects the city, and the open lines of underground electric transport (metro) in central districts represent an additional source of noise [7]. Air transport is also

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significant in this regard. The issue is that in recent years, parallel to economic growth, the intensity of aircraft flights has increased significantly, which in turn increases the scale of pollution. Additionally, the area of Tbilisi's residential zones has expanded, and consequently, aircraft must fly at low altitudes over urban and residential areas.

The following factors can also be considered as causes of transportation noise pollution in Tbilisi:

- Citizens' social behavior and cultural specifics
- Municipal transport problems
- Road infrastructure
- Construction policy

Forms of law enforcement, and others

It should be noted that from a legal regulation perspective, urban pollution from transportation noise represents a virtually deregulated sphere.

The only exception and extremely important document in this regard is Georgian Government Resolution No. 510 "On Periodic Technical Inspection of Motor Vehicles and Their Trailers," which directly defines the maximum permissible noise levels generated by the operation of land transport according to vehicle class (see Table 1). It is important to note that the permissible noise standards defined by technical regulations somewhat exceed the standards established by manufacturers and the legislation of leading European countries.

Table 1. Permissible Noise Levels Generated by Motor Vehicle Operation According to Vehicle Category in Georgia and European Countries

Vehicle Category	Permissible Noise Level According to Regulation #510	Maximum Permissible Noise Threshold According to EU Requirements
Diesel engine M1, N1 category motor vehicles	100 (dB) – 110 (dB)	68 (dB)
Diesel engine M2, N2 category motor vehicles	105 (dB) – 115 (dB)	79 (dB)
Diesel engine M3, N3 category motor vehicles	110 (dB) – 120 (dB)	79 (dB)
Gasoline engine M1, N1 category motor vehicles	95 (dB) – 105 (dB)	68 (dB)
Gasoline engine M2, N2 category motor vehicles	100 (dB) – 110 (dB)	72 (dB)
Gasoline engine M3, N3 category motor vehicles	105 (dB) – 115 (dB)	79 (dB)

Table 1 presents the permissible noise limits generated by the operation of motor vehicles of categories M1, M2, M3, N1, N2, and N3, in accordance with the legislative requirements applicable in Georgia and the European Union countries. Specifical-

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ly, column 2 of the table shows the noise permissible parameters defined by the Regulation of the Government of Georgia No. 510, "On Periodic Technical Inspection of Motor Vehicles and Their Trailers," while column 3 presents the relevant regulation valid across the European Union - REGULATION (EU) No 540/2014 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL, dated 16 April 2014, on the sound level of motor vehicles and of replacement silencing systems, amending Directive 2007/46/EC and repealing Directive 70/157/EEC, which defines the permissible noise limits generated by motor vehicles of categories M1, M2, M3, N1, N2, and N3.

5. Conclusion

Urban transportation systems are indispensable for modern cities, ensuring mobility and economic growth [8]. However, their contribution to environmental degradation, particularly noise pollution, represents a significant challenge. Within the framework of this research, we aimed to present the primary causes of transportation-induced noise pollution in Tbilisi in order to ultimately contribute to the effectiveness of urban transportation systems through their elimination.

Based on the results of conducted research and analysis of the existing environment, we conclude that the level of ecological noise pollution throughout Tbilisi can be considered high, which is predominantly a damaging byproduct of the operational processes of the transportation system existing in Tbilisi [9]. Specifically, research results on noise levels generated by the movement of transport vehicles in Tbilisi showed that "transport noise" is the primary source of noise pollution in Tbilisi. In conclusion, we separately identify the main causes that, in the case of Tbilisi, represent the primary sources of noise pollution generated by the operation of transport vehicles, specifically:

Aging vehicle fleet: The predominance of older vehicles with deteriorated noise control systems

Modified exhaust systems: Transport vehicles with arbitrarily modified exhaust systems by consumers on light automobiles and motorcycles (the so-called "popcorn effect")

Engine management modifications: In the case of light automobiles, modification of the electronic control system software for internal combustion engine operation, known as "chipping"

Regulatory standards gap: The somewhat excessive permissible noise standards under Georgian legislation compared to their analogous counterparts throughout the European Union

High-noise motorcycles: Certain motorcycle brands and models whose engine operation produces noise levels within the 95-110 dB range, while their operation is not restricted by current legislation

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Railway and metro systems: The railway system in Tbilisi and the open lines of underground electric transport (metro) require separate mention as additional sources of noise

Aviation impact: The intensity of aircraft flights increases the scale of noise pollution. Additionally, the area of Tbilisi's residential zones has expanded, consequently requiring aircraft to fly at low altitudes over urban and residential areas

Infrastructure factors: Road infrastructure and existing construction policies represent additional contributing factors to noise pollution in Tbilisi, though this direction, considering its scale and specificity, requires separate in-depth research

The analysis of the conducted research leads to the conclusion that, from a legal standpoint, urban transportation noise pollution remains largely unregulated. This highlights an urgent need for comprehensive legislation, particularly targeting the primary sources of noise generated by transport vehicles as identified in this study [10].

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Validation of an In-plane Two Degrees of Freedom Bus Model for Lateral Dynamics Investigation

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Abstract. The dynamic behavior of buses depends on their design parameters, the operating conditions, and the driver's behavior. Buses' parameters such as size, weight distribution, and center of gravity (CoG) height influence vehicle lateral dynamics. The dynamic behaviour of buses is particularly important during maneuvers in real driving conditions that require a specific driver's steering command. The aim of this paper is to validate the accuracy of a nonlinear in-plane bus model of 2 degrees of freedom (DOF) for three maneuvers (single-lane change, double-line change and, slalom driving). Bus modelling and simulation have been done in MATLAB/Simulink software. Two previously measured vehicle responses on bus IK 312 Lander were considered in validation (yaw rate and lateral acceleration). For slow maneuver (single-lane change), simulation and measured signals matched. For invasive maneuver (double-lane change) and fast maneuver (slalom driving) simulation responses have similar trends as measured ones, but values differ due to weight transfer phenomena.

Keywords: Validation, Measurement, Single-track model, Maneuvers, Simulation.

1 Introduction

The dynamic behavior of a bus depends on its design parameters, operating conditions, and driver's behavior. The vehicle must provide easy and precise steering, stability during movement, little uncontrolled motion in curves, as well as a quick response to the steering system commands [1].

Buses exhibit complex lateral dynamics due to their size, weight distribution, and high CoG. The dynamic behaviour of buses is particularly important in real driving conditions which require various maneuvers. Maneuvers such as single-lane change (when overtaking or avoiding an obstacle) or double-line change are common and complex because they depend on traffic conditions, road conditions (e.g. road friction, road roughness), and vehicle velocity. While driving a vehicle, the driver's steering command significantly affects the vehicle's lateral responses (e.g. yaw, yaw rate, lateral acceleration) [2, 3]. These responses are crucial for vehicle lateral stability assessment and vehicle safety. Understanding these responses could help in designing

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safer buses and enhancing training programs for drivers in avoiding traffic accidents caused by improper bus handling [4].

Investigation of a bus lateral dynamics could be performed in real driving conditions [5], on a proving ground [5, 6] or by driving simulator [7]. Another way of a bus lateral behaviour analysis is by simulations using software (e.g. multibody software such as ADAMS/Truck, TruckSim, etc.; toolkit such as MATLAB/Simulink, Python, etc.). Simulations are particularly important in cases when physical tests are expensive, involve dangerous maneuvers or for analysing of “*what-if*” scenarios. Bus models of different complexity have been used in simulations [8, 9, 10, 11, 12]. Complexity of the model depends on the aim of the investigations. For example, a high-fidelity bus model was used for the investigation of its responses to sweep hand wheel steering input [8]. A bus model of 8 DOF had been defined in [9] and used for obtaining bus lateral accelerations on a floating bridge under different storm conditions. Linear in-plane 2 DOF bus model had been used for lateral and yaw stability research for electric bus [10], for comparison of vehicle responses under adaptive control laws in electric buses [11], and for handling analysis as a function of passengers’ position [12].

The aim of this paper is to validate the accuracy of the single-track bus model for maneuvers specific to real driving conditions. For these purposes, a nonlinear in-plane bus model with 2 DOF was defined in the MATLAB/Simulink software. The model was loaded with a driver handwheel steering angle (HSA) previously registered on the prototype of an intercity bus - IK 312 Lander. Validation was performed by comparing the bus model responses (yaw rate and lateral acceleration) obtained by simulations against the measured responses of the intercity bus for three maneuvers (single-line change, double-line change, and slalom driving). Validation of 2 DOF models is important before implementation to various vehicle dynamics analysis and for control system development (such as lane-keeping and lateral stability systems).

2 Experimental research of the lateral dynamics of IK 312 Lander bus

Experimental research was conducted on a prototype of the IK 312 Lander intercity bus, made by the domestic manufacturer Ikarbus from Belgrade [5]. Lateral dynamics bus behaviour had been investigated through different maneuvers in real traffic conditions (single-lane change) and on a proving ground (slalom driving and double-lane change). Measured variables were HSA, yaw rate, lateral acceleration and longitudinal bus speed.

Single-lane change maneuvers were carried out on the Bubanj Potok - Vrčin highway section [5]. The geometrical characteristics of the track for lateral stability testing on proving ground for double-lane change maneuvers are given in Fig. 1. This is in accordance with ISO 3888 standard [13].

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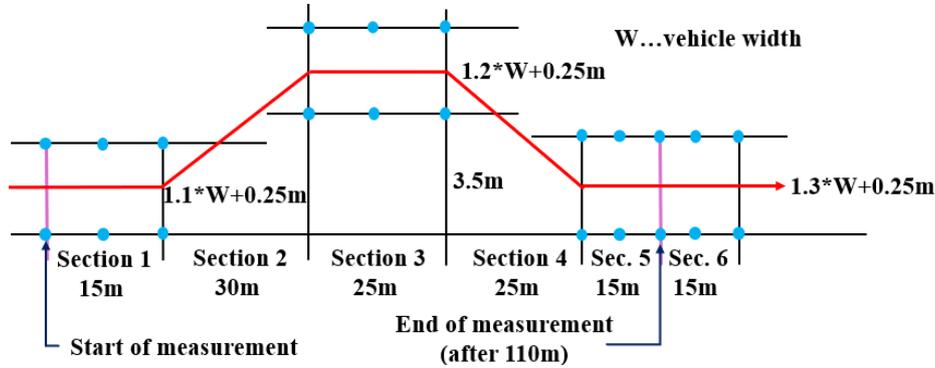


Fig. 1. Geometrical characteristics of the track for double-lane change maneuver (ISO 3888).

Intercity bus IK 312 Lander (Fig. 2a) parameters important for the definition of an in-plane bus model are given in Table 1. The measurements were performed using a modern digitalized acquisition equipment (Hottinger measuring bridge (Fig. 2b) with Hottinger HB 12/200 acceleration transducers (Fig. 2c). Longitudinal bus speed was monitored by a Global Positioning System (GPS) device (Fig. 3). Detailed information about measuring systems, measured responses and processing of registered data could be found in [5].

Table 1. Intercity bus IK 312 Lander parameters.

Intercity bus – IK 312 Lander	Parameters
Mass of the empty bus m [kg]	14000
Bus width W [m]	2.50
Bus length L [m]	12
Wheelbase l [m]	5.94
Distance from the front axle to the CoG of an empty bus l_f [m]	3.564
Distance from the rear axle to the CoG of an empty bus l_r [m]	2.376
Moment of inertia around bus z -axis J_z [kgm ²]	175290
Steering ratio (Handwheel steering angle/road wheel steering angle) [-]	22.7:1
Cornering stiffness coefficient C_{cy} [(N/rad)/N]	7
Road friction coefficient μ [-]	1
Vertical tire force on bus front axle Z_f [N]	54936
Vertical tire force on bus rear axle Z_r [N]	82404

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Fig. 2. Experimental research: a) prototype IK 302 Lander bus; b) Hottinger measuring bridge; c) lateral acceleration transducer - Hottinger HB 12/200.



Fig. 3. Bus velocity measurement by GPS device.

3 In-plane bus model with 2 DOF

A nonlinear single-track bus model with 2 DOF (Fig. 4) was used for analyzing simulation responses and for validation. The in-plane DOFs are the vehicle lateral motion and yaw motion (y, ψ), (Fig. 4b). Important assumptions for bus model are: the vehicle motion is considered in x - y plane (angular motions around longitudinal x -axis and lateral y -axis, as well as vertical displacement along z -axis are neglected [1, 14]); weight transfer from inner to outer wheels is also neglected; the vehicle is symmetrical against longitudinal x -axis; ground is flat and smooth; constant vehicle longitudinal speed v_x .

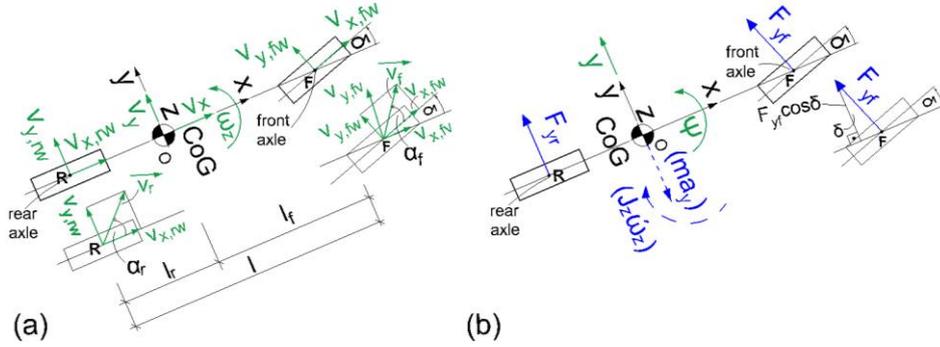


Fig. 4. In-plane single-track bus model: a) velocities; b) active forces with fictive force and fictive moment.

Differential equations of motion for the single-track bus model, considering the assumptions given above and Fig. 4b, are defined by Eqs. (1, 2)

$$m(\dot{v}_y + v_x \omega_z) = F_{yf} \cos \delta + F_{yr} \quad (1)$$

$$J_z \dot{\omega}_z = F_{yf} \cos \delta l_f - F_{yr} l_r \quad (2)$$

where F_{yf} , F_{yr} are lateral tire forces for the front and rear wheels, respectively; δ is the road wheel steering angle; l_f , l_r are distances from the front and rear axle to the bus CoG (Table 1).

Experimental investigation of bus IK 312 Lander lateral dynamics confirmed that measured lateral acceleration values went beyond 2 m/s² and almost reached 3 m/s² (e.g. for double-lane change maneuver [5]). For this reason, lateral tire forces are described by the brush tire model [15] given by Eq. 3.

$$F_{y,f/r} = \begin{cases} -\text{sign}(s_{y,f/r}) \cdot \left(C_{y,f/r} \cdot |s_{y,f/r}| - \frac{(C_{y,f/r} |s_{y,f/r}|)^2}{3 \cdot Z_{f/r} \cdot \mu} + \frac{(C_{y,f/r} |s_{y,f/r}|)^3}{27 \cdot (Z_{f/r} \cdot \mu)^2} \right); \\ \quad \text{if } |s_{y,f/r}| < \frac{3 \cdot Z_{f/r} \cdot \mu}{C_{y,f/r}} \\ -\text{sign}(s_{y,f/r}) \cdot \mu \cdot Z_{f/r}; \quad \text{else} \end{cases} \quad (3)$$

where $F_{y,f/r}$ is the lateral tire force on each axle; $C_{y,f/r}$ is the cornering stiffness for each axle; $s_{y,f/r}$ is the lateral tire slip for each axle; $Z_{f/r}$ is the vertical tire force on each axle (Table 1); and μ is the road friction coefficient. Experimental investigation has been carried out on dry and good asphalt road [5], which corresponds to a road friction coefficient value of 1 [1], Table 1.

Cornering stiffness is given by Eq. 4

$$C_{y,f/r} = C_{cy} \cdot Z_{f/r} \quad (4)$$

where C_{cy} is the cornering stiffness coefficient. Standard value for C_{cy} for heavy vehicles is presented in Table 1 [15].

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Lateral tire slips for front and rear axles, considering Fig. 4a, are given by Eqs. (5, 6)

$$s_{y,f} = \tan \alpha_f = \frac{v_{y,fw}}{v_{x,fw}} = \frac{v_{y,fv} \cos \delta - v_{x,fv} \sin \delta}{v_{y,fv} \sin \delta + v_{x,fv} \cos \delta} = \frac{(v_y + l_f \omega_z) \cos \delta - v_x \sin \delta}{(v_y + l_f \omega_z) \sin \delta + v_x \cos \delta} \quad (5)$$

$$s_{y,r} = \tan \alpha_r = \frac{v_{y,rw}}{v_{x,rw}} = \frac{v_y - l_r \omega_z}{v_x} \quad (6)$$

where α_f is lateral wheel slip angle at front axle (Fig. 4a); $v_{x,fv}$, $v_{y,fv}$ are front axle velocity (v_f) vector components expressed in wheel coordinates (Fig. 4a); $v_{x,fv}$, $v_{y,fv}$ are front axle velocity (v_f) vector components expressed in vehicle coordinates (Fig. 4a); α_r is lateral wheel slip angle at rear axle (Fig. 4a); $v_{x,rw}$, $v_{y,rw}$ are rear axle velocity (v_r) vector components expressed in wheel coordinates (Fig. 4a); v_y is lateral vehicle speed (Fig. 4a).

Vertical tyre forces on the front and rear axle for a constant bus longitudinal speed (v_x) are calculated by Eqs. (7,8) and given in Table 1.

$$Z_f + Z_r - mg = 0 \quad (7)$$

$$-Z_f \cdot l_f + Z_r \cdot l_r = 0 \quad (8)$$

Moment of inertia around bus z -axis is calculated according to Eq. 9

$$J_z = \frac{m}{12}(W^2 + L^2) \quad (9)$$

where m is the mass of empty bus (Table 1); W is bus width (Table 1); and L is bus length (Table 1).

4 Simulation results and bus model validation

Fig. 5 presents a bus model in MATLAB/Simulink software based on vehicle dynamics equations in section 3. Simulations were initiated by script files written in MATLAB. Runge–Kutta solver "ode45" with a variable step-size of numerical integration was used in the simulation. RWSA block (Fig. 5) denotes the road wheel steering angle obtained by the steering ratio given in Table 1.

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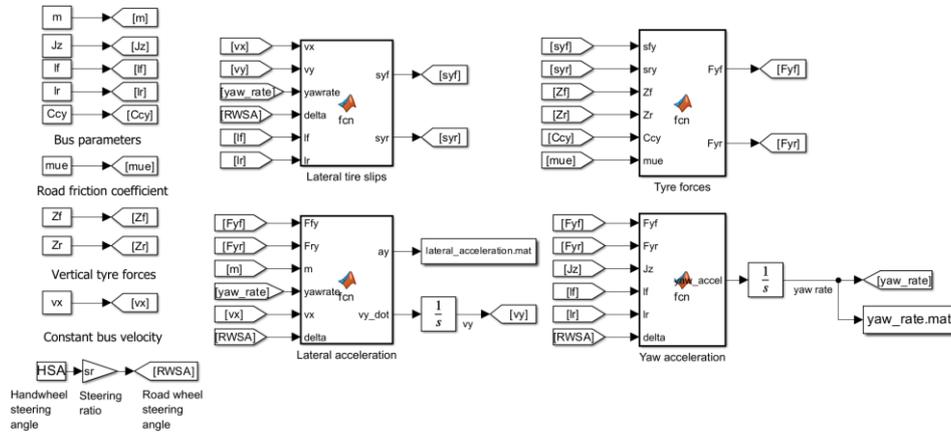


Fig. 5. In-plane 2 DOF bus model in MATLAB/Simulink software.

Fig. 6 compares two bus responses (yaw rate and lateral acceleration) obtained by measurement and simulations for a single-line change maneuver and a bus velocity of 80 km/h. This maneuver was performed in real driving conditions on the highway during overtaking and is described by one-period sinusoidal HSA (Fig. 6a). HSA maximum and minimum values are around +90 degrees and -110 degrees, respectively (Fig. 6a). The yaw rate and lateral acceleration obtained from simulations follow the same trend as from the measurement with similar values. For example, the minimum value for yaw rate is around -10 degrees/s (Fig. 6b) and for lateral acceleration is around -2 m/s² (Fig. 6c) for both measurement and simulation. This is a rather slow maneuver, and good agreements could be explained by low weight transfer between the left and right bus wheels during maneuver.

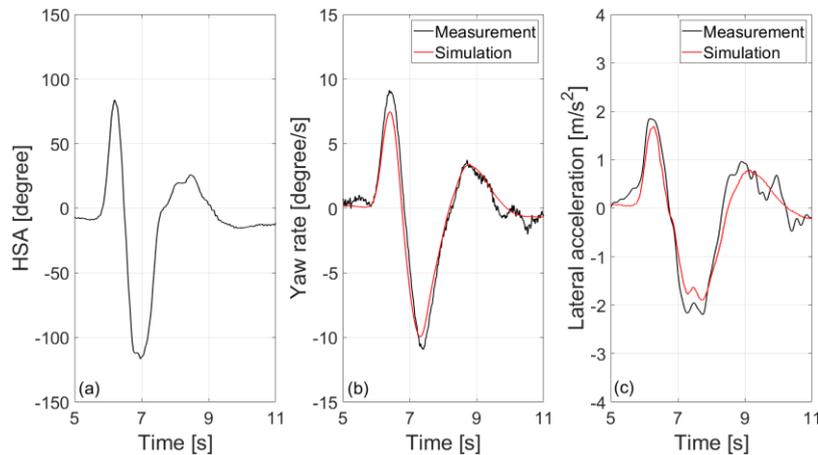


Fig. 6. Single-line change maneuver: a) one-period sinusoidal input, b) yaw rate, c) lateral acceleration, at bus velocity of 80 km/h.

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Fig. 7 compares the yaw rate and lateral acceleration confirmed by measurement and simulations for slalom driving and bus velocity of 60 km/h. HSA values are mostly concentrated within ± 90 degrees with the frequency of around 1 Hz (Fig. 7a). The yaw rate and lateral acceleration obtained from simulations follow the same trend as from the measurement (both signals have the same frequencies, Fig. 7b,c). Lateral acceleration values differ and are higher for measurement (Fig. 7b). One of the reasons for this difference may be omission the weight transfer in the single-track model definition (Fig. 4).

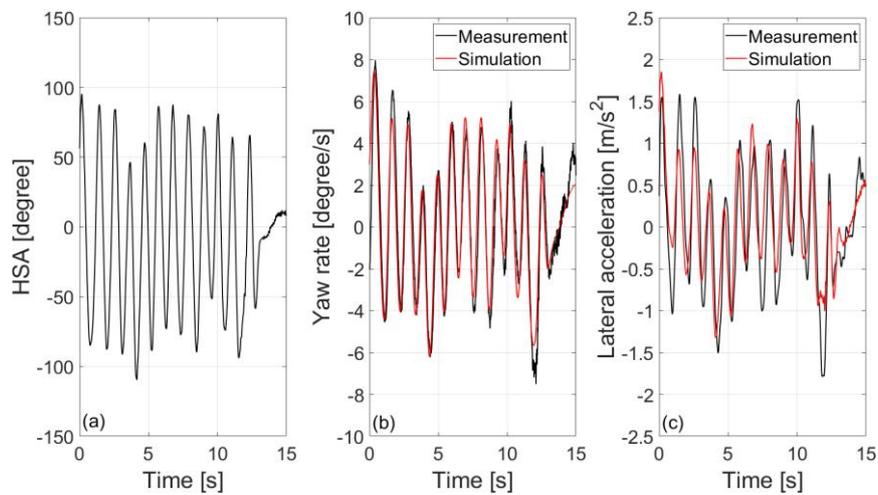


Fig. 7. Slalom driving maneuver: a) sinusoidal input, b) yaw rate, c) lateral acceleration, at bus velocity of 60 km/h.

Fig. 8 compares the yaw rate and lateral acceleration obtained by measurement and simulations for a double-line change maneuver and bus velocity of 70 km/h. Measurement was performed on a proving ground according to procedures proposed in ISO 3888 standard [5, 13]. Yaw rate and lateral acceleration obtained from simulations follow the same trend as from the measurement but with noticeable differences in their values. For instance, yaw rate maximum values obtained in measurement reached +13 degrees/s, whereas simulation reached +7 degrees/s (Fig. 8b). Lateral acceleration maximum values are matched for both measurement and simulation (Fig. 8c). In the third second, acceleration differs by around 1 m/s² (Fig. 8c). This is a rather invasive maneuver, and moderate agreement could be explained by the effect of weight transfer on bus handling.

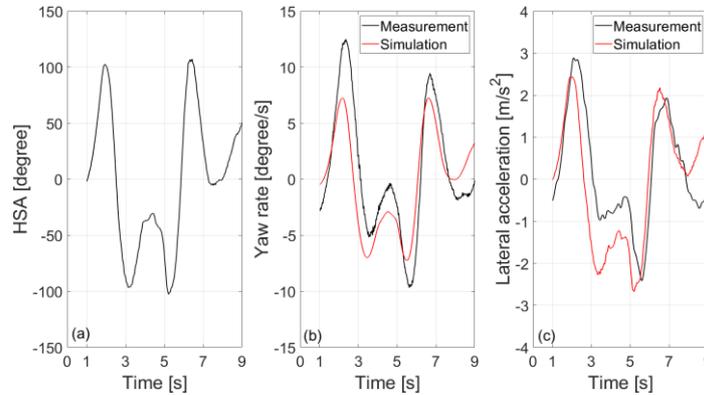


Fig. 8. Double-line change maneuver: a) HSA, b) yaw rate, c) lateral acceleration, at bus velocity of 70 km/h.

5 Conclusion

In this paper, a nonlinear in-plane bus model with 2 DOF is validated by comparing two simulated vehicle responses (yaw rate and lateral acceleration) against signals measured on intercity bus IK 312 Lander for three different maneuvers. Considered maneuvers (single-lane change, double-lane change, and slalom driving) often occur in real bus operating conditions.

The vehicle responses obtained by simulation were found to be in good agreement with the measured responses for a single-lane change maneuver at a bus speed of 80 km/h. The simulated responses follow the trend of the measured signals over time, and the values are identical. For example, for both the measurement and the simulation, the yaw rate minimum value is around -10 degrees/s, and the lateral acceleration minimum value is around -2 m/s². The maneuver is not intensive and, apparently, weight transfer has an insignificant influence on the analyzed responses.

During fast maneuver (slalom driving at a bus speed of 60 km/h) and intensive maneuver (double-lane change at a bus speed of 70 km/h), the simulation responses follow the change of real signals in time, but with deviations in their values. Deviation can be explained by the influence of weight transfer phenomena on the bus handling. Vertical tire forces change due to the weight transfer, i.e. tires cornering stiffness change affecting bus lateral dynamics behaviour. Also, the bus parameters influence responses values, especially the moment of inertia around z -axis. The value of this parameter was not based on measurement but calculated for this work.

A nonlinear in-plane 2 DOF bus model extends the classic linear model considering nonlinear tire forces. The defined model provides an accurate prediction of the lateral dynamic behavior for slow maneuvers (e.g. single lane change maneuver). However, defined in-plane model does not capture important coupling effects of vertical, roll and longitudinal motions which limit its scope of application in fast and aggressive maneuvers (e.g. slalom and double-lane change maneuvers).

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Future work could consider extension of the current model to predict bus lateral dynamics behaviour in intensive maneuvers more accurately. For example, by including roll dynamics in a bus two-track model with a suspension system, sprung and unsprung masses. Extended bus model could employ advanced nonlinear tyre models (e.g. Pacejka tyre models) for more realistic description of lateral tyre forces. Furthermore, future work could explore the use of the defined 2 DOF bus model for Hardware-in-the-Loop (HIL) and Driver-in-the-Loop (DIL) simulations.

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Highways with Electric Infrastructure for In-Motion Charging of Electric Vehicles

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Abstract. The rapid transition toward sustainable mobility has made the development of advanced electric vehicle (EV) charging infrastructure a key priority for reducing greenhouse gas emissions and fossil fuel dependence. This paper analyzes both static and dynamic highway charging technologies, focusing on Germany's leadership in implementing large-scale pilot projects such as the ELISA e-Highway. Static systems, which use high-power DC chargers at rest areas, enable quick battery replenishment but create peak load challenges for the grid. In contrast, dynamic charging achieved through inductive coils embedded in the pavement or overhead contact lines allows vehicles to receive continuous power while driving, improving operational efficiency and reducing downtime. Although the installation cost of dynamic infrastructure, estimated between €1.5 and €2.5 million per kilometer, remains high, the long-term benefits include lower vehicle battery degradation, reduced CO₂ emissions, and improved grid integration with renewable energy sources. The research highlights the technological, economic, and policy dimensions of highway electrification and assesses its contribution to achieving the European Green Deal objectives. Germany's investments within the Energiewende framework and alignment with the UN Sustainable Development Goal 7 (Affordable and Clean Energy) demonstrate that dynamic charging highways can become a cornerstone of future low-carbon, intelligent transportation networks.

Keywords: Electric vehicles, dynamic charging, e-Highway.

1 Introduction

Electric vehicles (EVs) play a critical role in achieving global sustainability and reducing dependence on fossil fuels. They represent one of the most effective ways to decarbonize the transport sector, which is responsible for nearly one quarter of global CO₂ emissions [1]. Despite significant advances in battery technology, the availability of fast and reliable charging infrastructure remains a key barrier to widespread adoption [2]. The lack of accessible charging points, especially on long-distance routes, continues to cause "range anxiety" among drivers, limiting the appeal of EVs for freight and passenger transport. Furthermore, growing urbanization and freight demands increase the pressure on existing transport infrastructure. The creation of elec-

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trified highways roads equipped with charging systems for vehicles in motion has emerged as a promising solution [3]. These systems could drastically reduce idle time, improve logistics efficiency, and accelerate the transition to low-emission mobility. Several European countries, including Germany, Sweden, and Italy, have launched large-scale research programs exploring both static and dynamic charging technologies [4]. Static charging involves high-power direct current (DC) chargers located at rest stops and service areas, while dynamic charging enables vehicles to receive energy while driving through inductive coils embedded in the pavement or through overhead contact lines [5]. Integrating such technologies also contributes to smart grid development, enabling energy optimization and load balancing. Predictive algorithms can determine when and where energy demand will peak, allowing infrastructure operators to distribute electricity efficiently [6]. These innovations combine transportation engineering, information technology, and environmental science into a single integrated mobility system.

The primary objectives of this paper are:

- Environmental Impact: Evaluate how highway electrification reduces CO₂ emissions and supports EU climate targets [3].
- Technological Advancement: Compare static and dynamic charging technologies in terms of efficiency, cost, and sustainability [4].
- Policy Relevance: Examine Germany's leadership in developing the ELISA eHighway system and its role in European energy transition goals [6].

By addressing these dimensions, this research aims to provide a comprehensive understanding of the opportunities and challenges in deploying in-motion charging systems on modern highways.

2 Technological Concepts: Static vs. Dynamic Charging

The electrification of highways relies on two primary approaches, static and dynamic charging. Each system offers distinct operational characteristics, cost implications, and environmental benefits. Static charging refers to conventional plug-in stations that allow EVs to recharge while parked. These stations are typically installed at highway service zones and can deliver up to 350 kW of power through direct current (DC), enabling vehicles to recharge 80% of their battery capacity within 20 - 30 minutes [4]. Static systems are simple to install and compatible with existing vehicle technology but require frequent stops and high peak power loads, creating demand fluctuations on the grid [5]. Dynamic charging, on the other hand, enables energy transfer while the vehicle is in motion. This approach relies on either inductive or conductive methods. Inductive charging uses magnetic resonance between coils embedded in the road surface and receivers on the vehicle, while conductive charging employs pantographs that connect to overhead lines, similar to electric trains or trolleybuses [6].

Germany, Sweden, and Italy are leading in dynamic highway demonstrations. The Smart Road Gotland project in Sweden uses inductive technology for passenger cars and buses, whereas Germany's ELISA project applies overhead catenary systems for

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freight transport [7]. Dynamic charging eliminates long charging stops and enables continuous driving, thereby improving energy efficiency and logistics performance. It also allows vehicles to operate with smaller batteries, lowering production costs and environmental impact. However, it requires substantial initial investment, complex road construction, and regular maintenance [8]. The following Table 1 provides a comparison between static and dynamic charging systems based on cost, efficiency, and technological attributes. Dynamic systems demonstrate greater operational efficiency and better alignment with renewable energy sources. However, their economic feasibility depends on large-scale deployment and supportive policy frameworks [9].

Table 1. Comparison Between Static and Dynamic Charging Systems

Parameter	Static Charging	Dynamic Charging
Charging Method	Plug in DC charging at fixed stations	Inductive or overhead charging while vehicle is in motion
Average Cost	€50,000 - €250,000 per station	€1.5 - €2.5 million per kilometer
Charging Time	20 - 30 minutes per session	Continuous while driving
Grid Demand	High peak load at stations	Distributed energy usage along the road
Energy Efficiency	85 - 90%	90 - 95%
Maintenance Cost	Moderate	High (overhead line maintenance and sensor calibration)
Battery Degradation	Higher due to fast-charging cycles	Lower due to stable power flow
Environmental Benefit	Reduces emissions during stops	Enables continuous low-emission operation
Example Projects	Ionity Network (EU), E.ON Fast Charging	ELISA (Germany), Smart Road Gotland (Sweden)

3 The ELISA Project in Germany: the operational analysis

Germany has established itself as the European leader in dynamic highway electrification through the ELISA (Electrified Innovative Heavy Traffic on Autobahns) project. Initiated by the Federal Ministry for the Environment (BMU) and developed by Siemens Mobility and Scania Group, ELISA is designed to test the technical, economic, and environmental feasibility of electric highways for heavy-duty freight transport [5,6].

3.1 Project Overview

The pilot section of ELISA is located on the A5 motorway between Frankfurt and Darmstadt, covering a 10 kilometer stretch of dual-lane highway. Trucks equipped with roof-mounted pantographs can connect to overhead contact lines to draw elec-

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tricity while driving at speeds up to 90 km/h [6]. When disconnected, the trucks operate in hybrid mode, using batteries or conventional engines to continue their journey.

The system operates at 670 V DC, powered by substations placed approximately every 5 kilometers, ensuring stable and efficient current distribution. The pantographs automatically raise and lower when the truck changes lanes, maintaining safety and operational flexibility [7]. To improve traffic management, the ELISA highway is equipped with intelligent sensors, IoT communication modules, and cloud-based control systems. These technologies monitor vehicle position, power consumption, and grid status in real time, optimizing electricity flow and minimizing system losses [5]. Predictive maintenance algorithms detect wear and faults early, ensuring continuous operation Figure 1.



Fig. 1. Pilot eHighway project in Germany with overhead power lines and pantograph-equipped hybrid truck [5,8]

3.2 Technical Features and Efficiency

The ELISA system combines several advanced technologies:

- Overhead catenary lines for conductive energy transfer.
- Power converters that transform alternating current (AC) from the public grid into direct current (DC).
- Digital monitoring systems that ensure voltage stability and communication between vehicles and infrastructure [6].

In practice, trucks connect to the overhead contact lines through automatically adjustable pantographs, as illustrated in Figure 2. Field testing confirmed energy transfer efficiency above 90%, a major milestone for heavy-duty mobility [7]. Hybrid trucks operating on the ELISA corridor emitted up to 40% less CO₂ than diesel-powered equivalents. Dynamic charging also reduces battery wear, improving lifespan and lowering maintenance costs. The project explores a combination of conductive and inductive systems, allowing future integration of wireless charging lanes for passenger cars. This hybrid approach could enable mixed traffic electrification, where both freight trucks and light-duty vehicles benefit from continuous in-motion charging [8].

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Fig. 2. Pilot project ELISA: Overhead contact line system for electric trucks [6]

3.3 Economic and Environmental Evaluation

The construction cost for ELISA's electrified lanes ranges between €1.8 and €2.3 million per kilometer, including infrastructure, substations, and monitoring equipment [8]. Although the initial investment is high, long-term fuel savings, CO₂ reduction, and lower operating costs demonstrate positive economic outcomes. According to the Federal Ministry for the Environment (BMU), large-scale deployment on Germany's key freight corridors could reduce national transport emissions by over 7 million tons of CO₂ annually [7]. Integration with renewable sources like solar and wind allows the system to align with the Energiewende policy and the European Green Deal [3]. Vehicle-to-grid (V2G) functionality enables trucks to feed excess energy back to the grid during low-demand periods, improving grid stability and energy utilization [9]. This bidirectional energy exchange also provides new economic opportunities for logistics operators.

3.4 Policy and Future Development

The success of ELISA has encouraged the expansion of electric highway concepts across Europe. Projects like E|MPOWER on the A6 motorway in Germany and Smart Road Gotland in Sweden build on ELISA's experience, showing that large-scale highway electrification is technically feasible and environmentally beneficial [3,7]. ELISA has contributed to establishing European standards for interoperability, vehicle authentication, and smart billing systems, ensuring compatibility across manufacturers and cross-border networks [8]. Public-private partnerships are key for funding, combining government support with private sector investment to secure economic sustainability and long-term operation [6].

Future ELISA phases include:

- High voltage 1000 V systems for faster energy transfer.
- AI-based traffic management to optimize lane usage and reduce energy losses.

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- Expansion of inductive charging lanes to urban and intercity passenger EVs, supporting mixed systems [6,7].
- Digital twin technologies for predictive maintenance, energy distribution planning, and real-time monitoring, minimizing downtime [9].

Recent pilot programs using the Dynamic Wireless Power Transfer (DWPT) concept demonstrate how electric roads can enable uninterrupted energy transfer for buses and light-duty vehicles, as shown in Figure 3. Integration with renewable energy sources and V2G functionality enhances grid stability and energy efficiency [5,9]. Despite high initial investment, operational savings, lower maintenance costs, and environmental benefits provide a strong long-term return on investment [8]. Overall, ELISA sets a precedent for electrified highway networks in Europe. Lessons from this project provide a blueprint for sustainable, connected, and intelligent transport corridors, supporting EU climate neutrality targets and demonstrating that dynamic charging infrastructure can be scaled efficiently across freight and passenger transport [3,7,9].



Fig. 3. Dynamic Wireless Power Transfer (DWPT) system tested on an electric shuttle bus and development of the electric road [5,9]

4 Conclusion

Highways equipped with electric infrastructure for in-motion charging represent one of the most innovative steps in sustainable mobility. The German ELISA project has proven that long-distance electric freight transport is both technically viable and economically efficient [5]. Its results demonstrate that electrified highways can drastically cut emissions, integrate renewable energy into national grids, and serve as a foundation for the EU's clean transport strategy [3]. Dynamic charging offers a clear advantage over static systems: it eliminates downtime, optimizes logistics, and enables smaller battery capacities, reducing both manufacturing costs and environmental impact [6]. By incorporating V2G technologies and renewable integration, electrified highways can also enhance grid flexibility and energy resilience [9].

To ensure successful large-scale implementation, standardization, interoperability, and cross-border cooperation are essential. Governments and industry stakeholders should establish common European frameworks that support research, investment, and infrastructure deployment [8]. Lessons learned from ELISA show that strategic

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planning and public-private collaboration can accelerate the transition to zero emission transport while preventing future economic and environmental costs. As Europe moves toward full electrification of its transport networks, dynamic charging highways will play a central role in achieving intelligent, connected, and sustainable mobility.

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A Review of Volume-Delay Functions and Calibration Methods Considering Local and Weather Conditions

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Abstract. In traffic assignment modeling, many resistance factors exist, with travel time being one of the most important, usually represented by a volume-delay function. Choosing the right function is crucial for strategic-level network planning and is key to understanding the statistical distribution of network load. However, the challenges involved in its practical application are not yet fully understood. This paper aims to summarize selected studies where different functions and their modifications were used to develop models and adapt them to changing local or temporal conditions. The literature review revealed that no single function provides both easy implementation and high applicability in a specific area without calibration or regional data. The conclusion suggests that a reliable model can only be built using real data collected under various traffic conditions on a country's road network, which helps minimize errors and discrepancies between the modeled and actual traffic loads.

Keywords: Traffic assignment modelling, volume-delay function, calibration, weather conditions.

1 Introduction

The traditional four-stage chain of traffic models (TPM – Transport Planning Model) implies the establishment of a balance between supply and demand through four groups of models, each with successive applications. The last group includes models for the distribution of flows on the network, whereby the allocation of trips from the origin to the destination is made based on input data on the network topology, performance functions, travel rates, and assumptions about user behavior when choosing a path [1], [2], [3]. Mathematically well-defined performance functions are cited as the basis for theoretical research into problems related to the use and design of mechanisms [4]. The performance of links within a network depends on travel time values and is most often described by the volume-delay function (VDF). According to [5], the VDF represents an estimate of the delay on a road segment due to an increase in traffic volume, while according to [6], the function expresses the delay time as a function of traffic flow and the theoretical capacity of the modeled facility.

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Different formulations of the mentioned function exist, with the BPR (Bureau of Public Roads), Davidson's, conic, and Akçelik's functions, or their modifications, being most commonly used in research. The shortcomings of conventional functions are addressed by improving them; for example, [7] developed a dynamic gravity model using an improved conical volume-delay function. In [8], a model based on the fundamental diagram was proposed, where an enhanced volume-delay function was applied, suitable even under congestion conditions.

Research generally indicates that no single volume-delay function is optimal for application under varying conditions. For this reason, the calibration of known functions is often carried out in different ways, and the impact on performance is quantified. In [9] and [10], calibration is performed based on travel time, where the results of the impact measurements show improved accuracy and adaptation to local conditions. Studies [11], [12], [13] perform calibration based on traffic volume, while [14] i [15] use a combined or hybrid (rolling-horizon) approach.

This paper provides an overview of selected studies in which the aforementioned volume-delay functions were used in the modeling process, with a focus on adapting existing formulations to specific spatial and temporal conditions. A detailed analysis was carried out based on:

- variables and parameters included in the functions, depending on whether it is a modification of one of the standard functions or a specific mathematical formulation;
- data sources used for the development and validation of the function, specifically including the location and time of research, road hierarchy, method of data collection, and sample size;
- methods applied during validation – statistical tests, comparative analysis, model adaptability, error rates, and statistical significance of the results.

2 Comparative analysis of volume-delay functions

In practice, the appropriate volume-delay function is chosen empirically, based on new research findings. An incorrect choice of volume-delay function produces poor results in modeling the distribution of traffic loads on the road network. The model should therefore be developed based on real data collected under various traffic conditions on a country's road network, to minimize errors and deviations between the modeled and actual traffic loads. Integrating VDF and queuing models enables the quantification of the marginal effects of flow variations, thereby mitigating the adverse environmental impacts of traffic [16].

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Table 1. Formulations of the most commonly used functions with the meaning of individual parameters

Function name	Function formulation
BPR Function [17]	$t(v) = t_0(1 + \alpha(x)^\beta)^2$
t – average travel time t_0 – (minimal) travel time α – ratio between travel time at practical capacity and travel time under free-flow conditions β - curvature parameter, defining the rate of increase in travel time when transitioning from free-flow to congested conditions	
Modified Davidson Function [18]	$t(v) = \begin{cases} t_0 \left(1 + J \frac{x}{1-x}\right); & x \leq \mu(ii) \text{ – original form} \\ t_0 \left(1 + J \frac{\mu}{1-\mu} + J \frac{x-\mu}{(1-\mu)^2}\right); & x > \mu(ii) \\ \text{– modified form} \end{cases}$
t_0 – minimal (free-flow) travel time μ – proportion of selected users (usually 0,85 – 0,95) $\mu(ii)$ – modification, i.e. substitution of the hyperbolic Davidson function with a linear extension for traffic volumes exceeding link capacity J – delay parameter (time loss coefficient) used in the original form of the function; related to land use and the surrounding environment, accounting for the frequency of elements that cause travel time losses x – degree of capacity utilization q/C	
Conical Function [19]	$t(v) = t_0(2 + \sqrt{\alpha^2(1-x)^2 + \beta^2} - \alpha(1-x))$
t_0 – (minimal) travel time $\beta = \frac{2\alpha-1}{2\alpha-2}$ α – any value greater than 1 – recommended value ³ (4 – divided roads with medians; 5 – undivided roads) x – degree of capacity utilization	
Akçelik Function [20]	$t = t_0(1 + 0,25r_f \left[x - 1 + ((x - 1)^2 + 8 \frac{J_A x}{C t_0 r_f})^{0,5} \right])$
t_0 – minimal (free-flow) travel time r_f – ratio of the analyzed observation period to travel time t_0 J_A – delay parameter (time loss coefficient); the suggested value is 0.1. Lower values are adopted for motorways/sections with coordinated signal control (interrupted flow), while higher values are used for intersections without signal coordination (uninterrupted flow) t_c – travel time at capacity	

The Bureau of Public Roads volume-delay function (BPR) is the most popular among VDF functions and is highly suitable for use in traffic assignment models. By adjusting its parameters, it can cover a wide range of flow–delay relationships. In the region, this function is most frequently applied in modeling, and after calibration, it yields excellent results both in urban areas and on higher-class roads.

² Note: The values of coefficients α and β are estimated depending on local conditions and empirical data.

³ Recommendation of the Minnesota Regional Development Council

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The values of the coefficients α and β are variable and are estimated based on field data. The recommended starting values of the coefficients are 0.15 for α and 4 for β [21]. These values vary with road and traffic conditions on particular sections. For roads with saturated traffic flow, smaller values of parameter α (0.8–0.9) and larger values of parameter β (2.5–3) are applied, while for urban road sections, larger values of α (1.2–1.5) and smaller values of β (1.5–1.8) are recommended [22]. [23] replaced the base capacity with the operational capacity in the original form of the function and generated data for high values of the q/C ratio, based on which the parameter values $\alpha=2.62$ and $\beta=5$ were proposed. [24] estimated that the parameter values for signalized intersections in urban areas are $\alpha\approx 0.83$ and $\beta\approx 3.36$, while [6] used $\alpha=0.33$ and $\beta=4.04$ for highways, with the range of α 0.5-2 and β 1.4-11.

The function has a simple form and is successfully applicable when the flow–capacity ratio is less than 1.2. Moreover, when the traffic load equals the capacity, the speed is assumed to be half of the free-flow speed, regardless of the values of α and β . Within the BPR function, under real network loads, it is assumed that the degree of capacity utilization varies up to 1 or slightly above 1. However, recent research has indicated that the Bureau of Public Roads function, despite its widespread adoption, may not accurately capture the complexities of dynamic traffic conditions, especially during severe congestion, leading to inaccuracies in traffic assignment [25].

Davidson's volume-delay function, based on intersection queuing theory, was first published in 1966. In the original formulation, the saturated flow was used instead of capacity, without considering that these two parameters do not have the same value for uninterrupted traffic flows [18]. The original form of the function has been modified several times due to its inapplicability in situations where flow exceeds capacity in repeated traffic assignment procedures. The issue was that travel time tended to infinity as the flow value approached capacity. By improving the original formulation, definite travel time values were obtained for all variations of the capacity utilization factor.

The conical volume-delay function represents a solution to the shortcomings identified in the BPR function [19]. The high values of the coefficient β applied in the BPR formulation revealed two major deficiencies that motivated the development of the conical function, namely:

- When modeling traffic distribution in the network, the assumption that the flow–capacity ratio varies from 0 to 1 (or only slightly above 1) results in an irregular allocation of section weights, poor model convergence, and a loss of precision in implementation.
- Although the function's formulation is relatively simple, the estimation of individual parameters requires logarithmic and exponential calculations to establish the relationship between travel time and flow and to determine the value of the coefficient β .

Accordingly, the conical function does not include the parameter β in the exponent and is therefore more suitable for use under congested conditions. The basic assumption is that the estimated travel time at capacity is twice the free-flow travel time. For

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calculation purposes, it is recommended that the coefficient α be greater than 1. For traffic planning, the recommended coefficient values provided by the Minnesota Regional Development Council are as follows: $\alpha = 4$ for divided roads; $\alpha = 5$ for undivided roads [26].

The conical function, like the BPR function, does not explicitly account for signalized intersections. However, the advantage is that both functions share the same interpretation of the variables that characterize traffic behavior, namely, flow and capacity. This enables a direct and practical transition from one function to the other. For peak-period traffic assignment, the conical function is often applied, as congestion is considered the critical factor in such conditions.

Akçelik's volume-delay function is the result of a modification of the Davidson function by applying the coordinate transformation technique, taking into account values of the capacity utilization factor greater than 1. After ambiguities in the interpretation of the parameters in the original Davidson formulation were identified, complicating parameter definition and model calibration, the author introduced the delay parameter J and modified the function. However, due to insufficient theoretical justification, Akçelik subsequently developed a time-dependent concept of the function.

The value of the delay parameter is correlated with the arrangement of signalized intersections along the analyzed route and can be defined as [20]:

$$J_D = k' = k * p \quad (1)$$

Where the individual parameters are defined as follows:

- k – coefficient, with the values: 0.6 for isolated signalized intersections; 0.3 for intersections with coordinated signal operation; 1 for unsignalized intersections and roundabouts;
- p – parameter representing the frequency of delay elements along the road section (e.g., the number of signalized intersections per unit length).

The value of the delay parameter can also be determined using the following expression:

$$J_D = \frac{c(t_m - t_0)^2}{0,5} \quad (2)$$

where t_m is the travel time at capacity.

In his paper [20], Akçelik provided a tabular overview of delay parameter values for different road categories. The application of Akçelik's function incorporates both vehicle travel time and delays at intersections, which represent a significant share of the total travel time. This implies that the function is less suitable for higher-class roads (expressways, highways), because the delay parameter is substantially higher on routes with closely spaced signalized intersections compared to roads without flow interruptions or with coordinated signal operations.

Caution is required when applying this function as an aggregate for several different functional elements within the network. Accuracy is reduced when multiple ele-

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ments are combined into a single composite element, and this must be considered when interpreting the parameter values obtained through calibration of the function proposed in [20]. The procedure for determining the capacity of a composite element is therefore subject to uncertainty. Individual links may have different numbers of lanes, but this problem can be addressed by analyzing the critical lane.

The theoretical basis for the delay parameter requires applying the function separately to each lane, meaning that the throughput and capacity values used in the function refer to the individual lane. Consequently, the most appropriate solution is to apply the function to the critical lane of the road section under analysis. For simplification purposes, it is assumed that the capacities of the lanes are equal.

Table 2. Advantages and disadvantages of the most commonly used volume-delay functions

Function name	Advantages	Disadvantages
BPR function [17]	<ul style="list-style-type: none"> – minimal input data – universal – it usually has the most favorable RMSE values in travel demand estimation models 	<ul style="list-style-type: none"> – travel time and flow are underestimated under uncongested conditions and overestimated under congested conditions – extreme function values may appear in the early stages of distribution – not based on queuing theory – operational traffic conditions are not taken into account
Modified Davidson function [18]	<ul style="list-style-type: none"> – flexibility, adaptable to a wide range of traffic conditions with parameter μ – good performance on almost any roadway facility 	<ul style="list-style-type: none"> – The original Davidson function had several shortcomings, later addressed by Davidson, Akçelik, and Tisato; the most significant drawback was the inability to achieve finite travel time values when the flow-to-capacity ratio exceeded 1
Conical function [19]	<ul style="list-style-type: none"> – developed to overcome the shortcomings of the BPR function – BPR function parameters can be directly transferred – traffic conditions are not explicitly considered 	<ul style="list-style-type: none"> – signalized intersections are not explicitly taken into account
Akçelik function [20]	<ul style="list-style-type: none"> – good convergence – realistic speed values under congestion – superior for signalized arterials – intersection delay is considered – conciseness (avoids the application of complex intersection delay parameters) 	<ul style="list-style-type: none"> – weaker convergence compared to the conical function – inferior performance on highways

3 Methodological approaches to the calibration of travel time functions

The analysis of previous research was conducted in the context of the most commonly used travel time functions for traffic distribution modeling, with particular emphasis on those that account for adverse weather patterns and are adapted to local conditions. It was found that no function combines low implementation complexity with high applicability in a given area without requiring calibration or local data. The suitability of a function for application in a particular area depends on the characteristics of the road network, such as the frequency of signalized intersections, lane configuration, and elements such as roadside parking or side streets. Functions that incorporate the changing behaviour of demand, congestion thresholds, and delays at intersections are more likely to produce accurate predictions in urban areas with complex road networks and variable traffic conditions.

Accordingly, researchers have reached different conclusions when comparing the functions and their modifications. Study [14], based on empirical research and calibration, concluded that the BPR function provides the most accurate results after calibration with a genetic algorithm, yielding the smallest mean square error as a measure of precision. In contrast, [9] emphasized the importance of local calibration and found that the BPR and logistic functions provide the best fit. In some studies, the application of BPR function modifications proved more successful. For example, [27] concluded that such variants capture travel time heterogeneity more accurately and observed a 13% reduction after adjusting traffic signal operations. Other authors, such as [28], found that modified models more closely reflect observed data, with intersection delay identified as a crucial factor. Finally, [12] highlighted the importance of analysing bottlenecks, i.e., queues, and of incorporating local data.

Table 3. Complexity of implementation and practical applicability of commonly used volume-delay functions

Function type	Data requirements	Implementation complexity	Applicability
Bureau of Public Roads [9], [12], [14], [27], [28]	Traffic flow, capacity	<i>Relatively low</i>	<i>High</i> (with calibration); can be generalized
Davidson (Akçelik) function [9], [12], [14], [18]	Traffic flow, capacity, level of service (m), saturation flow	<i>Moderate</i>	<i>Moderate</i> ; sensitive to parameter specification
Conical function [9], [12], [14]	Traffic flow, capacity, slope	<i>Moderate</i>	<i>Moderate</i> ; accuracy may deteriorate in off-peak periods
Logistic function [9]	Traffic flow, capacity, curve parameters	<i>Moderate</i>	<i>High</i> for one-way, congested, or nonlinear roads
Modified BPR function [24],	Traffic flow, capacity, uncertainty	<i>Relatively high</i>	<i>High</i> under variable conditions; requires local data

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Function type	Data requirements	Implementation complexity	Applicability
[27]	parameters		
Modified uniform/Webster function [24], [28]	Traffic flow, geometry, and signalization data	<i>Relatively high</i>	<i>High</i> for urban arterials with signalized intersections; less applicable to motorways
New urban function [29]	On-street parking, geometry, and local characteristics	<i>High</i>	<i>High</i> for historical/complex urban areas; requires local calibration

Certain authors, such as [11], [13], [30], analyze and compare the performance of the given functions in the local context, where the BPR function is often used as a reference point. When unfavorable weather conditions are taken into account, a decrease in saturated flow and average travel speed, as well as an increase in vehicle headway, were observed. Based on this, the need for explicit adaptation of traffic distribution models to weather-related changes is emphasized. Such adaptation can be approached either by developing entirely new functions or by introducing correction factors and modifying existing parameters [31], [32].

The calibration procedure is mainly carried out using regression analysis and minimization of the root mean square error (RMSE). Other applied methods include Python-based algorithms, fixed parameter estimation/adoption, simulation and empirical approaches, comparative analysis, and cross-validation. In [33], calibration was performed using a combination of cross-entropy and a variation of the LASSO regression method, based on data from probe-equipped vehicles. Cross-entropy was applied to fine-tune the model so that its output probabilities closely match real data, while regression was used to select the most relevant input variables, thereby improving prediction accuracy.

Other studies mention the use of data from induction loops, GPS, and weather stations, although without specifying the estimation algorithms applied. The authors in [34] and [35] consider the influence of rainfall intensity, where distribution modeling was performed at the postal-code level on an hourly basis. Probabilities of different weather conditions were defined and applied to specific functional links within the network, depending on the postal code. In [36], correction factors were calibrated for different metropolitan areas in the USA, which were subsequently used as inputs to a simulation system that integrates weather conditions for dynamic traffic distribution.

Temporal patterns (time frames) are incorporated using regression or probabilistic models, simulation frameworks, and deep learning methods. In [37], travel time functions were calibrated under adverse weather conditions, specifically snow and ice, using a regression-based approach within a traffic simulation system. On the other hand, [33] and [38] apply probabilistic models with dual time scales, combined with gradient boosting machine (GBM) algorithms and recurrent neural networks, to adapt to adverse weather conditions. Some studies provide quantitative performance measures (RMSE and MAE) [39], while most report only qualitative or partially defined validation results.

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Table 4. Various approaches to traffic modeling under variable weather conditions

Reference	Type of weather and magnitude of impact	Calibration method	Implementation approach
[37]	Snow and ice/qualitatively high impact	Regression, calibration within the TRANSIMS system	Micro and macro-modeling
[33]	Hurricane Sandy	Two-phase probabilistic model, GBM, cross-entropy	Functional data analysis
[36]	Rain, snow, fog/significant impact on flow and speed	Correction factors	Modified Greenshields model (dual-regime) ⁴
[34]	Rain (rainfall intensity)	Rainfall distribution models	Calibration by postal code and hour
[35]	Heavy precipitation, snow/qualitatively (capacity reduction)	Occupancy-based prediction	RWIS ⁵ system data, new predictive model
[40]	Unspecified adverse weather/high impact during peak hours	Monte Carlo simulation, probabilistic models	Conditional probability functions
[38]	Weather conditions without specified details	LSTM and GRU neural networks	Machine learning for short-term prediction

4 Conclusion

Volume-delay functions (VDFs) represent a fundamental analytical tool for modeling the relationship between traffic flow and travel time and play a key role in the planning and management of transportation systems. The most commonly used models, including the basic form of the BPR function and its modified variants, have proven their practical value due to their flexibility and wide range of applications, particularly in urban areas. Their applicability, however, largely depends on careful and precise calibration based on local traffic characteristics, which allows for a more realistic representation of existing conditions in the network.

Standard VDF functions provide satisfactory results under free-flow conditions, but in congestion regimes, they often underestimate delays, especially at signalized intersections and complex junctions. For this reason, numerous modifications have been developed, such as MBPR and Webster's delay function, which better describe

⁴ A modification of the standard model in which traffic flow is represented through two distinct functional segments, either density or degree of saturation.

⁵ Road Weather Information System

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traffic dynamics in urban environments. Logistic and Akcelik functions allow for capturing nonlinear congestion effects and the disproportionate growth of travel time, although they require more complex parameter estimation methods. In recent studies, dynamic and stochastic VDF functions are increasingly applied, improving modeling accuracy in networks with complex geometry and variable traffic conditions.

The reliability of VDF models largely depends on the quality of local calibration, as well as on the integration of various traffic data sources, road types, and congestion levels. Modern calibration methods, which include combined approaches and advanced optimization algorithms, further enhance model accuracy and increase their practical value in planning and investment decision-making processes.

Based on an analysis of the available literature and identified research gaps, key directions for future research can be clearly defined:

- Development of VDF models that include explicit congestion identification and integration of data from multiple sources (GPS, video, and sensor networks);
- Improvement of model reliability through the integration of travel time variability indicators and network reliability measures;
- Extension of existing concepts to multimodal transportation systems, taking into account interactions between different modes of transport;
- Development of specific VDF approaches for regimes with high penetration of connected and automated vehicles (CAVs);
- Creation of multi-resolution VDF models that enable more precise planning and design of transportation networks under conditions of temporally variable demand.

These directions establish a key foundation for advancing theoretical models and their real-world applications. By incorporating new technologies, advanced data sources, and modern analytical methods, the future development of VDF functions can greatly enhance the creation of robust and flexible transportation models, allowing for more efficient planning, management, and design of complex traffic networks.

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Contemporary Approaches to Traffic Calming: A Review of Measures and Application Possibilities

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Abstract: Vehicle speed is one of the most critical risk factors in road traffic, with speeding significantly contributing to both the occurrence and severity of crashes. Previous studies have confirmed a strong relationship between impact speed and crash outcomes, particularly for vulnerable road users such as pedestrians and cyclists. The aim of this paper is to provide a structured review of the most commonly applied traffic calming measures and to analyze their characteristics, advantages, and limitations. The methodology is based on a literature review and the synthesis of documented applications of measures in different contexts. Special attention is given to physical measures (e.g., speed bumps, raised platforms, road narrowings), optical-acoustic solutions, radar speed displays, fixed speed cameras, and infrastructural interventions such as mini-roundabouts. The findings indicate that these measures differ significantly in their effectiveness, side effects, and suitability depending on local conditions. No single approach can be regarded as universally applicable; rather, an appropriate combination of measures is required to achieve both safety improvements and functional traffic flow. This review provides a useful basis for policymakers and practitioners in selecting and adapting traffic calming strategies, while also opening avenues for further research on their optimization and integration into sustainable road safety systems.

Keywords: Traffic calming measures; speed management; road safety; vulnerable road users.

1 Introduction

Vehicle speed is one of the key risk factors in road traffic. Speeding is a frequent driver behavior that significantly contributes to both the occurrence and severity of traffic accidents. The primary goal of speed management is therefore to prevent accidents and reduce their severity, with special attention to road sections characterized

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by high speed dispersion and the presence of vulnerable users, where conflicts and overtaking risks are most pronounced [1].

Accidents involving pedestrians, cyclists, and motorcyclists usually result in more severe outcomes, with the risk of fatality directly linked to impact speed. For instance, at a speed of 30 km/h, the probability of a pedestrian fatality is approximately 10%, while at 60 km/h it rises to 80% [1,2]. Even an increase in speed of just 1% can result in a 2% rise in injury rates and a 3% rise in the rate of serious injuries [3].

Previous research confirms that physical barriers, such as speed bumps of various dimensions, have a significant impact on reducing vehicle speed. An analysis conducted in Belgrade demonstrated that higher bump heights led to greater reductions in average speeds and increased pedestrian safety [4]. Similar findings have been reported elsewhere, confirming that measures such as bumps and raised platforms are highly effective, although they may have negative effects on ride comfort and pavement durability [5, 6].

International experience further confirms the benefits of traffic calming. For example, in Spain, traffic fatalities decreased from 9,344 in 1989 to 1,680 in 2013, partly due to the wide application of speed reduction measures [7]. In addition to physical measures, many authors emphasize the importance of procedures and criteria that precede their implementation in order to ensure both justification and long-term sustainability [8]. Bus routes represent a particular challenge, where speed cushions are often used as a compromise solution to balance safety and service quality [9].

Finally, the concept of “traffic calming” in European and American practice is more broadly defined and encompasses a wide range of methods that do not restrict vehicle passage but instead create conditions that encourage lower speeds, thereby providing a better balance between motor vehicles, pedestrians, and cyclists [10].

In this context, the present paper aims to synthesize existing knowledge by providing a structured review of the most commonly applied traffic calming measures, analyzing their characteristics, advantages, and limitations. The intention is to highlight both their potential and their constraints and to offer a concise basis for their practical application and future improvement under local conditions.

2 Overview of Traffic Calming Measures

One of the most frequent traffic violations is exceeding the permitted speed limit, which often leads to traffic accidents with serious consequences. In order to reduce this risk, a range of measures has been developed to influence drivers and compel them to reduce their speed. Some of these measures are regulated by national guidelines, while others—although not formally defined—are widely applied in practice and have proven to be highly effective. Among the most common measures are traffic calming devices, the installation of which must comply with current standards and regulations. It is particularly important to ensure adequate traffic signage that informs drivers in advance about the presence of speed humps, so that their full effect can be achieved [6].

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In this section, traffic calming measures are presented according to their prevalence and practical application in the Balkan region. The selection is based on relevant literature, national standards, and documented examples of practical use. For clarity, the measures are grouped into five categories: vertical, optical–acoustic, horizontal, electronic enforcement and monitoring, and intersection redesign (mini-roundabouts). While numerous additional solutions exist in international practice, the focus here is on those most frequently applied locally, as they provide the most relevant basis for assessing effectiveness under regional conditions.

2.1 Vertical Traffic Calming Measures

Among the most widespread solutions are various types of speed humps and raised platforms on the roadway. Raised platforms extend across the entire width of the carriageway and are typically constructed from asphalt, rubber, or plastic. They are often combined with pedestrian crossings, thereby facilitating the movement of persons with disabilities and parents with strollers. Their advantages include durability and low installation costs, while their disadvantages involve the risk of vehicle damage if crossed at inappropriate speeds, as well as the potential for increased noise (Figure 1).



Fig. 1. Asphalt Platform (Full-Width Plateau)

Artificial speed humps are also commonly found in urban areas. Their dimensions are adapted to the permitted speed limits, with heights ranging from 3 to 7 cm and widths from 60 to 120 cm. They are particularly effective near schools and pedestrian crossings. Speed humps are typically made of rubber materials (Figure 2) or asphalt, the latter being a cheaper and more durable solution. However, rubber humps pose challenges in regions characterized by heavy snowfall during winter months, as they are frequently damaged during snow removal operations.

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Fig. 2. Rubber Speed Hump

Small dot-shaped bumps represent a specific type of traffic calming device typically installed in residential areas, where speed limits are lower (Figure 3). They are semi-circular or circular elements of smaller dimensions, arranged in a sequence so that drivers must adjust their speed in order to pass over them safely. Unlike conventional rubber humps, they are lower in height and visually less prominent, yet still effectively reduce vehicle speed. They are most commonly made of concrete, plastic, or rubber, with advantages including durability and relatively easy maintenance. They are particularly suitable in zones where speed reduction is desired without causing significant discomfort for drivers and passengers.



Fig. 3. Small Modular Traffic Calming Bumps

Narrow speed bumps represent a type of traffic calming device that differs from conventional humps by their reduced width and stronger impact. Their height typically ranges between 2 and 5 cm, causing abrupt deceleration and noticeable jolts when vehicles pass over them. For this reason, they are used in areas where very low speeds are required—most commonly in parking lots, entrances to shopping centers, or internal roads of residential and industrial complexes (Figure 4). They are made of durable plastic or wear-resistant rubber, are easy to install, and are usually produced in bright colors with reflective segments for improved visibility. Their advantages include low

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cost and simple installation, while their main drawback is the uncomfortable deceleration they produce, which is why they are not installed on primary roads.



Fig. 4. Speed Bumps

Speed cushions do not extend across the entire roadway but only over part of it, leaving space for wider vehicles such as buses or emergency service vehicles. In terms of shape and profile, they resemble conventional raised platforms and speed humps, but their design allows for a differentiated impact on various categories of vehicles. They are most commonly constructed from asphalt or rubber and have proven particularly effective on streets with frequent public transport traffic. An additional advantage is that they facilitate easier drainage toward stormwater systems, making them especially suitable for areas with heavy rainfall (Figure 5).



Fig. 5. Asphalt Speed Cushion

2.2 Optical and Acoustic Traffic Calming Measures

In addition to vertical deflections, optical–acoustic measures also play an important role in moderating vehicle speeds within traffic flow. White transverse lines, arranged in series with varying widths and spacing, create a visual effect of approaching and alert drivers to the need for deceleration before a critical location, such as an intersection or pedestrian crossing.

Audible (rumble) strips represent a measure whose primary function is to provide both auditory and tactile warnings to drivers. When vehicles pass over them, mild noise and vibrations are generated, prompting drivers to adjust their speed to roadway conditions. Their installation involves surface roughening of the pavement, followed by the application of coarse aggregate or thermoplastic markings with a height of 8–

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12 mm. They are typically placed in pairs, spaced 1.8–2.0 m apart, and extend across the full width of the traffic lane. Their width ranges from 15–40 cm, while height varies between 5–12 mm, with spacing determined by the expected vehicle speeds in the critical road section [11].

These measures are most commonly applied near schools, kindergartens, railway crossings, pedestrian crossings, intersections, and hazardous curves, where even minor vibrations and sound signals can provide significant warning effects to drivers (Figure 6).



Fig. 6. Rumble (Audible) Strips

Vibratory (audible) strips represent a traffic calming measure, as the passage of vehicles over them produces stronger vibrations and sound effects that warn drivers of the need to reduce speed on critical road sections (Figure 7). They are constructed using coarse aggregate or thermoplastic horizontal strips, 20–40 cm in width and 18–25 mm in height, typically arranged in pairs or sets at intervals of 1.8–2.0 m. Up to three sets are commonly installed: the first with 5 strips, the second with 6, and the third with 7 strips [11].

In addition to their speed reduction function, vibratory strips also serve a warning role. Shoulder rumble strips (SRS) are placed on the outer edges of the roadway to signal lane departure, while center line rumble strips (CLRS) are installed on or adjacent to the centerline to alert drivers of encroaching into the opposite lane, thereby reducing the risk of head-on collisions [12].



Fig. 7. Vibratory Strips

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Andrijašević et al. conducted a study in Bar, on the M-1 main road, intending to examine the impact of vibratory strips on vehicle speed in the pedestrian crossing zone. Traffic was recorded using a drone, and the collected data were processed with DataFromSky software, where four gates (cross-sections of the roadway) were defined. The sample included 472 vehicles (95% passenger cars). The mean speed was 60.44 km/h, which exceeds the 50 km/h limit, while 83.1% of vehicles showed deceleration between the gates (positioned before and after the strips). The average speed decreased by 4.93 km/h (-1.31 m/s^2 toward the city center and -0.42 m/s^2 toward Ulcinj). The study concluded that vibratory strips contribute to speed reduction, but not to significant compliance with speed limits, as the mean speed at the entry gate was 63.14 km/h and 58.21 km/h at the exit gate [13].

2.3 Horizontal Traffic Calming Measures

Road narrowing influences drivers by creating a sense of spatial confinement, which encourages them to reduce speed and drive more cautiously. A wider carriageway gives drivers a sense of safety and induces faster driving, while a narrower one has the opposite effect (Figure 8). This measure is most often implemented through the use of central islands, sidewalks, traffic calming elements, or by allowing vehicle parking along the carriageway. It contributes to reducing aggressive driving and increases the safety of pedestrians and cyclists in urban areas, but it may also cause reduced roadway capacity and the emergence of “bottlenecks” in zones with high traffic volumes.



Fig. 8. Pedestrian Crossing Road Narrowing [14]

Horizontal deflection as a traffic calming measure involves the deliberate introduction of slight directional changes on straight roadway segments, encouraging drivers to reduce speed (Figure 9). Vehicles are subjected to centrifugal force, whose magnitude increases with curve sharpness and the square of speed; therefore, drivers must adjust speed to the curve radius to avoid skidding or running off the carriageway [15]. In practice, this effect is achieved through central islands, green belts, parking spaces, traffic calming elements, or sidewalk extensions.



Fig. 9. Horizontal Curvature of the Roadway [16]

2.4 Electronic Speed Enforcement and Monitoring Measures

Preventive radar speed displays are electronic devices that measure vehicle speed and simultaneously present it on an LCD or LED display. In addition to numerical values, they may also provide textual messages such as “SLOW DOWN” accompanied by flashing yellow lights for additional warning. The dimensions of these devices are harmonized with traffic signs [11]. Their primary role is to exert a psychological effect on drivers, making them aware of speeding. An additional advantage is the ability to store vehicle speed data, while drawbacks are related to equipment maintenance and the absence of a physical speed-reduction element, which causes some drivers to ignore the warnings. They are most commonly installed in school zones, residential areas, and near pedestrian crossings.

Stationary radar speed cameras represent a repressive measure aimed at reducing speeding and have demonstrated significant effects on improving compliance with prescribed limits. They are installed on poles beside or above the roadway and operate by photographing vehicles, identifying license plates, and automatically initiating the penalty procedure. In addition to speed enforcement, they are also used to detect other violations, such as running a red light, using a mobile phone, not wearing a seat belt, or illegal overtaking. Their greatest advantage lies in long-term effects, as drivers in camera-controlled zones tend to adhere more closely to speed limits. Additional benefits include high efficiency, continuous operation (24/7), and the ability to collect violation data useful for road safety analysis. Research confirms that fixed radar speed cameras lead to a significant reduction in traffic accidents and injuries in the areas of their application [17].

2.5 Mini-roundabouts

Roundabouts can also be considered a traffic calming measure, as their geometry compels drivers to reduce speed. Traffic circulates around a central island in a counterclockwise direction, and when negotiating the curvature, vehicles are subjected to centrifugal force, similar to the effect of horizontal roadway curvature. Additionally, drivers are, in most cases, required to yield to vehicles already circulating within the

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roundabout. The advantages of this type of intersection include smoother traffic flow without constant stopping, the ability to connect multiple entry roads, and the elimination of direct 90° conflict points, since all turns are executed to the right. On the other hand, disadvantages include limited pedestrian protection, difficulties in signalization with traffic lights, reduced capacity, and the requirement for a larger land area [15].

In recent decades, several modern variants of roundabouts have been developed to address different traffic needs, including improvements in capacity, safety, and operational efficiency [18]. However, when viewed strictly as traffic calming measures, the most relevant form is the mini roundabout. Characterized by a significantly smaller central island radius, mini roundabouts force vehicles to reduce speed both when entering and circulating (Figure 10). They are typically applied on the secondary street network, especially in urban areas with limited space, where they simultaneously improve safety and maintain acceptable traffic flow. Previous studies confirm that mini roundabouts contribute to reducing conflict points and lowering crash severity, while requiring fewer construction works and lower costs compared to conventional roundabouts.



Fig. 10. Mini-roundabout [19]

All of the discussed measures have their own advantages and disadvantages that vary with location, traffic intensity, and road environment, yet they ultimately share the common goal of reducing speeds, lowering accident risks, and improving overall road safety.

3 Conclusion

Vehicle speed represents one of the key determinants of traffic safety, with its impact being particularly evident in the severity of crash outcomes. A review of the relevant literature indicates that a wide range of traffic calming measures – including physical obstacles, optical–acoustic elements, psychological interventions, and modern technical monitoring systems – can make a significant contribution to reducing vehicle speed and improving the safety of all categories of road users. Nevertheless, despite their undeniable positive effects, previous studies suggest that the influence of these measures is not yet fully understood, especially regarding the long-term effects

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of their application and their variability depending on the local context and traffic flow structure.

The results of the review indicate that no single measure can be considered a universal solution; rather, their effectiveness depends on the spatial characteristics and the needs of specific groups of road users. Vertical physical obstacles (such as speed humps and raised platforms) are shown to be the most effective in residential areas and school zones, where the protection of vulnerable road users is crucial. Optical-acoustic and vibratory strips provide timely warnings to drivers on critical road sections such as hazardous curves, intersections, and other high-risk locations. Electronic measures, including radar speed displays and stationary cameras, contribute to long-term behavioral changes and systematic data collection but require considerable financial resources and institutional support. Infrastructure-based solutions, particularly mini roundabouts, illustrate the potential to improve both safety and traffic flow where space is limited.

For decision-makers, these findings emphasize that the selection of traffic calming measures must be adapted to the specific street function, traffic intensity, and composition of road users. Choosing the right measure in the right place can maximize safety benefits, improve cost-effectiveness, and support the development of sustainable urban mobility policies.

Future research should be directed toward accurately quantifying the effects of different traffic calming measures, not only in terms of average vehicle speeds and deceleration values but also regarding their broader implications. Of particular importance is the study of their impact on vulnerable road users, the dynamics of traffic flow in urban environments, and environmental protection through the reduction of noise and harmful gas emissions. In this respect, future studies should contribute to the development of integrated and innovative solutions that will ensure a long-term sustainable balance between safety, efficiency, and comfort for all road users, while remaining adaptable to local specificities.

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The Influence of Biodiesel Fuel on the Operating Characteristics of the Internal Combustion Engine at a Cold Start

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Abstract. This paper presents an investigation into the potential utilization of biodiesel as an alternative to conventional fossil diesel fuel in internal combustion engines. Particular attention is devoted to examining the influence of biodiesel on engine performance during cold start conditions, with a specific focus on parameters such as power output and torque. The study synthesizes contemporary scientific knowledge together with experimental findings, which suggest a modest reduction in engine performance when biodiesel is employed in comparison with conventional fuel. Furthermore, the experimental methodology is elaborated in detail, accompanied by a description of the laboratory equipment, manufactured by AVL, that was utilized in conducting the experimental investigations.

Keywords: Biodiesel, internal combustion engines, cold start, effective power, torque, exhaust emissions.

1. Introduction

Biodiesel, derived from renewable biological sources such as vegetable oils and animal fats, has gained significant attention as a substitute for petroleum diesel due to its environmental and energy sustainability advantages. Compared to fossil diesel, biodiesel provides lower emissions of carbon monoxide (CO), unburned hydrocarbons (HC), and particulate matter (PM), while contributing to reductions in overall greenhouse gas emissions [1]. However, one of the critical challenges associated with biodiesel use is its behavior under low-temperature and cold-start conditions.

During engine start-up at low ambient temperatures, incomplete fuel vaporization, poor atomization, delayed ignition, and increased oil viscosity can substantially influence combustion stability, emissions, and mechanical wear. These effects are particularly pronounced for biodiesel due to its higher viscosity, higher density, and lower volatility compared to conventional diesel [2].

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The BD20 fuel blend exhibited a slight decrease in brake thermal efficiency of about 1.5%, whereas the BD100 blend showed a more substantial decline. This reduction can be attributed to the lower calorific value and energy density of biodiesel relative to conventional diesel. As a result, engines fueled with biodiesel or its blends tend to exhibit higher brake-specific fuel consumption (BSFC), since a larger quantity of fuel is required to achieve equivalent power output [3].

The present study aims to evaluate the impact of biodiesel–diesel blends on engine performance during cold-start conditions. It specifically analyzes torque, power, and fuel consumption changes between BD20 and conventional diesel under controlled low-temperature environments. The results provide insights into how biodiesel’s thermophysical properties influence engine operation at low temperatures.

2. Synthesis of Scientific Knowledge on the Application of Biodiesel in Internal Combustion Engines

Biodiesel has been extensively investigated as a renewable, biodegradable, and environmentally friendly fuel alternative for internal combustion engines (ICE). Its molecular structure—comprising long-chain fatty acid methyl esters (FAME)—provides oxygen content that enhances combustion efficiency but also introduces several cold-flow limitations.

Researchers such as Lapuerta et al. [1] and Knothe [4] established that biodiesel combustion produces lower smoke opacity and particulate matter emissions due to its inherent oxygen content, which promotes more complete oxidation of soot precursors. However, this advantage is partially offset by a tendency toward slightly higher NO_x formation due to elevated combustion temperatures in locally oxygen-rich zones.

Tesfa et al. [5] developed predictive models linking biodiesel’s physical properties (density and viscosity) to its spray behavior and injector performance. Their results confirmed that increased viscosity can lead to larger droplet formation, delayed atomization, and longer ignition delay at low ambient temperatures. Dwivedi and Sharma [6] emphasized that cold-flow properties—such as pour point and cloud point—significantly affect fuel delivery, especially under cold-start conditions.

Santos et al. [7] reported that the operation of both small and large diesel engines using biodiesel fuels resulted in minimal performance penalties, with observed reductions in power and torque of no more than approximately 2% compared to conventional diesel.

Overall, scientific literature agrees that biodiesel–diesel blends can be used safely in compression-ignition engines, provided that cold-start challenges are mitigated through improved fuel heating, optimized injection timing, and use of cold-flow improvers. The synthesis of these findings forms the basis for the experimental validation presented in the following chapters.

3. Methodology

The objective of the conducted research was to examine the impact of applying biodiesel fuel blended with fossil diesel in a ratio of 20% m/m biodiesel (BD20) on engine performance characteristics. Laboratory testing was carried out to compare engine performance, including effective power and torque, during cold start conditions, using both pure diesel (D100) and a diesel–biodiesel blend (BD20). The obtained results enable the quantification of biodiesel’s influence on the initial operating characteristics of the engine, which is essential for assessing the applicability of biodiesel under real operating conditions.

In the engine testing laboratory, designed for determining engine performance and recording engine characteristics (speed and load characteristics), a modern electric dynamometer “Dyno Perform 160 kW” manufactured by AVL, Austria, was installed (Figure 1). This dynamometer measures engine torque and rotational speed, thereby enabling the determination of effective engine power. It is designed for testing engines with outputs up to 160 kW and torque up to 400 Nm, allowing both static and dynamic performance tests, including those of hybrid powertrains.



Fig. 1. “Dyno Perform 160 kW” engine dynamometer.

The operating principle of the electromagnetic brake is based on the phenomena of electromagnetic induction, in accordance with Faraday’s and Lorentz’s laws (Figure 2). By supplying direct current to the stator windings (1), a homogeneous magnetic field (2) is generated. During rotor (3) rotation, the moving gears intersect the lines of

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the magnetic field, inducing eddy currents in the surface material of the cooling rings (4), positioned opposite the front and rear edges of the gears (5). These currents generate a secondary magnetic field oriented opposite to the direction of rotor motion, thereby producing a braking effect. In this way, the mechanical energy of the rotor is converted into thermal energy, which is efficiently dissipated through cooling water, ensuring stable and controlled brake operation during engine testing.

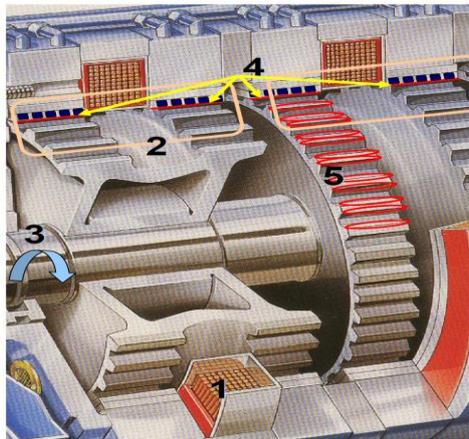


Fig. 2. Magnetic circuit of the brake.

The characteristics of the test engine, Volkswagen 1.9 TDI PD BKC, are presented in Table 1.

Table 1. Characteristics of the Test Engine

Characteristic	Value
Engine displacement	1898 cm ³
Power output	77 kW
Engine code	BKC
Number of cylinders	4 OHC
Compression ratio	1:19
Fuel supply system type	EDC 16
Fuel pump type	U
Tandem fuel pump pressure	7,5 bar
Injection sequence	1-3-4-2
Air flow measurement type	Mass-based
Idle speed	900 o/min ±100 o/min
Maximum no-load speed	4650 o/min to 5050 o/min
Oil temperature	80 °C
Oil pressure	2 bar at 2000 1/min

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3.1 Fuel Properties

The BD20 blend was prepared from rapeseed methyl ester (RME) biodiesel that met the EN 14214 specification. Conventional diesel fuel (B0) served as the baseline. Compared with pure diesel, BD20 exhibited higher density (+1.8%), higher kinematic viscosity (+6.2%), and a lower heating value (LHV) approximately 2.5% lower than B0. These differences significantly affect combustion and fuel atomization at low temperatures, leading to slightly reduced engine output.

3.2 Cold Start Definition and Procedure

A cold start is defined here as an engine start event where both engine coolant and oil temperatures are below 15 °C. The specific conditions used for all tests were: ambient air temperature 5 ± 1 °C, coolant 10 ± 2 °C, oil 10 ± 2 °C, and soaking time of 12 hours in a climate-controlled chamber. The engine was soaked overnight to achieve uniform thermal equilibrium. No preheating devices were used. The starter motor cranked the engine for 5 s at approximately 200 rpm. Data acquisition began once stable idle was achieved and continued until engine temperatures stabilized. This methodology ensures reproducibility and eliminates uncontrolled environmental variations.

4. Results and discussion

A comparison of brake torque versus engine speed (Figure 3) reveals that maximum torque for diesel (B0) was 138.88 Nm, whereas BD20 reached 136.53 Nm, indicating a 1.7% reduction. The torque–speed curve maintains similar shape, suggesting that combustion phasing remains consistent but with slightly delayed peak pressure timing for BD20.

The torque difference is most pronounced between 1200 and 1600 rpm, where wall temperatures are still below 60 °C and mixture preparation is incomplete. Once the engine reaches 80 °C coolant temperature, the torque values for both fuels converge within ± 0.5 Nm. This behavior confirms that viscosity and vaporization, rather than energy density, dominate performance deviations during cold starts.

The mechanical efficiency (η_m) of the system, calculated from indicated and brake power, averaged 81.3% for diesel and 80.7% for BD20, reflecting negligible mechanical loss differences between fuels. Therefore, the observed torque variation primarily stems from combustion efficiency.

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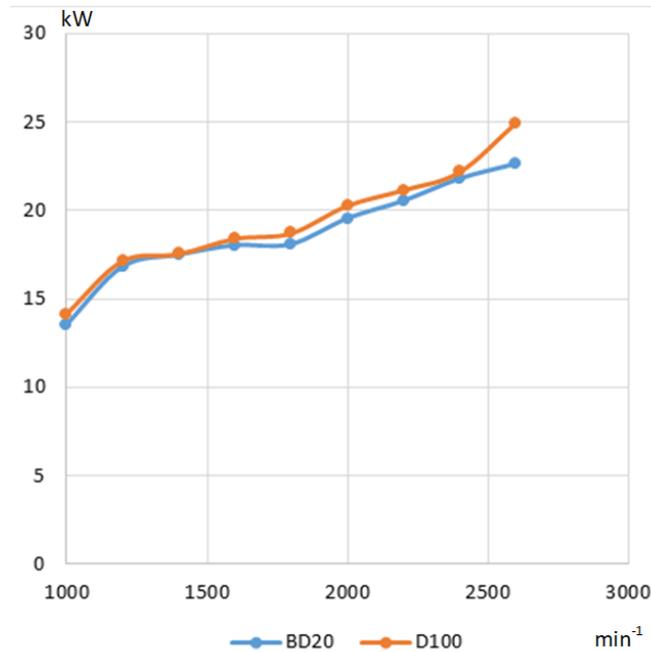


Fig. 3. Diagram of effective power (P_e) variation at 50% load during cold engine start

The brake power trend shown in Figure 4 parallels the torque behavior. At 2800 rpm, brake power (P_e) for diesel reached 26.75 kW, while BD20 achieved 26.21 kW — a 2.0% decrease. Across the 1400–2800 rpm range, the average power reduction remained below 3%, which aligns with the expected loss due to the 2.5% lower heating value (LHV) of BD20.

At low speeds (below 1200 rpm), the power difference exceeded 4%, caused by incomplete vaporization and delayed ignition. This effect diminished progressively as the chamber reached stable thermal conditions. The rate of increase in brake power with engine speed (dP_e/dn) was lower for BD20 during the first minute of operation, with a slope of 0.0095 kW/rpm compared to 0.0102 kW/rpm for diesel.

The analysis confirms that biodiesel's cold-start performance penalty is mainly transient and thermally driven. Once steady-state operation is achieved, BD20 provides nearly identical brake efficiency to pure diesel.

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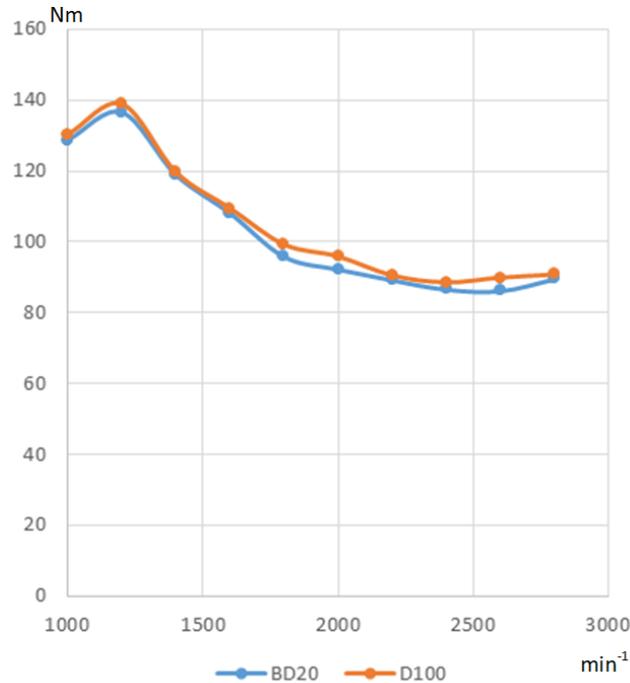


Fig. 4. Diagram of torque variation at 50% load during cold engine start

Although not the main objective of this study, emission data were recorded to assess qualitative differences. During the initial 60 s after start-up, **CO emissions** for BD20 averaged **1.28% vol**, compared to **1.06% vol** for diesel, representing a **20.7% increase**. This difference decreased rapidly as the engine warmed up, with BD20 exhibiting lower CO by approximately 6% after 5 min of operation.

Unburned hydrocarbons (HC) showed a similar pattern: initially higher by 12–15% for BD20, then dropping below diesel levels at stabilized temperatures. **NO_x emissions** remained nearly constant ($\pm 3\%$) between fuels, consistent with the modest temperature differences during the short cold-start phase.

Overall, BD20 demonstrated a slight initial disadvantage in incomplete combustion products due to poor spray atomization, followed by superior oxidation efficiency once sufficient temperature was reached. These transient effects underline the importance of optimized injection timing and fuel preheating strategies for biodiesel operation in cold climates.

5. Conclusion

This experimental study comprehensively investigated the impact of biodiesel fuel on diesel-engine performance under cold-start conditions, focusing on comparative behavior between BD20 (20% biodiesel blend) and conventional diesel (B0). The research employed controlled laboratory testing using an AVL Dyno Perform 160 kW dynamometer, ensuring precise replication of real-world low-temperature start-up scenarios.

The analysis demonstrated that the BD20 blend exhibits a **modest but consistent reduction in brake torque and brake power**, averaging **1.7–2.5% lower** than pure diesel during the cold-start phase. This decrease is primarily attributed to the **higher viscosity, lower volatility, and reduced lower heating value (LHV)** of biodiesel, which collectively delay atomization and combustion onset. Once the engine reaches normal operating temperature, these differences become negligible.

From an operational standpoint, biodiesel's cold-start challenges are primarily **thermal and physical**, not chemical. The delayed vaporization and slower warm-up process can be effectively mitigated by preheating strategies, optimized fuel injection timing, and improved atomizer design. These measures could virtually eliminate the transient power losses and enable biodiesel to perform equivalently to diesel even in cold climates.

The experimental results are consistent with literature data [1-7], validating the reliability of the test procedure and demonstrating that small biodiesel blends (up to BD20) do not impose significant penalties on performance when modern fuel systems are used.

In conclusion, **BD20 remains a viable, sustainable substitute for conventional diesel**, even under adverse starting conditions, provided that engine calibration accounts for its slightly different thermophysical properties. Future research should emphasize:

1. **Adaptive fuel-heating systems** to improve atomization and ignition at sub-zero temperatures.
2. **Computational fluid dynamics (CFD) modeling** of spray and vaporization behavior in cold environments.
3. **In-cylinder pressure analysis** combined with optical diagnostics to better characterize combustion phasing and cold ignition delay.
4. **Optimization of injection strategies** (timing, pressure, and pilot injection) tailored specifically for biodiesel–diesel blends.

These advancements would strengthen biodiesel's role as a clean, renewable energy source capable of replacing fossil diesel in modern compression-ignition engines, supporting both energy independence and environmental sustainability goals.

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Vibration Control Using Shunted Piezoelectric Systems: Experimental Investigation.

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Abstract. Controlling resonant oscillations at individual eigenfrequencies is vital for reducing noise, fatigue, and passenger discomfort in urban transport structures. This study experimentally compares two passive Shunt Piezoelectric System (SPS) topologies—resistive (R) and resonant (RL) shunts—applied to a cantilever beam instrumented with piezoelectric patches. Under open-circuit, R-shunt, and RL-shunt conditions, the beam was excited at its second natural frequency (286.5 Hz), and vibration responses were recorded via FFT spectral analysis. The resistive shunt produced a modest 1.96 % reduction in peak amplitude, demonstrating broadband energy dissipation. In contrast, the resonant R-L circuit, tuned to the target mode, achieved a 31.37 % attenuation at 286.5 Hz while leaving off-resonance frequencies largely unaffected. These results highlight the trade-off between implementation simplicity and peak attenuation: R shunts offer ease of deployment with moderate damping, whereas RL shunts deliver superior single-frequency suppression. The findings inform the design of tailored SPS solutions for applications demanding precise vibration control.

Keywords: Shunt Piezoelectric Systems, vibration control, mobility control.

1 Introduction

Urban transport systems—such as electric buses, trams, and shared micro-mobility vehicles—are increasingly deployed to meet sustainability and low-emission targets. However, these advances introduce new challenges in managing noise, vibration, and harshness (NVH), which directly impact passenger comfort, structural integrity, and component lifespan [1], [2]. Excessive oscillations at structural eigenfrequencies can amplify stresses and fatigue, while broadband vibrations generate undesirable noise.

Shunt Piezoelectric Systems (SPS) have emerged as a promising passive solution for vibration control and energy harvesting. By bonding piezoelectric transducers to a host structure and connecting them to electrical impedances, mechanical strain energy is converted into electrical and dissipated or stored [3], [4]. For structures, piezoelectric patches must be integrated into plate and shell structures, following developments

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in computational mechanics, see [5], [6], [7]. Resistive (R) shunts offer broadband damping, whereas resonant (RL) shunts incorporate inductance to target a specific mode, yielding high attenuation near the tuned frequency [8], [9].

Numerous theoretical and numerical studies have characterized single-mode and multi-mode SPS performance [3], [10]. Resonant shunts have demonstrated peak attenuation exceeding 30 % at tuned eigenfrequencies, but require precise tuning of inductance and resistance values [11], [12]. In contrast, resistive shunts simplify implementation and offer moderate damping over a wide band with lower peak reduction [8], [9]. Despite these advances, direct experimental comparisons under identical excitation conditions—for single-frequency suppression—remain limited.

This paper presents an experimental investigation comparing resistive and resonant shunt behaviors for controlling the second natural frequency of a cantilever beam. Vibration amplitudes and Fast Fourier Transform (FFT) are measured. The results quantify damping efficiency and frequency selectivity, providing guidance for selecting the optimal SPS configuration in applications.

2 Methodology

To damp the vibrations, an electrical circuit, consisting of either a resistor or a resistor-inductor in series, is connected to piezoelectric pads placed on the structure. Due to piezoelectric patches capacitive behavior in combination with the electrical circuit (RL), the phenomenon of resonance occurs, resulting in the damping of vibrations at a specific natural frequency. The piezoelectric patches are placed on the beam with reversed polarity and connected in series with the shunt circuit. Figure 1 shows the model of the experimental setup, which represents the beam with the piezoelectric patches and the resistor-inductor circuit in series.

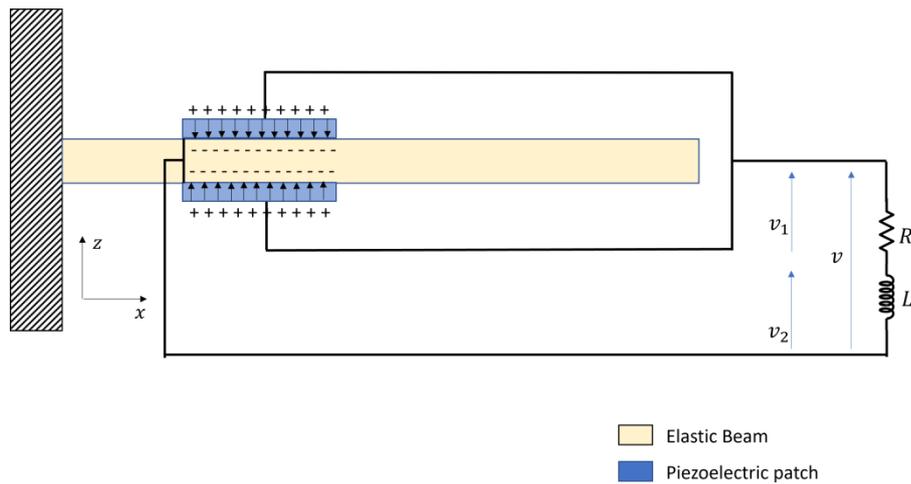


Fig. 1. A beam model with a resonant shunt piezoelectric circuit.

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2.1 Piezoelectric Constitutive Equations

The two global electromechanical equations (1), (2) are presented as follows, and they have been derived from discretized structural models. More specifically, Equation 1 describes the equilibrium state of the mechanical forces, while equation 2 describes the electrodynamic state of the electric potential. The constitutive relations for the piezoelectric layer can be expressed as [13]. Details about the FEM model are given in [14].

$$M_u \ddot{\mathbf{d}} + K_u \dot{\mathbf{d}} + K_{uv} \mathbf{v} = \mathbf{F}_m \quad (1)$$

$$-K_{uv}^T \dot{\mathbf{d}} + K_{vv} \mathbf{v} = \mathbf{Q} \quad (2)$$

where \mathbf{d} is the global vector of mechanical displacements and \mathbf{v} is the global vector of the electrical degrees of freedom. \mathbf{M}_u is the global mass matrix, \mathbf{K}_u is the stiffness matrix, \mathbf{K}_{uv} is the global electromechanical coupling matrix, \mathbf{K}_{vv} is the diagonal global capacitance matrix, \mathbf{F}_m is the global vector of mechanical forces and \mathbf{Q} is the global vector of electric charges.

2.2 Optimization of the shunt system

To achieve maximum damping of the system, it is important to determine optimum resistance and inductance values. Various methods have been proposed for this purpose, which relate to one degree of freedom system [8], [10], [11]. To calculate the optimal values of R and L, the following equations are used:

$$k_c = \sqrt{\frac{e^2}{K^E C^\epsilon}} \quad (3)$$

$$\omega_e = \frac{1}{\sqrt{L C^\epsilon}} \quad (4)$$

$$\omega_o = \sqrt{\frac{K^D}{m}} \quad (5)$$

$$K^D = K^E + \frac{e^2}{C^\epsilon} \quad (6)$$

$$\omega_s = \sqrt{\frac{K^E}{m}} \quad (7)$$

$$\xi_e = \frac{R}{2} \sqrt{\frac{C^\epsilon}{L}} \quad (8)$$

The equation (3), using the equations (4), (5), (6) and (7) can be rewritten as follows:

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$$k_c = \sqrt{\frac{\omega_o^2 - \omega_s^2}{\omega_s^2}} \quad (9)$$

From the resonant circuit, the optimal inductance and resistance are:

$$L = \frac{1}{C^\varepsilon \omega_o^2} \text{ and } R = \sqrt{\frac{3}{2}} \frac{k_c}{C^\varepsilon \omega_o} \quad (10)$$

Here k_c is the coupling factor, ω_e is the resonant shunt angular frequency, ω_o is the natural angular frequency in open-circuit, K^D is the stiffness of the structure when the shunt system is open-circuited, ω_s is the natural angular frequency in short-circuit, and ξ_e is the damping factor.

2.3 Fast Fourier Transform (FFT) for Vibration Attenuation Analysis

Vibration signals measured in the time domain often conceal overlapping modal components and intermittent events that drive machinery wear or instability. Applying the Fast Fourier Transform (FFT) converts these time-series data into the frequency domain, where each sinusoidal component—characterized by its amplitude and phase—becomes explicitly visible. This decomposition enables pinpointing of dominant frequencies, resonances, and faults such as misalignment or bearing defects, which are critical for designing effective attenuation strategies.

The discrete Fourier transform (DFT) that underpins the FFT is given by:

$$X_k = \sum_{n=0}^{N-1} x_n * \exp\left(-j * 2 * \pi * k * \frac{n}{N}\right) \quad (11)$$

where x_n is the n th time-sample, X_k the spectral coefficient at bin k , and N the total number of samples. The FFT algorithm reduces computational complexity from $O(N^2)$ to $O(N \log N)$ making real-time spectral monitoring feasible in electromechanical systems.

3 Experiment description and procedure

Passive shunt circuits can contribute significantly to vibration damping, especially for the critical eigenfrequency modes. As presented in the literature, similar passive damping methods have been used for this purpose. This report studies a system consisting of an aluminum beam on which two piezoelectric patches are mounted. The piezoelectric patches are responsible for converting mechanical energy into electrical energy and vice versa, are made of PIC255 material, have been placed very close to the clamped end and with opposite poling directions, as mentioned above. The beam is excited via the coil. Figure 2 shows the layout of the experimental setup.

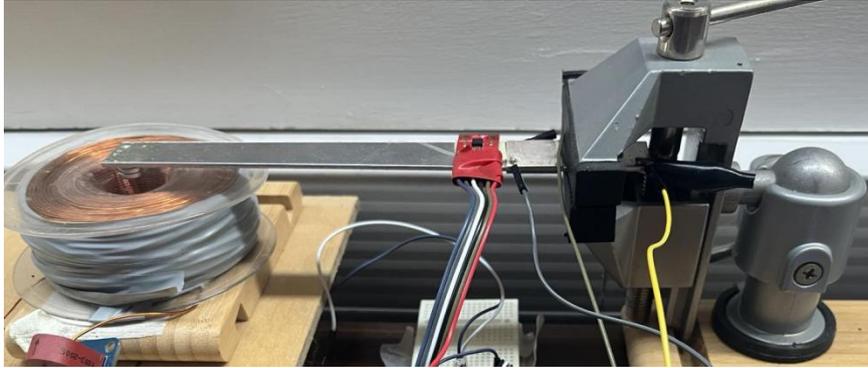


Fig. 2. Experimental configuration with contactless coil excitation system, accelerometer, cantilever beam and piezoelectric elements.

A signal generator is used to create a sinusoidal signal. An accelerometer is used to measure the vertical displacements for open circuit, closed circuit, and short circuit conditions and to take the corresponding experimental measurements. An oscilloscope is used to display the results measured by the accelerometer.

Table 1. Measured Values of Shunt Piezoelectric Systems (SPS).

Shunt Piezoelectric Systems (SPS)	Resistance R (k Ω)	Inductance L (H)	Piezoelectric Terminals
Open Circuit	-	-	Open without contact
Short Circuit	-	-	short-circuited
Resistive Circuit	81.60	-	in series
Resonant Circuit	6.60	56.98	in series

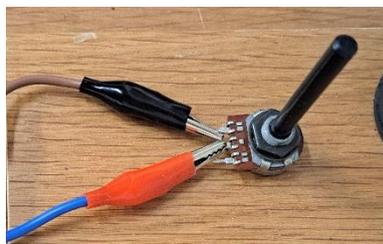
To calculate the optimum R and L values for the system, the oscillation amplitudes must be measured in both open circuit and short circuit conditions. Then, once the optimal values for the resistive circuit and the resonant circuit have been determined, measurements are taken of the oscillation amplitudes after the activation of the corresponding shunt circuit for damping the second mode. Beyond optimization of electromechanical parameters for the fine tuning of the system, as is presented here, a more general optimal design problem must include, optimal placement of piezoelectric elements, using classical [13] or even topology optimization techniques.

4 Experimental results

An experimental investigation was conducted to assess the effectiveness of the Shunt Piezoelectric System (SPS) under specified laboratory conditions, which can be con-

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sidered a preliminary approximation of real-world scenarios. The experimental setup, shown in Figure 2, consists of an aluminum beam excited contactless by a coil. Piezoelectric patches are attached to the beam, converting mechanical oscillation energy into electrical energy and vice versa, through the direct and inverse piezoelectric effect. The two piezoelectric patches, made from PIC255 material, are oriented with opposite polarities and connected in series. This series configuration results in a total capacitance that is half of the capacitance of a single patch. A critical component of the experimental setup is the insertion of two shunt circuits, as shown in Figure 3. The first circuit (Figure 3) consists of a resistor, while the second circuit (Figures 4 and 5) incorporates both a resistor and an inductor. These circuits are connected in series with the piezoelectric patches and are specifically designed to attenuate the beam's second eigenfrequency, thereby damping its oscillations.



(a)



(b)

Fig. 3. Resistive shunt circuit (a) Component of Resistive Circuit and (b) Measurement of Resistance.



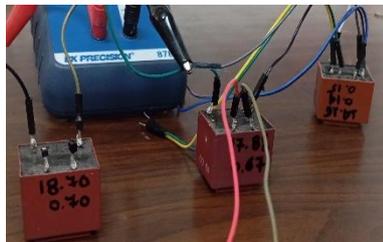
(a)



(b)

Fig. 4. Resonant shunt circuit (a) Component of Resonant Circuit and (b) Measurement of Resistance.

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(a)



(b)

Fig. 5. Resonant shunt circuit (a) Component of Resonant Circuit and (b) Measurement of Inductance.

The electrical quantity V_{pp} is measured as the peak-to-peak voltage, representing the difference between the maximum and minimum values of the waveform. The measured values for the open piezoelectric terminals (open), short-circuited piezoelectric terminals (short), the in-series resistive R circuit, and the in-series resonant R-L circuit (shunted) are summarized in Table 2.

Table 2. Results of Shunt Piezoelectric Systems for Amplitude Reduction

Shunt Piezoelectric Systems (SPS)	Excitation frequency (Hz)	Beam frequency (Hz)	Output signal Measurement V_{pp} (mV)	Damping Efficiency
Open Circuit	286.5	286.5	408	-
Short Circuit	286.5	286.9	408	-
Resistive Circuit	286.5	285.7	400	1.96%
Resonant Circuit	286.5	286.5	280	31.37%

The measurements for each category of Shunt Piezoelectric Systems (SPS) during the experiment. The damping effectiveness for each SPS configuration was calculated based on the V_{pp} values obtained from these measurements.

Figure 6 compares the FFT spectra of the beam under open-circuit and resistive-shunt conditions at an excitation frequency of 286.5 Hz. In the open-circuit case (Fig. 6a), a dominant spectral peak appears at the beam's second natural frequency of 286.5 Hz with a V_{pp} amplitude of 408 mV. Activating the 81.6 k Ω resistive shunt (Fig. 6b) produces a slight frequency shift to 285.7 Hz and reduces the peak amplitude to 400 mV, corresponding to a 1.96 % damping efficiency. This result illustrates the resistive

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circuit's ability to dissipate vibration energy broadly, yielding modest attenuation across the spectrum.

Figure 7 shows the FFT spectra for the open-circuit beam (Fig. 7a) and the same beam with the resonant R-L shunt engaged (Fig. 7b). The open-circuit spectrum again exhibits the 286.5 Hz peak at 408 mV. When the 6.6 k Ω –56.98 H resonant circuit is connected, the tuned mode is sharply attenuated to 280 mV—31.37 % reduction—while leaving adjacent frequencies largely unaffected. These results confirm that the resonant shunt selectively absorbs energy at the target mode, delivering high peak attenuation without compromising broadband response.

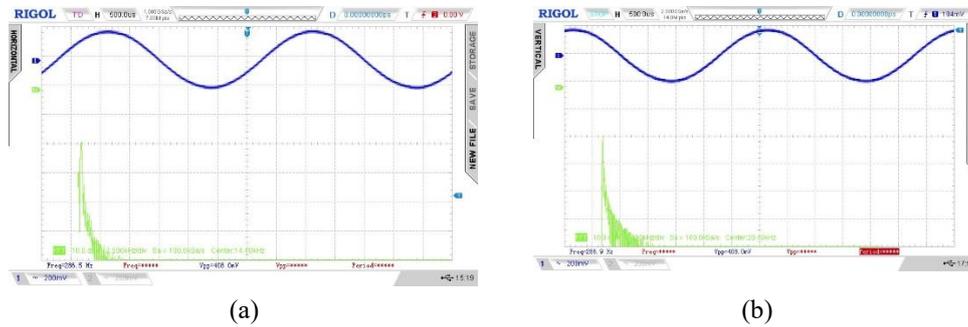


Fig. 6. Response of beam with open and resistive circuit terms, having amplitude V_{pp} 408 mV at 286.5 Hz.

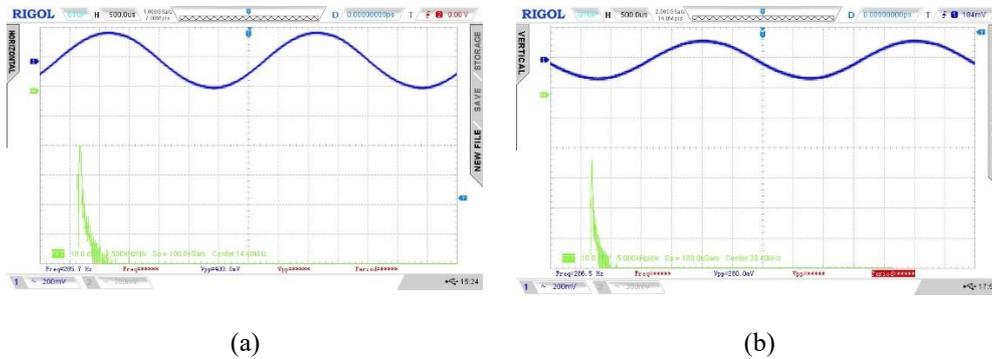


Figure 7. Beam response in open circuit and resonant shunt terms, amplitude width V_{pp} 280 mV at 286.5 Hz.

The results from the application of a shunted resistive and resonant circuit are shown in Figures 8 and 9. Where the continuous excitation from the coil is shown in pink, and the disturbance of the beam before and after the application of the shunted piezoelectric system is shown in blue. The moment the resistance and resonance circuits are connected, respectively, they are circled in red for better understanding of the graph.

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The experimental results indicate that the R-L shunt circuit is highly effective in damping oscillations at the beam's second natural frequency, outperforming the R shunt circuit in terms of amplitude reduction.

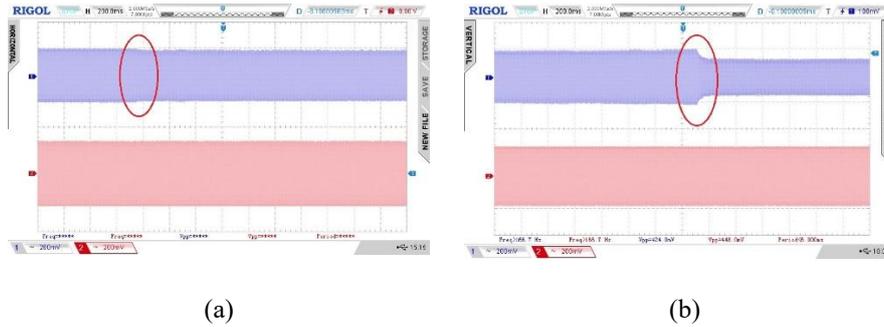


Fig. 8. Attenuation of oscillation amplitudes through the application of (a) shunt resistive circuit and (b) shunt resonant circuit.

5 Conclusions and Future Work

An experimental investigation demonstrated the effectiveness of Shunt Piezoelectric Systems (SPS) in attenuating oscillation amplitudes, particularly at the beam's second natural frequency. Among the two shunt circuit configurations tested, the resonant R-L circuit outperformed the resistive R circuit, providing a more substantial reduction in vibration. The resonant circuit achieved superior performance, with a damping percentage of 31.37%. These findings validate SPS as a promising solution for passive vibration control. Additionally, the simplicity and versatility of the system make it suitable for a wide range of mechanical applications.

Future research could investigate the effectiveness of SPS in systems exhibiting multiple natural frequencies or more complex dynamic behaviors. Further optimization of the R-L circuit—such as fine-tuning the resonant frequency—could enhance its damping performance. The integration of adaptive SPS, capable of responding to varying excitation frequencies or environmental conditions, could significantly improve system efficiency.

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Railway Transport

Hybrid Traction Systems for the Zillertal Railway in Austria

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Abstract. Many branch lines and even some main railway lines are still operated with diesel engines. As soon as these engines came close to their end of life, the question about alternative drive systems will come up. This happened in 2017 for the narrow gauge railway from Jenbach to Mayrhofen in Tyrol, Austria. The attempt to introduce hydrogen empowered trains failed in 2023. The following investigation about the best suitable decarbonized energy supply for traction and auxiliary usages taught once again that only the common and synchronous optimization of vehicle, infrastructure, and operation leads to a global optimum. The various scenarios are compared and rated for technical, commercial, and timeline factors. To realize an electric operated railway with a catenary may cause local resistance. We will show how it was solved in the specific case. The mobility plan with 18% less travel time will be fulfilled based on simulation calculation, the results have already been considered by the local authorities.

Keywords: Battery-hybrid-trains, electrification, diesel trains.

1 Initial Situation

A detailed investigation of different traction systems for the Railway in Zillertal was already presented a year ago [1]. Here we will provide a short summary and the latest updates of this ongoing process to decarbonize this railway lines as a case study.

1.1 Time 1860 to 2018

The Railway into the beautiful Zillertal in Tyrol, Austria, was under discussion since the late 1860s because of the really bad means of transportation. After the decision of the Austrian emperor in 1872 to build a standard gauge, twin track mainline from Salzburg to Innsbruck “Giselabahn” (to bypass Bavaria) over the Hochfilzen Pass and Kitzbühel, avoiding a long base-tunnel under the Gerlos Pass, the Zillertal was once again isolated from the worldwide network of railways.

Local authorities used the following twenty years for discussions and founded in 1892 a “railway committee” to solve the transportation problem. Because of a chronic

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lack of funding a decision was made to build a narrow gauge railway following the national standard of 760mm gauge, the “Bosnian gauge”, fully compatible to all other narrow gauge railways in the Austrian monarchy. This was only cost driven, because the topography of the Zillertal required neither tunnels nor narrow bends and the two main bridges were designed for heavy loads to carry standard gauge freight cars.

On Dec 2nd 1899 the concession was approved, in 1900 the civil works started, and on July 31st 1902, the line was finally opened (31,7 km, single track). The traction was done by various steam locomotives.

In 1967, the Zillertalbahn purchased the first diesel operated passenger train consisting of two electric 750V DC tramway cars from 1954 of the German type ET195. In 1967 this train set came into the Zillertal and was re-gauged to 760mm. It was the first electric powered passenger train. It was in operation till 1997 (see Fig. 1).



Fig. 1. Zillertal’s first electric train, powered by a diesel generator car 1967 © 1980 wikipedia, originally operating in Ravensburg. After the shutdown there, it came to RTM (Rotterdamsche Tramweg Maatschappij), where an intermediate diesel powered generator car was added to operate without catenary. The gauge was changed from 1000mm to 1067mm.



Fig. 2. Zillertal’s 3-car-train, powered by a diesel locomotive © MfV, 240315_1243

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In the early 1980s, Zillertalbahn started to purchase new diesel-electric railcars. 7 railcars, 2 cab cars, and 5 passenger cars were put into operation till 1998. See Fig. 2.

From 2004 to 2009, 4 new diesel-hydraulic locos, 5 passenger coaches, and 3 cab cars were ordered and another railcar from Salzburg's Pinzgaubahn came in 2013. In 2018, a fleet of 6 complete push-pull trains, all diesel powered, were available. In 2018, the oldest railcar had an age of 34 years and replacement became urgent. See Fig. 3.



Fig. 3. Zillertal's 3-car-train, powered by a diesel locomotive © MfV, 240315_1326

1.2 Time 2018 to 2025

Thinking about an entire replacement of the actual aging fleet, the ideas to choosing diesel-powered trains was no longer satisfying. New opportunities started to become enabled by various test-engines as standard gauge locomotives and railcars:

- Fuel cell drives
- Battery drives
- Fully electrical drives (conventional)

Whereby this usual wording "drives" is a little bit incorrect, all three types have electric drive motors. The difference is, where the electrical power is coming from.

In the first both cases, the electric power is stored within the train, either in form of liquidized hydrogen (350 or 700 bars) or in form of batteries (approx. 9 metric tons for a single run in one direction) or in the third case by construction of a 31,7 km long catenary (approx. 45 km total length of the catenary and several substations).

The plan to hype Zillertal as a region of Innovation using cheap electric power during the night hours in Mayrhofen, the line's end. So the decision was made in favor of using hydrogen, locally produced by green electrolysis during the night. Some over-production of hydrogen should also be used for hydrogen busses and snow groomers. This was a smart decision with the knowledge in the year 2018.

But nothing happened. Contracts were prepared, but finally the trains were not been ordered, the electrolyzers were not built. Stand still. But the population and local majors were sensitized, that the new Zillertalbahn will not need any catenary, destroying the lovely landscape. This contradiction is important to know, because a catenary

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was claimed impossible in the future. In the early summer of 2023, political parties in opposition to the local government claimed that the fuel cell operated trains would cause immensely higher operational costs (due to poor efficiency) calculated over the next 30 years. Also, the idea with the snow groomers was approved by trials not to be applicable, because the quite sensitive fuel cells do not like the lateral movements and gradients in the mountains. Also, the bus technology made big progress and test runs between Mayrhofen (633 m above sea level) and Hintertux (1501 m) led to the decision to order ecologically friendly battery busses, which are running “better than expected” and became – after some childhood illnesses in the heating system – very satisfying.

Finally, the local government ordered in 2023 a new study for the decarbonization of the Zillertalbahn, which was realized by the Technical University of Vienna [2].

This long introduction is necessary to understand why this “simple” decarbonization project becomes so complicated and so many discussions are required. Unfortunately, the long period of discussions causes extremely high additional costs to keep the existing fleet running.

2 Results of Comparison of various power supply systems

In 2023 and 2024, when the study of the Technical University of Vienna [2] was developed, technology has been going ahead and a lot of experience with test vehicles has been collected by ÖBB (Österreichische Bundesbahnen) [3] and the railway industry.

2.1 Scenarios

Six scenarios, much more than in 2018, have been investigated, and all of them are using electro-mechanical drives with asynchronous motors and inverters [2]:

- Sc. 0: Diesel-Electric Multiple Unit (DEMU) – for reference
- Sc. 1: Electric Multiple Unit (EMU) – requires catenary everywhere
- Sc. 2: Hydrogen Electric Multiple Unit (HEMU) – original proposal
- Sc. 3: Battery Electric Multiple Unit (BEMU) – with charging at line’s end
- Sc. 4: BEMU-hybrid (BEMU-hy) – requires sections of overhead catenary
- Sc. 5: BEMU-optimized (BEMU-hy-opt) – higher level batteries and various short sections of catenary (and also a set of sub-scenarios)

The train configuration was normalized to make the various concepts comparable.

The electro-motoric drive systems with rotating (asynchronous) motors are doubtless the best technical choice. Not so clear is the answer, where the electric power shall be generated: onboard or stationary at track side. Vehicle or infrastructure? Storage and generation onboard require either battery packs or hydrogen tanks and a fuel cell pack inside. Stationary power supply requires energy transmission to the train by local overhead catenary or a combination of them. Main technical differences are the total mass of the train, the number of remaining seats (meaning: the capacity), maybe

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the acceleration rates, the time loss for charging or taking fuel, but also the total costs, the time till availability and the costs of adapted infrastructure. Table 1 gives an overview of the main parameters.

Table 1. Main parameters of calculated cases [1, 2]

	DEMU	EMU	HEMU	BEMU	BEMU -hy	BEMU -hy-opt
Number of cars	4	3/4	4	3/4	3/4	3/4
Length of train [m]	68,5	3: 57,8 4: 76,4	76,4	3: 56 4: 75,5	3: 56 4: 75,5	3: 56 4: 75,5
Passenger capacity [seat]	323	3: 303 4: 413	373	3: 278 4: 392	3: 278 4: 392	3: 278 4: 392
Total Mass of train with load [t]	151.4	118.4	164	121.2	122.2	120.3
Traction weight (adhesion) [t]	58.0	88.0	90.4	86.0	87.0	85.1
Maximum speed in service [kph]	80	100	100	100	100	100
Traction power at wheel [kW]	500	1400	1400	1400	1400	1400
Battery storage capacity [kWh]	-	-	310	650	325	264
Maximum deceleration [m/s ²]	0.8	1.0	1.0	1.0	1.0	1.0
Maximum acceleration [m/s ²]	0.65	1.0	1.0	1.0	1.0	1.0

In a long-term view, double traction of ten 3-car-units in peak hours, when required, is much more efficient compared to six 4-car-units (originally only five), even if the main platforms must be extended from 80 m to 120 m. This is not only much more flexible in operation, it is also more resilient regarding crashes on one of the over 60 level crossings or other accidents. These ten 3-car-units can be ordered in two batches, first six, later four.

The proposed electrical equipment along the lines will be prepared to supply a double traction train in every section in each direction in full acceleration at the same time as a peak requirement.

2.2 Assessments and ranking

The running dynamics of the various train concepts and their positive results in simulator calculations are basically requirements for acceptance.

The time schedule is a must-have criterion. Trains must have an acceleration and braking rate of 1,0 m/s² to fulfill the requirements of 45 min service time from start to end (today 55 min) [4]. The traction energy consumption is related to the later costs of operation, whereby only differential costs are considered regarding the various scenarios in general, but never the entire costs. So only the different energy supply systems and their different efficient degrees are considered, but no costs for driver, conventional maintenance, or cleaning. They are independent of the various train concepts. The main criteria focused on based on [5] and [6] as well as [7-9] were:

- Costs for rolling stock
- Costs of rolling stock maintenance

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- Costs for infrastructure
- Costs of infrastructure maintenance
- Costs of scheduled operation

These costs of scheduled operation are divided in four main groups [2] [5] [8, 9]:

- Costs for prime energy
- Special tax for CO₂-emissions (or equivalent measures)
- Cost for plannable, periodic substitution of concept specific components (e.g. traction battery packs, hydrogen fuel cells, etc.)
- Costs of risk premium (by suppliers)

Costs for traction energy and also the specific auxiliary components of the traction system are put into the first bullet. They are the most important and recurring factor because of 30 years of operation, and they influence the costs per train-km. They are crucial for the marginal costs of train services at times of low demand.

Three main assessment criteria have been defined in decreasing importance [2]:

1. Differential costs of scheduled operation [Eur/train-km],
2. Differential total costs (in Eur/train-km),
3. Differential total costs (in Eur-cent/seat-km).

The third criterion considers the different needs for space for additional energy equipment inside the car body. The assumed and used parameters of this comparison calculation model have been analyzed with a sensitivity analysis, see Table 2.

Table 2. Differential costs modifications and trends as result of the sensitivity analysis for assessment criteria 1 [2]

diff. costs of scheduled operation [€/train km]	DEMU	EMU	HEMU	BEMU	BEMU -hy	BEMU -hy-opt
Reference point (basic calculation)	2.49	1.09	6.94	1.88	1.43	1.30
Catenary invest (price only 50%)	2.49	1.09	6.94	1.88	1.43	1.30
Primary energy (price 200%)	2.49	2.17	11.49	3.26	2.70	2.47
Double traction in peak time	2.50	1.09	7.09	2.21	1.55	1.41
15 min-interval (instead of 30 min-interval)	2.49	1.09	6.32	1.96	1.47	1.34
Low H ₂ price (special contract)	2.49	1.09	3.78	1.88	1.43	1.30
60 years view (2 nd train gen.)	2.50	1.09	6.94	1.88	1.43	1.30
average	2.49	1.17	7.07	2.13	1.64	1.49
	214%	100%	606%	183%	140%	128%

Table 1 shows a clear winner considering today's and tomorrow's timetable considering the first main criterion the differential operating costs per train-km [2, p87]:

1. EMU
2. BEMU-hy-opt
3. BEMU-hy
4. BEMU
5. DMU
6. HEMU

In the second and third criteria, the sequence can slightly change because of the investment costs for the catenary. But in the sensitivity analysis, similar as shown in Table 1, it becomes clear that any kind of additional services in comparison to today's

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timetable, means, a more intense usage of the infrastructure will underpin this ranking.

As the continuous catenary was not applicable anymore by political reasons (chap 1.1), the chance of 2018 was gone (the knowledge was available since 2014 [4]), the second best and today's best solution BEMU-hy-opt was investigated in detail in a second study [10].

3 Challenges of a continuous catenary

Based on [2] and the chosen concept of BEMU-hy-opt more detailed investigation was required, done by the civil engineering office of Actes Bernard [10]. The specification had two phases and the main results of [2] were independently confirmed.

Originally, the electric power system was not finally defined. The four most probable and standardized systems were

- 1.500 V DC
- 15 kV 16,7 Hz AC
- 15 kV 50 Hz AC
- 25 kV 50 Hz AC

During the investigation, the 15 kV 16.7 Hz and 25 kV 50 Hz were eliminated, because they had no serious differences compared with the two other AC systems in terms of the infrastructure. The insulation distances remain unchanged by international standards. For the vehicles, 50 Hz is better than 16,7 Hz (lighter transformers) and DC is better than AC (no transformers), but only to support the synergies with other narrow gauge railways in Salzburg, Styria, and lower Austria, DC were discarded later on. Therefore, the main system of investigation remains 15 kV 50 Hz AC.

3.1 Phase 1 – technical feasibility

In Phase 1, the entire line of 31,7km was separated in 200 m long sections. Every section was investigated to meet the 6 categories:

0. Feasible (no limitations at all)
1. Feasible (crossing foreign infrastructure, vegetation, causing higher attention in planning, but no significant limitations or costs in realization)
2. Feasible (some limitations, requires additional investments or approvals, may require adjustment in foreign infrastructure (cable, gas pipes))
3. Technically possible, some uncertainties, may cause time delay or significant additional costs
4. Technically possible, high effort or extraordinary high costs and time delay
5. Not feasible

To check the line, a detailed investigation in local maps, line routings of infrastructure supplier and a photo documented train run (driver's eye) in both directions were done. The result was pleasing:

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0. 24 %	2. 11 %	4. 0 %
1. 62 %	3. 3 %	5. 0 %

86 % of the line can carry a catenary without any problems, 97% with some additional planning and approval effort. Only 3% or exactly 4 locations need additional care. They are

- The 40 m long underpass of state highway A12 at milepost 1.4 km is limited in height, especially for transportation of standard gauge freight cars onto narrow gauge carriers.



Fig. 4. Underpass of state highway A12 at milepost 1.4 km © MfV, 240315_1338

To lower the track is not possible, because beside the underpass there is a bridge crossing the Inn river. Changing the clearance profile for freight cars from G2-type (4650 mm) to G1 type (4280 mm) helps. See Fig. 4.

- The 13 m long underpass of B169 main road of Zillertal at mile post 2.8 km, very close to the north portal of 1336 m long Brettfall-Tunnel. The track can be lowered approx. 0.5 m. See Fig. 5.



Fig. 5. Underpass of B169 at milepost 2.8 km © MfV, 240315_1336

- The underpass of the 220 kV high-voltage lines of APG (Austrian Power Grid) between milepost 30.6 km and 30.8 km, where the deepest height under worst conditions is not sufficient to fulfill the insulation requirements against the 15 kV catenary. Here, the catenary can be stripped through, but must be grounded.

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- The underpass of the 110 kV high-voltage line of APG between milepost 30.8 km and 31.0 km. Solutions see above.

Finally, there is a clear result: the entire line can be electrified by a conventional catenary.

To solve the problem with the politically driven opinion against the ugly catenary posts (there are some really bad examples in Tyrol built by ÖBB infrastructure, so the discontent is understandable), first investigations are started to minimize the height of the posts and use local materials instead of concrete posts. This is an ongoing innovative process and not finished yet.

3.2 Phase 2 – proposed sections

In Phase 2, the study [10] investigates the best locations for the catenary section, following the proposal of study [2] using battery-hybrid-trains. The optimized version requires approx. 50 % catenary as an optimum of battery size, acceleration behavior, and minimum additional weight and costs for batteries and catenary.

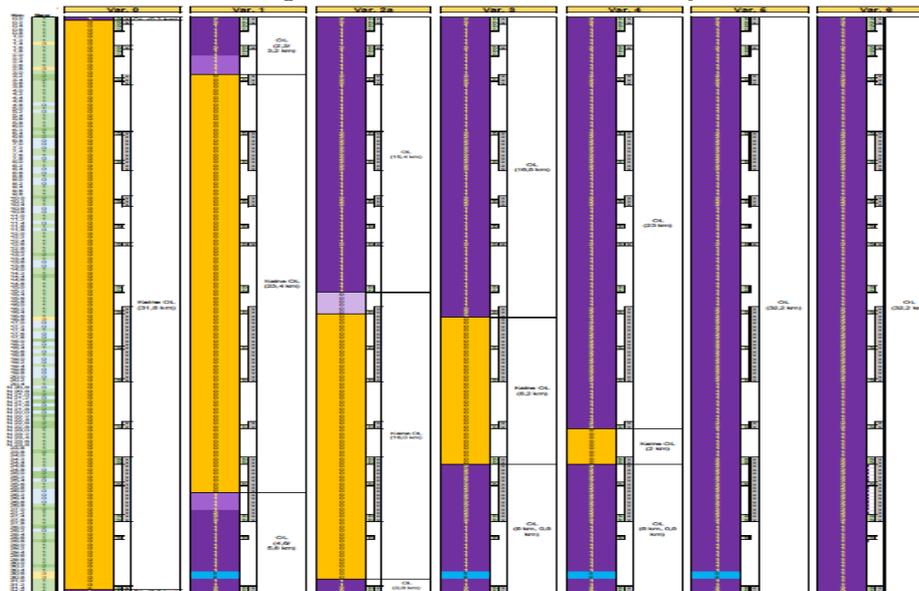


Fig. 6. Variants of catenary section Var. 0 to Var. 6, violet = catenary, yellow = battery, Jenbach on the top, Mayrhofen on the bottom, light violet = for 1.5kV DC only, grey = double track. Proposed Var 2a is the third column from the left [7]

The optimized version there requires approx. 50 % catenary on the free line as an optimum of battery size, acceleration behavior (discharge rate of the batteries during acceleration under worst case conditions), and minimum additional weight and costs for batteries and catenary. Seven Scenarios were investigated (see Fig. 6), from charging via catenary only in the terminal stations in stand-still (Var. 0) up to full catenary

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(Var. 6). Var. 0 represents the BEMU and Var. 6 the EMU for comparison. The various variants are not the subject of this article; Fig. 6 shall only document the kind of approach. The winner is Ver. 2a, which has also only two sections, a very short 0.8 km section in Mayrhofen, avoiding the high-voltage line underpasses and a 16.5 km long section at Jenbach.

4 Actual Status and Outlook

Main investigations for the de-carbonization of the Austrian Zillertalbahn are done, the technical feasibility is approved, and a favorite concept has been decided with a 50 % catenary of 15 kV 50 Hz AC and battery-hybrid trainsets.

Main parameters of the trains are specified, the catenary is feasible all over the line, and the substations of power supply are defined. The investments costs for the vehicles and for the catenary and substations are granted. Trains have a longer lead time than the catenary, so their specification and tender are urgent as the next step. The catenary will be planned in detail after the train order.

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Benchmarking and Strategic Analysis of Metro System; Enhancing Sustainability and Efficiency

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Abstract. With increasing urbanization and growing demand for sustainable transportation, metro systems have become vital components of modern urban infrastructure. This study presents a comprehensive benchmarking analysis of approximately 40 global metro systems, addressing the dual challenges of energy efficiency and indoor air quality (IAQ) management. Using statistical methods such as correlation, regression, and Monte Carlo simulations, we examine how operational parameters (number of lines, stations, vehicles, network length, and ridership) influence key sustainability indicators: total annual energy consumption and peak PM_{2.5} concentrations. The findings reveal strong positive correlations between operational scale and energy use, with vehicle count ($r = 0.9738$) and vehicle kilometers traveled ($r = 0.9404$) emerging as primary drivers. Tokyo's metro system demonstrates the highest recorded energy consumption (95,798.6 GWh), reflecting its massive scale, while Singapore achieves remarkable efficiency (1,224.7 GWh) alongside improved IAQ (PM_{2.5}: 19.6 $\mu\text{g}/\text{m}^3$). In contrast, Barcelona (102 $\mu\text{g}/\text{m}^3$) and Beijing (163 $\mu\text{g}/\text{m}^3$) face severe IAQ challenges. Case studies from Santiago, Amsterdam, and Paris demonstrate effective sustainability strategies such as renewable energy use, solar-powered stations, and regenerative braking. Simulations highlight divergent energy and IAQ trends across cities. The study identifies network size, operational intensity, and passenger density as key factors. Recommended actions include renewable integration, energy-efficient technologies, optimized ventilation, and supportive policies, along with a monitoring framework. These findings offer actionable guidance for improving metro system sustainability and public health.

Keywords: Metro systems, Energy efficiency, Sustainable transportation, Indoor air quality, PM_{2.5}.

1 Introduction

Urban transportation systems are vital to modern cities, offering high-capacity, energy-efficient mobility while easing congestion and reducing environmental impact. Metro rail systems, in particular, efficiently transport large passenger volumes with relatively low emissions and land use compared to road-based alternatives. Their

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benefits reduced congestion, improved air quality, and lower greenhouse gas emissions, make them central to sustainable urban development and global goals such as SDG 11 (sustainable cities and communities) and SDG 7 (affordable and clean energy) [1].

However, the environmental advantages of metro systems are increasingly offset by two major concerns: high energy consumption and poor indoor air quality (IAQ), especially in underground stations. While metros consume significantly less energy per passenger-kilometer than buses or private vehicles [2], their extensive networks, frequent operations, and reliance on artificial ventilation result in high overall energy use. Major metros like Tokyo and London consume energy comparable to medium-sized power plants [3, 4]. Metro systems often exhibit elevated PM_{2.5} (particulate matter under 2.5 microns) concentrations, frequently exceeding the World Health Organization's recommended 24-hour limit of 25 µg/m³ [5]. Recorded levels include 102 µg/m³ in Barcelona, 204 µg/m³ in Beijing, and 284 µg/m³ in Chicago [6]. These particles mainly stem from brake and wheel-rail wear, tunnel dust, and infiltration of outdoor pollutants [7]. Due to their small size, PM_{2.5} can penetrate deep into the lungs and bloodstream, causing serious cardiovascular and respiratory issues [8]. Despite increasing investment, many metro systems lack integrated strategies to enhance energy efficiency and reduce PM_{2.5} exposure. To address this, the present study benchmarks and analyzes 47 metro systems worldwide. By correlating operational characteristics (fleet size, ridership, network length) with sustainability indicators (energy consumption and peak PM_{2.5} levels), the study identifies key drivers of inefficiency and pollution and offers data-driven recommendations to guide more sustainable and health-conscious metro operations globally.

2 Literature Review

Metro systems are under increasing scrutiny for their environmental impact, particularly concerning indoor air quality and operational energy consumption. Studies across cities like Montreal, New York, Paris, Stockholm, Seoul, and Chengdu report highly variable PM_{2.5} levels, influenced by tunnel design, braking systems, station depth, ventilation, and maintenance practices [9]. For example, Chengdu's in-carriage PM_{2.5} ranged from 11 to 74 µg/m³, spiking during transitions between aboveground and underground segments [10]. Key sources include brake and wheel-rail abrasion and infiltration of outdoor air, which produce metallic dust mainly iron raising PM_{2.5} levels in systems such as Barcelona, Athens, and Porto [11]. PM_{2.5} levels often exceed ambient air even in modern systems [12]. Energy consumption in metro systems is mainly driven by network size, passenger volume, and infrastructure characteristics. Underground stations are especially energy-intensive, averaging 217 kWh/m² annually, much higher than the 131–144 kWh/m² seen in overground stations in China [13]. Major energy demands come from train traction, lighting, HVAC, escalators, and other station operations. A strong correlation exists between passenger throughput and energy use, as larger or busier stations require extended operating hours and enhanced ventilation [14]. For instance, in 2016, China's metro systems consumed about

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11.1 billion kWh, roughly 0.2% of the country's electricity supply [15]. In the UK, the London Underground alone used ~1.22 TWh in 2022–23, making it one of the top electricity consumers in UK transport [16].

In response to sustainability challenges, metro systems worldwide are increasingly adopting renewable energy. Santiago Metro in Chile secures over 60% of its electricity from wind and solar through 15-year power purchase agreements [17]. Similarly, Delhi Metro sources around 60% of its daytime electricity about 345 million kWh annually from India's 750 MW Rewa Solar Power Park, supplemented by rooftop solar and waste-to-energy initiatives [9]. Indian Railways has also partnered with large-scale solar farms to further decarbonize rail-based transport [18].

3 Research Gaps and Objectives

While previous studies have examined metro systems in terms of either energy consumption [19] or PM_{2.5} pollution [20], few have explored how operational parameters such as fleet size, network length, and ridership jointly affect both sustainability indicators. Some research suggests ridership can influence in-carriage PM_{2.5} levels [21], while station-level energy use is also strongly linked to passenger volume [19]. However, a comprehensive, integrated analysis across both domains remains limited, constraining the development of unified strategies for metro system optimization.

This study addresses that gap by pursuing the following objectives:

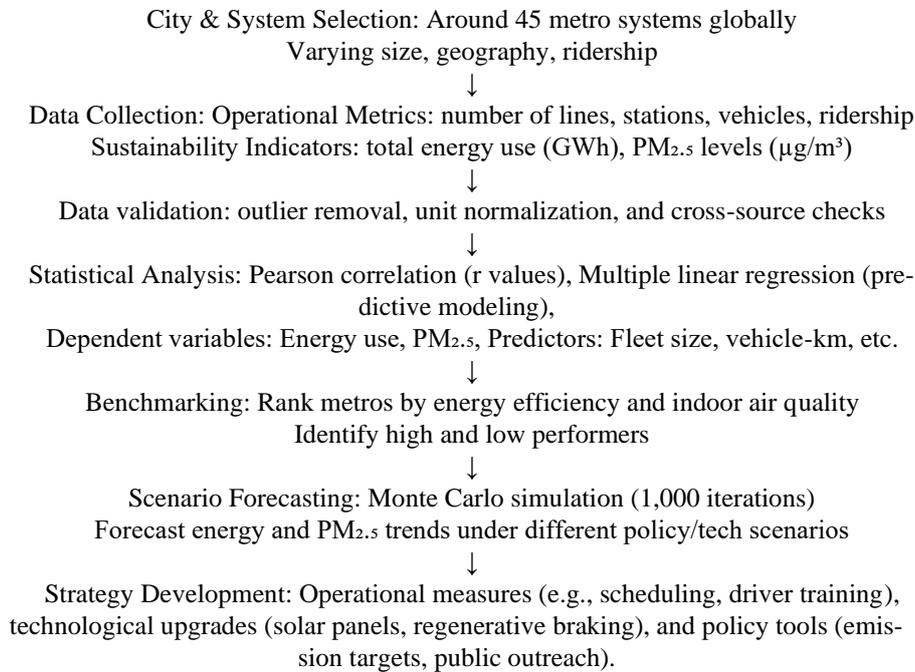
- Analyze relationships between operational metrics (e.g., network length, ridership, vehicle-kilometers) and sustainability indicators (energy use and PM_{2.5} levels).
- Identify key drivers influencing both energy consumption and indoor air quality across diverse metro systems.
- Propose strategic solutions to enhance operational efficiency and reduce environmental impact.
- Forecast future trends using simulation methods to support long-term sustainability planning.

By achieving these aims, the study provides actionable insights for metro operators and urban policymakers, contributing to the advancement of Sustainable Development Goals, specifically SDG 7 (Affordable and Clean Energy) and SDG 11 (Sustainable Cities and Communities).

4 Methodology

To achieve the study's objectives, a structured methodology was applied, combining data collection, statistical analysis, benchmarking, forecasting, and strategy development. The process was designed to ensure both analytical rigor and practical relevance. The overall approach is summarized in the flowchart below.

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5 Data Presentation and Analysis

5.1 Data Collection and Methodology

The study analyzes 47 metro systems worldwide, focusing on key operational and sustainability metrics:

- Network Characteristics: Number of lines, stations, and total length (km)
- Fleet Data: Number of vehicles and cars
- Operational Metrics: Annual vehicle-km, passenger-km, and ridership
- Sustainability Indicators: Total energy consumption (GWh) and PM_{2.5} (µg/m³)

This study utilized secondary data obtained from a variety of publicly available reports, environmental assessments, and peer-reviewed publications related to air quality and metro systems in different global cities. These sources were used solely to extract numerical values for statistical analysis (e.g., regression and correlation) and are not discussed individually in the main text. The complete list of these data sources is provided in the references [1-36]. Where direct energy data were unavailable, estimates were derived using modal share ratios (10%–33%) of public transport energy use to ensure comparability despite inherent uncertainties. Total annual energy consumption (GWh) is used as the primary sustainability indicator. Given the diversity in

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metro system size and operations, absolute energy use enables direct comparison without distortions caused by normalization or unit transformation.

Rather than adjusting energy data per kilometer or passenger, the analysis retains GWh units to preserve data fidelity. Variations in system scale are addressed through explanatory variables like network length, station count, fleet size, ridership, and vehicle-kilometers in regression and benchmarking models, enabling transparent identification of energy consumption drivers. Metro energy use includes multiple subsystems as Train traction (main energy demand), Station operations (lighting, HVAC, escalators, elevators), Auxiliary infrastructure (signaling, IT, ventilation). Although station-level energy intensity (e.g., kWh/m²) is useful in some contexts, it is not the primary indicator here. Instead, station count and network length act as proxies for system scale and complexity. The second indicator, peak PM_{2.5} concentration (µg/m³), was compiled from public reports and peer-reviewed studies. Data were drawn from platforms, train carriages, or underground corridors, using maximum values to ensure consistency under peak exposure. While PM_{2.5} levels are influenced by external factors ambient pollution, climate, tunnel design they still represent real passenger exposure risks and align with the study's focus on IAQ in enclosed transit environments.

Table 1 presents the Pearson correlation coefficients and Table 2 presents Regression Outputs calculated by using excel.

Table 1: Pearson Correlation Coefficients (n = 47 metro systems)

Independent Variable	PM2.5 (µg/m ³)	Energy Consumption (GWh)	Statistical Significance
Number of lines	0.496	0.791	p < 0.01
Number of stations	0.450	0.788	p < 0.01
System length (km)	0.491	0.772	p < 0.01
Number of cars	0.347	0.974	p < 0.001
Number of vehicles	-0.259	-0.288	p > 0.05 (NS)
Passenger-km (×10 ⁶)	0.056	0.872	p < 0.001
Vehicle-km (×10 ⁶)	0.490	0.940	p < 0.001
Annual ridership (×10 ⁶)	0.062	0.759	p < 0.01

NS = Not Significant (p > 0.05)

Table 2: Regression Model Summary

Indicators	P.M.2.5		Total energy	
	Regression equation	R2	Regression equation	R2
No. of lines	y = 0.0488x + 3.5464	0.2464	y = 0.0001x + 4.696	0.6266
No of stops	y = 1.0149x + 52.888	0.2031	y = 0.0025x + 76.779	0.6216
Length	y = 1.7492x + 32.275	0.242	y = 0.003x + 82.059	5958
no. of cars	y = 4.8387x +	0.1206	y = 428.87e2E-05x	0.9492

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No. of vehicles	606.55 $y = -0.5696x + 268.36$	0.0671	$y = -5E-09x^2 - 0.0014x + 183.12$	0.0832
Pass. Km	$y = 6E+06x + 7E+09$	0.0031	$y = 704977x + 7E+08$	0.7597
Vehicle km	$y = 2E+06x - 4E+07$	0.24	$y = 28441x + 4E+07$	0.8845
annual ridership	$y = 769463x + 7E+08$	0.0038	$y = 21908x + 5E+08$	0.5761

5.2 Correlation and Regression Insights

Analysis shows strong positive correlations between energy consumption and key operational metrics, especially number of cars ($r = 0.974$), vehicle-kilometers ($r = 0.940$), and passenger-kilometers ($r = 0.872$). These confirm that larger, busier metro systems consume more energy. $PM_{2.5}$ levels showed moderate correlation with infrastructure size ($r \approx 0.45$), but weak or no links with ridership or passenger-kilometers. Interestingly, vehicle count showed a slight negative correlation with $PM_{2.5}$ ($r = -0.259$), suggesting newer fleets may reduce pollution. Regression analysis further confirms that metro characteristics are stronger predictors of energy use than $PM_{2.5}$. System size variables (length, lines, stops) moderately explained energy use ($R^2 \approx 0.60$) but had weak predictive power for $PM_{2.5}$ ($R^2 < 0.25$). Cars and vehicle-kilometers were the best energy predictors ($R^2 > 0.88$), while their influence on air quality remained limited. Ridership and passenger-kilometers had good explanatory power for energy ($R^2 = 0.58-0.76$) but almost none for $PM_{2.5}$ ($R^2 < 0.01$). Number of vehicles had low correlation with both indicators ($R^2 \approx 0.07-0.08$), confirming limited relevance. In summary, energy use is clearly linked to system scale and intensity, while $PM_{2.5}$ levels are likely shaped more by external or localized environmental conditions. To complement the statistical analysis, scatter plots were created in Excel to visualize key relationships. Each includes a trendline, regression equation, and R^2 value to illustrate correlation strength. Two representative examples are shown below (Figure 1 and 2):

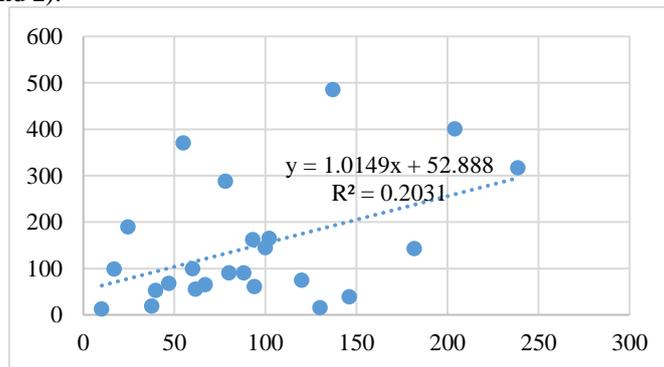


Fig. 1: Regression and correlation Graphs between. no. of stop and pm

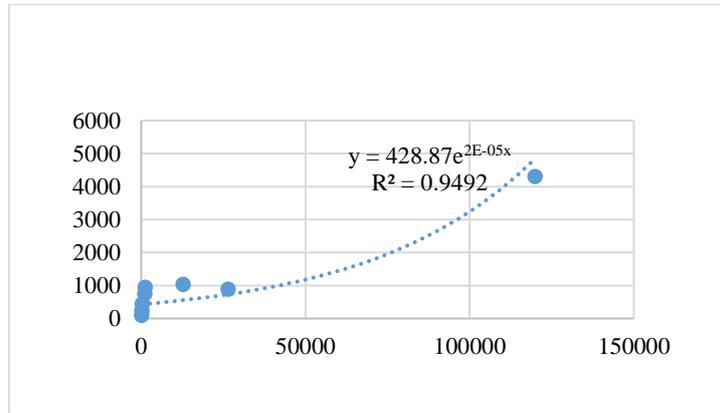


Fig. 2: Regression and correlation Graphs between. no. of cars and energy

6 Benchmarking Metro Systems: Energy Efficiency and Air Quality

Metro systems were ranked by total energy use (GWh), with lower values indicating greater efficiency. Table 3 lists the top five most energy-efficient systems. Sydney, Amsterdam, and Copenhagen lead due to solar power, regenerative braking, and wind-powered trains.

Table 3: Top 5 Most Energy-Efficient Metro Systems

Rank	City	Energy Use (GWh)	Key Practices
1	Sydney	84.13 [34]	Solar-powered, emission controls
2	Amsterdam	85.16 [36]	Regenerative braking, cycling integration
3	Copenhagen	93.40 [31]	100% wind-powered trains
4	Los Angeles	115.2 [27]	Small-scale, efficient network
5	Medellin	126.39 [30]	Hybrid energy use

Conversely, systems with the highest total energy use reveal operational inefficiencies and infrastructure challenges. Among the least energy-efficient systems were High energy use in Tokyo, Vancouver, and Barcelona stems from fossil reliance and operational intensity.

Air quality was benchmarked using PM_{2.5} levels (µg/m³), where lower values indicate cleaner air. Table 4 lists the five cleanest metro systems. Sydney ranks first due to strict emission policies, followed by Hong Kong, Singapore, and others benefiting from green infrastructure and low-emission environments.

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Table 4: Top 5 Metro Systems with Best Air Quality

Rank	City	PM2.5 ($\mu\text{g}/\text{m}^3$)	Contributing Factors
1	Sydney	10.1 [29]	Strict emission policies
2	Hong Kong	16.9 [32]	Green public transport policies
3	Singapore	24.5 [26]	Air-purifying infrastructure
4	Jakarta	37.6 [28]	Low industrial emissions
5	Vancouver	39.7 [24]	Clean energy usage

Metro systems with the highest PM_{2.5} levels include Chicago (284 $\mu\text{g}/\text{m}^3$) [33], London (238.7) [25], Beijing (204) [6], and New York (200) [35], mainly due to traffic, industrial activity, and coal power. In contrast, high-performing systems like Sydney, Copenhagen, Singapore, and Paris demonstrate transferable strategies—combining renewable energy with air quality measures such as emission-free zones, green tunnels, and infrastructure upgrades

Table 5: Strategies for Energy Efficiency & Air Quality Improvement

City	Energy Efficiency Measures	Air Quality Measures
Sydney	Solar-powered stations	Zero-emission zones near metro hubs
Copenhagen	Wind-powered trains	Bike-friendly infrastructure
Singapore	Regenerative braking	Green tunnels with air filtration
Paris	20% energy recovery from braking	Ban on diesel trains in city center

Underperforming systems need targeted actions like adopting renewables, upgrading infrastructure, and enforcing stricter emission policies. Tokyo could adopt renewables and regenerative braking; Barcelona needs fleet upgrades and congestion pricing; Beijing requires solar integration and emissions control; and Los Angeles should expand its network and use renewable microgrids.

Benchmarking reveals key trends: smaller networks like Sydney and Amsterdam are more energy-efficient than larger ones like Tokyo or Beijing. Cities with steady green policies, such as Singapore and Copenhagen, maintain cleaner air even at scale. Overall, expanding renewable energy is vital for balancing growth and sustainability. This study provides actionable insights for metro operators and policymakers to boost efficiency and reduce environmental impacts.

7 Scenario Forecasting Using Monte Carlo Simulation

To assess the impact of future interventions, Monte Carlo simulations were conducted for energy consumption and PM_{2.5} levels under scenarios involving 15–25% reductions from policies like renewable energy integration, efficiency upgrades, and air quality regulations. Each simulation included 1,000 iterations per city, based on his-

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torical means (μ) and standard deviations (σ), producing probabilistic outcome distributions.

Energy Forecasts showed high variability in cities like Tokyo ($95,799 \pm 3,449$ GWh) and Vancouver ($28,387 \pm 1,022$ GWh), while Sydney (67.2 ± 2.4 GWh) and Amsterdam (68.1 ± 2.5 GWh) remained stable and efficient. Cities such as Los Angeles and Singapore showed moderate, balanced profiles. PM_{2.5} Trends indicated severe pollution in Chicago (226.9 ± 8.2 $\mu\text{g}/\text{m}^3$), London (190.7 ± 6.9), and Beijing (163.0 ± 5.9), contrasted by low levels in Sydney (8.1 ± 0.3), Hong Kong, and Singapore. Volatility in cities like New York and Chicago was linked to industrial and seasonal factors.

City Insights highlight Beijing's high energy and pollution levels due to industrial activity; Singapore's high energy use but excellent air quality reflects strong policy execution; and Copenhagen, with moderate energy use, still shows elevated PM_{2.5}, warranting further investigation.

Policy Implications include promoting smart grids and renewables in high-variability cities, enforcing emission regulations, and expanding green infrastructure. Singapore stands out as a successful model balancing energy demand and air quality.

Limitations involve data gaps in cities like Hong Kong and Delhi, and missing PM_{2.5} data in parts of Europe (e.g., Vienna, Milan), which restrict the comparative depth. Expanding data coverage and refining models will be essential for future forecasting.

8 Strategy Development for Sustainable Metro Systems

To enhance sustainability in metro systems, a combination of operational, technological, and policy measures is recommended:

Operational Improvements include real-time dynamic scheduling (e.g., Paris: 2,461.4 GWh) and training drivers in energy-efficient techniques (e.g., Los Angeles: 92.3 GWh), both shown to reduce energy waste significantly.

Technological Upgrades such as regenerative braking (e.g., Santiago achieves 15–20% energy recovery) and solar panel installation (e.g., Delhi: PM_{2.5} = 62.5 $\mu\text{g}/\text{m}^3$, with a 20% renewable target) are essential for reducing emissions and operating costs.

Policy Interventions should focus on setting measurable PM_{2.5} reduction targets (e.g., Beijing aims to cut from 163.5 to 131 $\mu\text{g}/\text{m}^3$ by 2028) and launching public engagement campaigns to raise awareness (e.g., Bangalore: PM_{2.5} = 53.7 $\mu\text{g}/\text{m}^3$).

An effective implementation framework involves pilot projects (e.g., based on Paris and Santiago), phased rollouts emphasizing scalable, cost-effective actions, robust monitoring systems for both energy and air quality, and collaboration among transit agencies, academia, and industry to drive innovation.

9 Comprehensive Summary and Conclusions

This study offers a benchmarking and strategic evaluation of 45 global metro systems, focusing on two key sustainability indicators: total energy consumption and PM_{2.5} pollution. By correlating these environmental outcomes with operational metrics such as network length, vehicle-kilometers, and ridership, the analysis reveals how system scale and intensity influence sustainability performance.

Strong positive correlations were found between energy consumption and operational scale, particularly fleet size ($r \approx 0.97$) and vehicle-kilometers ($r \approx 0.94$). Tokyo, with the highest ridership, also had the highest energy use ($\approx 95,800$ GWh/year), whereas smaller but technologically advanced systems like Singapore and Sydney achieved higher energy efficiency. PM_{2.5} levels showed moderate correlation with infrastructure size, suggesting that factors like ventilation design, braking systems, and urban air quality also play critical roles. Sydney recorded the lowest PM_{2.5} ($8.1 \mu\text{g}/\text{m}^3$), while Beijing and Chicago exceeded $200 \mu\text{g}/\text{m}^3$, highlighting serious health and environmental challenges. Case studies from Santiago, Paris, and Amsterdam illustrate effective sustainability measures. Santiago sources 60% of its metro electricity from solar and wind. Paris uses regenerative braking and efficient HVAC systems, while Amsterdam combines clean energy use with active mobility integration. These examples offer transferable insights for metros at various development stages. To support sustainability across metro systems, the study recommends an integrated strategy:

- Operational: Dynamic scheduling, energy-efficient driving, demand-responsive service.
- Technological: Regenerative braking, solar power, advanced air filtration.
- Policy: Emissions standards, modal integration, and public awareness programs.

Monte Carlo simulations forecasted the long-term effects of these interventions. Cities with robust policy and technology frameworks like Sydney are likely to sustain low energy use and pollution. In contrast, systems such as Tokyo and Chicago may face growing instability without reform.

Metro systems remain fundamental to sustainable urban mobility, yet environmental performance varies widely. Bridging these gaps requires a holistic approach that blends operational, technological, and policy innovation. This research provides a roadmap for aligning metro infrastructure with Sustainable Development Goals.

Despite broad geographic and technical scope, the study faces several limitations:

- Data inconsistencies: Gaps and variations in PM_{2.5} and energy data required estimation and normalization, introducing uncertainty.
- Geographic imbalance: Underrepresentation of African systems limits global generalizability.
- External variables: PM_{2.5} is influenced by urban traffic, industry, and climate beyond metro control.
- Policy and technology diversity: Varying local regulations and tech adoption hinder direct comparisons.

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- Modeling constraints: Monte Carlo simulations rely on historical data and cannot fully capture future innovation.
- Case study coverage: Focuses on select high-performing cities; broader examples are needed.
- Resource limitations: Time, data access, and institutional constraints restricted deeper longitudinal or causal analysis.

To address these gaps, future research should:

- Collaborate directly with metro authorities to improve data access and accuracy.
- Include African and emerging cities for better global representation.
- Apply machine learning and AI to more precisely isolate variable impacts.
- Conduct longitudinal studies to assess sustainability trends over time.
- Evaluate cost-effectiveness of interventions such as solar deployment or HVAC upgrades.
- These steps will help build a more actionable, evidence-based framework for advancing metro sustainability across diverse global contexts.

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Performance Analysis of European Rail Freight Corridors

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Abstract. Since their introduction under EU Regulation 913/2010, Rail Freight Corridors have been intended to enhance the competitiveness, interoperability, and efficiency of international rail freight. However, more than a decade later, persistent operational, infrastructural, and coordination challenges suggest that the expected benefits have not been fully achieved. Existing studies often focus on individual corridors, specific performance or policy aspects, leaving a gap in comprehensive, comparative analyses based on harmonized indicators. This paper addresses that gap by evaluating the market and operational performance of all corridors using publicly available key performance indicators. The analysis covers offered and requested capacity, utilization of pre-arranged paths, average planned train speeds, and train volumes at border crossings. Despite institutional progress, the findings show limited improvement in overall efficiency, as enduring structural and operational barriers continue to hinder rail's competitiveness across Europe.

Keywords: Freight transport, rail corridors, performance indicators.

1 Introduction

European Rail Freight Corridors (RFCs) were established to support the development of a competitive, integrated, and efficient rail freight market in Europe. Introduced under Regulation 913/2010, they aim to facilitate international freight transport along strategic axes by improving cross-border coordination, harmonizing infrastructure capacity, and creating conditions for a modal shift from road to rail. By linking major airports, logistics hubs, industrial centers, and inland terminals, RFCs ensure the continuity and reliability of cross-border freight flows within and beyond the EU.

The initiative was a direct response to longstanding operational and regulatory challenges, including fragmented and nationally oriented infrastructure management, non-standardized operational rules, complex border procedures, and insufficient coordination among infrastructure managers (IMs) and railway undertakings (RUs). Through dedicated governance structures, standardized capacity allocation mechanisms, and the Corridor One-Stop Shop (C-OSS), Regulation 913/2010 sought to address these structural and operational barriers.

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Since the initial implementation of Regulation 913/2010, eleven RFCs have been established. While institutional alignment and corridor-based instruments have improved, measurable performance gains remain limited and unevenly distributed. More than a decade on, persistent gaps between policy objectives and operational results are evident: capacity utilization is below expectations, cross-border barriers still exist, and punctuality and reliability indicators reflect low performance.

Previous papers have examined these challenges from multiple perspectives. Dedík et al. [1] analyzed the RFCs with the aim of improving the efficiency and competitiveness of rail freight transport in European countries operating under the CIM transportation regime [1]. Finger and Kupfer [2] discussed the issues facing European rail freight, with a particular focus on RFCs. Troche [3] examined EU railway policy on international corridors for rail freight, using the Orient/East-Med Rail Freight Corridor No. 7 as a case study. Finger et al. [4] addressed governance shortcomings of RFCs, advocating for stronger supranational coordination and the digitalization of operational procedures. Djordjević et al. [5] assessed the efficiency of eight RFCs using Data Envelopment Analysis, evaluating the potential benefits of digital automatic coupling and intelligent video gates. Abramović et al. [6] examined the Alpine–Western Balkan RFC, focusing on its role in enhancing accessibility and service quality between Central and Southeast Europe. Despite these contributions, there remains no comprehensive, up-to-date assessment of RFC performance covering all corridors and border-crossing points.

This paper addresses that gap by evaluating the performance of all RFCs using selected indicators compiled from official corridor data and by developing a heat map of traffic flows at each border crossing. The analysis has three objectives: to examine capacity management practices and the attractiveness of market-oriented capacity products; to assess traffic performance, including train volumes, planned versus actual commercial speeds, and punctuality; and to investigate market development through utilization patterns and the impact of operational and regulatory barriers, such as border dwell times and national prioritization rules.

By undertaking this comprehensive assessment, the paper identifies structural limitations and operational inefficiencies that continue to constrain RFCs effectiveness. The findings provide evidence-based insights to inform policy decisions and guide the development of targeted measures aimed at improving the overall performance of the RFCs.

2 Performance Analysis of Rail Freight Corridors

RFCs required EU Member States to develop international rail freight corridors governed by dedicated management structures. Initially, the Regulation 913/2010 defined nine corridors, six of which were to become operational by November 2013, and the remaining three by November 2015. Subsequently, the network was expanded with the addition of two more corridors, RFC 10 and RFC 11, bringing the total to eleven.

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These are: RFC 1 Rhine–Alpine; RFC 2 North Sea–Mediterranean; RFC 3 Scandinavian–Mediterranean; RFC 4 Atlantic; RFC 5 Baltic–Adriatic; RFC 6 Mediterranean; RFC 7 Orient/East–Mediterranean that was ceased in 2025 [7]; RFC 8 North Sea–Baltic; RFC 9 Rhine–Danube; RFC 10 Alpine–Western Balkan; and RFC 11 Amber.

To monitor RFCs performance, a set of key performance indicators (KPIs) has been established, grouped into three main categories: capacity management, traffic performance, and market development. A detailed description of these indicators and their definitions can be found in [8].

Our performance analysis began with capacity management, a core RFC objective aimed at improving coordination between governments, IMs, RUs, and terminals through a unified framework for train path planning and allocation. This framework is implemented via the C-OSS, a digital interface allowing RUs to request paths across an entire corridor without contacting individual IMs.

Two key market products have been introduced through the RFC framework: Pre-arranged Paths (PaPs) and Reserve Capacity (RC). PaPs represent pre-allocated train paths offered to RUs in advance of the regular capacity allocation process and are dedicated exclusively to international freight services. In contrast, RC consists of pre-defined paths that remain available throughout the timetable period to accommodate ad-hoc requests from the market. This product is designed to provide flexibility in capacity allocation, reflecting the often volatile and unpredictable nature of rail freight demand. Both products, PaPs and RC, are measured in *kilometer-days*, which represent the product of the train path length (between service points) and the number of days the path is available [8].

The infrastructure capacity offered by IMs is represented by the volume of PaPs, which constitute a harmonized offer jointly developed by IMs along the corridor. These train paths are defined with precise technical and operational parameters, including permissible axle load, train length, locomotive type, and harmonized arrival and departure times at border stations. PaPs are published as part of the annual timetable 11 months before their entry into force, providing a foundation for long-term capacity planning [8].

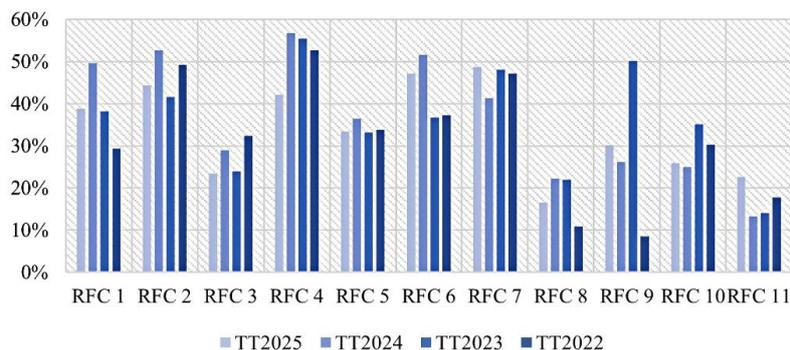


Fig. 1. Ratio between offered and actually allocated PaPs, developed by authors based on data from [9]

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An analysis of the ratio between offered and allocated capacity for the 2022–2025 timetables, based on data from the RNE website and illustrated in Figure 1, shows that PaPs utilization remains well below the total volume offered. In most cases, allocation does not exceed 50% of available capacity, with the highest rates on RFC 2, RFC 4, and the now-discontinued RFC 7, and the lowest on RFC 8 and RFC 11. This imbalance reflects the limited attractiveness of PaPs for RUs. The fixed parameters of PaPs, departure times, train weight, locomotive type, often fail to match dynamic market needs, while their early publication in the annual planning cycle reduces their applicability once operational requirements are fully defined.

A further issue is the misalignment between IMs’ capacity offers and the commercial priorities of RUs. In the absence of a reliable guarantee that ad-hoc requests will meet their needs, RUs frequently reserve capacity during annual planning to avoid future shortages, even without a clear intention to use it. At this stage, however, they often lack essential operational details such as exact departure times, train composition, and traction requirements. As a result, many initial requests are later modified or withdrawn, adding administrative and technical burdens for both RUs and IMs. According to RNE and Forum Train Europe data, only 20–25% of path requests remain unchanged, while 75–80% require modifications, consuming significant time and resources [10].

While capacity utilization analysis highlights procedural challenges in planning, it is equally important to examine how these factors translate into actual traffic volumes. One of the core indicators used to evaluate corridor performance within the market development category is the number of trains per border crossing. This indicator captures the total number of commercial freight trains that have passed through a specific border point along RFC [8]. Given that complete and harmonized data has been available for all corridors since 2021, this analysis focuses on the period from 2021 to 2023. Accordingly, two heat maps have been developed to visualize corridor performance. The first, presented in Table 1a, displays the median number of freight trains per border crossing during the observed period, with the aim of identifying the most heavily utilized cross-border sections. The second, shown in Table 1b, illustrates the relative increase or decrease in train volumes in 2023 compared to 2021, highlighting significant shifts in traffic flows and helping to identify potential underlying drivers behind these changes.

Table 1. Heatmap for median number of trains a) and Heatmap of growth of number of trains compared to 2021 b), developed by authors based on data from [9]

<i>a)</i>			<i>b)</i>		
RFC	Borders	Number of trains	RFC	Borders	Growth/decline
RFC 1	DE - CH	49,842	RFC 8	PL - LT	89.67%
RFC 8	NL - DE	46,187	RFC 4	Hendaye	26.05%
RFC 1	NL - DE	46,175	RFC 9	DE - CZ	18.36%
RFC 1	CH - IT	45,782	RFC 3	Komsjo	17.01%
RFC 9	DE - AT	41,528	RFC 6	SI - HR	11.84%
RFC 7	DE - CZ	27,447	RFC 7	RO - BG	11.55%
RFC 8	DE - CZ	27,447	RFC 9	AT - SK	11.52%
RFC 8	DE - PL	27,355	RFC 5	AT - SK	11.14%

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RFC 5	PL - CZ	26,454	RFC 7	AT-SK	11.14%
RFC 3	Kufstein	24,768	RFC 10	RS - BG	10.18%
RFC 1	BE - DE	22,232	RFC 10	HR - RS	8.28%
RFC 8	BE - DE	22,232	RFC 5	CZ - AT	7.43%
RFC 11	SK - HU	20,301	RFC 7	CZ-AT	7.41%
RFC 7	AT - HU	20,289	RFC 5	PL - CZ	5.88%
RFC 9	AT - HU	20,289	RFC 2	FR - CH	4.25%
RFC 3	Brenner/Brennero	19,866	RFC 10	AT - SI	1.67%
RFC 5	AT - IT	19,147	RFC 10	SI - HR	1.17%
RFC 7	SK - HU	16,759	RFC 9	DE - AT	0.90%
RFC 7	CZ - SK	16,688	RFC 4	Irun	0.89%
RFC 10	AT - SI	14,964	RFC 8	NL - DE	0.03%
RFC 9	CZ - SK	14,270	RFC 3	Padborg/Flensburg	-0.68%
RFC 5	CZ - SK	13,418	RFC 1	NL - DE	-1.33%
RFC 5	CZ - AT	12,027	RFC 2	BE - LU	-1.75%
RFC 7	CZ-AT	12,027	RFC 11	HU - SI	-3.12%
RFC 2	BE - FR	11,634	RFC 2	NL - BE	-3.38%
RFC 7	HU - RO	10,904	RFC 8	NL - BE	-3.44%
RFC 9	HU - RO	10,904	RFC 6	SI - HU	-3.89%
RFC 4	DE - FR	9,759	RFC 8	DE - PL	-4.48%
RFC 5	AT - SI	9,154	RFC 7	DE - CZ	-4.49%
RFC 3	Padborg/Flensburg	9,116	RFC 8	DE - CZ	-4.49%
RFC 5	AT - SK	8,749	RFC 5	AT - IT	-4.67%
RFC 7	AT-SK	8,749	RFC 1	CH - IT	-4.67%
RFC 9	AT - SK	8,604	RFC 4	ES - PT	-4.90%
RFC 2	NL - BE	8,465	RFC 6	HR - HU	-4.94%
RFC 8	NL - BE	8,465	RFC 9	CZ - SK	-5.08%
RFC 6	FR - IT	8,271	RFC 1	DE - CH	-5.11%
RFC 5	IT - SI	7,940	RFC 1	BE - DE	-5.18%
RFC 6	IT-SI	7,612	RFC 8	BE - DE	-5.18%
RFC 6	SI - HR	7,161	RFC 3	Lernacken	-6.27%
RFC 10	SI - HR	7,161	RFC 3	Brenner/Brennero	-6.62%
RFC 3	Lernacken	6,965	RFC 7	AT - HU	-6.76%
RFC 6	HR - HU	6,741	RFC 9	AT - HU	-6.76%
RFC 11	HU - SI	6,544	RFC 5	CZ - SK	-7.45%
RFC 6	SI - HU	6,492	RFC 2	LU - FR	-9.59%
RFC 2	LU - FR	5,842	RFC 5	IT - SI	-11.51%
RFC 2	FR - CH	5,322	RFC 9	SK - HU	-12.94%
RFC 9	SK - HU	5,295	RFC 4	DE - FR	-13.60%
RFC 6	ES - FR	4,562	RFC 9	FR - DE	-13.92%
RFC 7	RO - BG	4,183	RFC 3	Kufstein	-14.25%
RFC 10	HR - RS	4,132	RFC 7	HU - RO	-14.94%
RFC 10	RS - BG	3,711	RFC 9	HU - RO	-14.94%
RFC 9	DE - CZ	2,811	RFC 6	IT-SI	-15.17%
RFC 4	Irun	2,465	RFC 11	SK - HU	-15.29%
RFC 4	ES - PT	2,393	RFC 7	SK - HU	-16.72%
RFC 2	BE - LU	2,190	RFC 6	ES - FR	-19.38%
RFC 11	PL - SK	1,972	RFC 2	BE - FR	-23.38%
RFC 9	FR - DE	1,961	RFC 7	CZ - SK	-25.89%
RFC 4	Hendaye	1,812	RFC 5	AT - SI	-30.79%
RFC 8	PL - LT	1,666	RFC 11	PL - SK	-33.28%
RFC 3	Komsjo	1,401	RFC 8	LT - LV	-39.32%
RFC 2	GB - FR	1,136	RFC 2	GB - FR	-40.27%
RFC 8	LT - LV	891	RFC 6	FR - IT	-59.47%
RFC 8	LV - EE	830	RFC 8	LV - EE	-68.32%
RFC 7	BG - GR	396	RFC 7	BG - GR	-74.24%

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The heat map of median train numbers identifies the busiest border crossings as those involving Germany, notably Germany–Netherlands (RFCs 1 and 8), Germany–Switzerland (RFC 1), Germany–Austria (RFC 9), and Germany–Czech Republic (RFCs 7 and 8). Germany, together with Switzerland and Italy, handles over 40,000 freight trains annually on average, confirming its role as the central transit and distribution hub of the European rail freight network. These results align with the 2022 transport market study presented in Figure 2, which also highlights Germany's dominant position and its connections with the Netherlands, Belgium, France, Austria, Switzerland, and the Czech Republic [11].

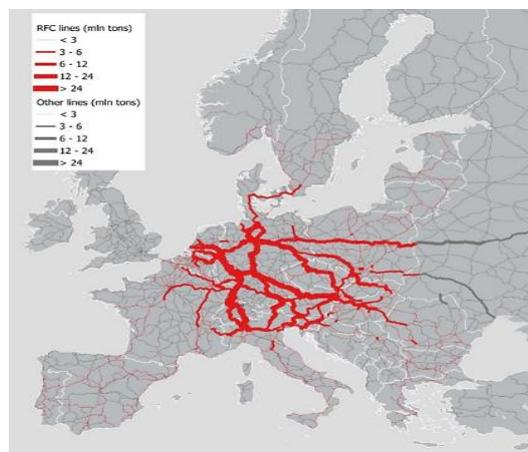


Fig. 2. Traffic flows along RFCs [11]

Significant volumes are also recorded on routes linking Poland with the rest of Europe, particularly RFCs 5 and 8, reflecting intercontinental flows from Ukraine and China and the rising importance of Polish terminals in Euro-Asian freight. In contrast, the Baltic States connected with RFC 8 and the Bulgaria–Greece border on RFC 7 is among the least utilized sections.

Between 2021 and 2023, freight volumes increased substantially at certain border crossings, most notably Lithuania–Poland, which recorded a 90% rise. This shift was primarily driven by the war in Ukraine and the consequent re-routing of traffic from traditional eastern routes through the Baltic States. Significant growth was also registered at the Hendaye crossing on RFC 4, with an increase of 26%, whereas the alternative France–Spain crossing on RFC 6 experienced a decline of 19%. Additional growth was observed at crossings involving Austria, the Czech Republic, and Slovakia, further underscoring their strategic importance as key links between Southeastern and Western Europe.

However, of 64 monitored crossings, 44 recorded volume declines in 2023, with the steepest drops in Southeastern Europe. RFC 7 was particularly affected, with volumes on the Bulgaria–Greece section falling by over 74% compared to 2021, and further declines at the Romania–Bulgaria border, contributing to the partial withdraw-

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al of RFC 7 services. In Western Europe, Italy–France traffic fell by over 30%, primarily due to the August 2023 landslide in the Maurienne Valley, which disrupted operations through the Fréjus tunnel and severed a key rail link between the two countries [12].

The total volume of international land freight within the catchment area of the eleven RFCs is approximately 1.5 billion tons, of which only 265 million tons, about 18%, is carried by rail. This modest share underscores the continuing dominance of road transport and the challenges in positioning rail as a competitive option for international freight in Europe [11].

To explore the link between transport volume and operational or regulatory barriers, we examined KPIs such as the average planned speed of PaPs, an indicator of corridor performance measured in kilometers per hour between defined origin–destination pairs in both directions [8]. Table 2 presents planned speeds for selected PaPs on RFCs traversing Central and Western Europe (RFC 1 and 3) and Southeastern Europe (RFC 7 and 10), including only those crossing at least two border stations. The results show that RFC 1 and RFC 3 consistently achieve higher planned speeds than their Southeastern counterparts.

This disparity reflects differences in infrastructure quality and operational environments. RFC 1, for example, runs entirely through EU and Schengen Member States, avoiding duplicate border procedures, whereas RFC 10 includes non-EU Serbia and EU as Romania and Bulgaria, where customs and border controls are required. Planned speeds also tend to overstate actual commercial speeds, which are reduced by operational and technical delays. In end-to-end intermodal transport, further reductions occur due to shunting, terminal handling, and last-mile delivery [10].

Table 2. Average planned speed of selected PaPs, developed by authors based on data from [9]

Corridor	PaPs	Length (km)	Number of borders	Average speed (km/h)
RFC 1	Maasvlakte - Milano Sm	1148	3	56.2
RFC1	Y.Schijn - Milano Sm	1092.9	3	51.1
RFC1	Karlsruhe Gbf - Gallarate	519.4	2	50.2
RFC 7	Bremerhaven - Kúty	1051.4	2	45
RFC 7	Kolín - Soroksári út rendező	560.3	2	39.5
RFC 10	Svilengrad - Jesenice	1338.5	3	32.7
RFC 7	Dresden - Dunajská Streda	618	2	30.6
RFC 10	Ljubljana Zalog - Svilengrad	1266.7	3	26.8
RFC 10	Ljubljana Zalog - Beograd Ranžirna	557.1	2	26.6
RFC 10	Salzburg Hbf - Svilengrad	1750.2	4	23.2

Figure 3 illustrates departure and arrival punctuality across the RFCs for 2023. Only RFC 2 and RFC 4 recorded arrival punctuality above 50% within a 15-minute delay window, while most other corridors remained at or below 30%. A significant share of delays originates at departure, typically due to issues within RUs, including the late availability of locomotives, wagons, or delays related to terminal operations. These initial disruptions often propagate along the train’s route, further compromising punc-

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tuality and increasing operational costs for both RUs and the wider freight market. In the Rhine–Alpine Corridor Transport Market Study, 41% of surveyed stakeholders, including logistics providers and freight forwarders, identified poor punctuality as the primary factor discouraging the use of rail freight services [13]. One key underlying cause of poor punctuality is excessive dwell time at border crossings. Despite its operational significance, this aspect remains insufficiently monitored. In fact, most RFC Management Boards do not systematically track border delays, even though Article 18 of Regulation 913/2010 explicitly mandates such monitoring.

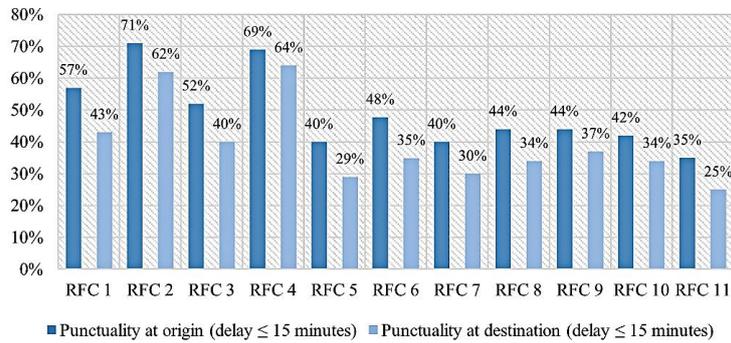


Fig. 3. Punctuality at origin and destination with delay threshold of 15 minutes for 2023, developed by authors based on data from [9]

Figure 4 shows the planned versus actual dwell times for 2023 where the data reveals significant discrepancies between expected and actual values for a few RFCs.

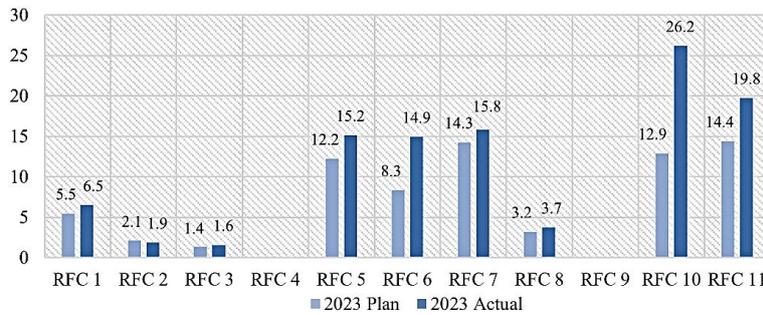


Fig. 4. Planned versus actual dwell times at border crossings for 2023, developed by authors based on data from [9]

Corridors such as RFC 1, RFC 2, RFC 3, and RFC 8 report the shortest dwell times, typically under five hours. These corridors link EU Member States that are also part of the Schengen Area, such as Germany, the Netherlands, Belgium, Denmark, and France, where there are no duplicate border control procedures and where administrative processes are harmonized and digitalized.

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In 2023, the longest and most inconsistent border dwell times were recorded on RFC 10 and RFC 11, averaging over 26 and 19 hours, respectively, well above both planned values and levels on other corridors. On RFC 10, these delays are largely due to transits through non-EU and non-Schengen countries such as Serbia and Bulgaria, where complex border procedures and technical inspections are required. Contributing factors include poor coordination between RUs under the traditional traction handover model, leading to delays when locomotives or crews are unavailable at borders [10]. Freight trains are also frequently scheduled during night hours, coinciding with infrastructure maintenance windows, which increases exposure to temporary closures and capacity restrictions. In congested nodes, particularly in urban areas, conflicts with high-frequency passenger services further limit timetable flexibility for freight, heightening the risk of cascading delays [14]. These operational challenges are compounded by the absence of harmonized traffic prioritization rules across the EU and third countries. While Regulation 913/2010 sought to guarantee capacity and unhindered passage for international freight, in practice, such trains often lack formal priority in traffic management. Provisions granting them preference over domestic services exist in some countries, but there is no EU-wide definition of their status. The responsibility for prioritization remains with IMs, resulting in significant regulatory inconsistencies across Europe [15].

3 Conclusion

Over a decade since their inception, RFCs remain central to the EU's strategy for enhancing the competitiveness and interoperability of international rail freight transport. However, the performance analysis indicates that outcomes still fall short of expectations. Utilization of capacity products like PaPs and reserve capacity remains low on most corridors, with few exceeding 50%, while persistent disparities exist in train volumes, planned speeds, dwell times, and punctuality across the RFC network. In 2023, 44 of 64 monitored border crossings recorded declines in the number of trains operated, with the sharpest reductions observed in Southeastern Europe.

Germany continues to serve as the core hub of the European rail freight network, where flows from major Northern European ports, such as Rotterdam, Amsterdam, and Antwerp, converge before being redistributed across the continent and neighboring countries. By contrast, corridors traversing non-Schengen or non-EU states, such as RFC 10, face prolonged border dwell times, technical constraints, and the absence of harmonized train prioritization rules, factors that undermine competitiveness against road transport.

While the regulatory and institutional framework was established more than a decade ago, the RFC system has yet to deliver a decisive improvement in performance or achieve a substantial modal shift. Addressing these shortcomings will require greater flexibility and market responsiveness in capacity products, more effective C-OSS operations, robust performance monitoring, and the adoption of common rules for traffic prioritization and border procedures. Without such reforms, the RFC network

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will remain constrained in its ability to function as a fully integrated and competitive freight transport system, aligned with the EU's sustainability and modal shift objectives.

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Simulation of Network Resilience: A Case Study of Belgrade Metro

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Abstract. In today's fast-growing cities, a resilient metro system is essential for achieving sustainable mobility. Resilience simulation reveals critical elements and network bottlenecks, enabling the development of proactive mitigation and recovery strategies. The resilience of the planned Belgrade metro network was simulated using network theory principles, pointing out that network modelling has become widely used for assessing the resilience of transport systems. The simulation proceeds through four steps: (1) construction of the network model; (2) definition of resilience indicators (metrics); (3) generation of disruption scenarios; and (4) measurement of resilience by tracking changes in indicator values before and after each disruption. Three main disruption categories are analyzed: random failures, targeted attacks, and natural hazards. Results show that the planned Belgrade metro, when combined with the BG voz line, maintains moderate resilience under random failures, weak resilience to targeted attacks, and no effective resilience to severe flooding.

Keywords: Resilience, Simulation, Metro, Disruptions, Scenarios.

1 Introduction

Metro systems are the lifelines of modern cities, moving thousands of passengers every hour while alleviating street congestion and cutting travel times. They are essential for achieving sustainable mobility in large, densely populated cities such as Belgrade.

The metro network can be exposed to various unplanned events that can cause major disruptions in its functionality. When even a single critical station or track segment goes out of service, cascading failures can manifest across the entire city and disrupt daily life and economic activity. Understanding how a metro responds to such disruptions, therefore, demands a study of its resilience.

Resilience can be understood as a system's capability to anticipate and be prepared for upcoming disruptions, maintain an acceptable level of functionality during their occurrence, and recover in a timely manner from their negative impacts. It is often associated with the term critical infrastructure. Resilience is a key determinant of the reliability of critical infrastructure subsystems [1].

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The resilience of the railway transport system is defined as the system's ability to provide effective service under normal conditions, as well as to withstand, absorb, adapt to, and quickly recover from disruptions. For a comprehensive understanding of resilience applications in railway transport systems we refer to [2].

In this paper, the assessment of resilience is based solely on topological metrics, as the Belgrade metro has not yet been constructed and no data is available on passenger flows or train schedules.

The resilience assessment was conducted using concepts from network theory by simulating three categories of disruption: random failures, targeted attacks, and natural hazard (flooding). Each disruption category was tested through node and link removals to evaluate the structural connectivity and efficiency of the planned metro system.

This paper contributes to the understanding of how the combined network of the planned Belgrade metro and Belgrade's BG voz would respond to various types of disruptions, providing valuable insights into its structural vulnerabilities even before construction. By applying network theory and resilience metrics to scenarios such as random failures, targeted attacks, and severe flooding, the analysis identifies the network's strengths and weaknesses.

The remainder of the paper is structured as follows. Section 2 presents the resilience simulation approach based on the network theory. Section 3 describes the applied methodology. Section 4 outlines the case study of the planned Belgrade metro and BG voz network. Section 5 presents the results of simulated disruption scenarios. Section 6 provides the concluding remarks.

2 Resilience Simulation: Network Theory Approach

Network theory has been used to assess network resilience. In the literature, a variety of approaches have applied graph-based principles to model disruptions, evaluate connectivity, and conduct recovery planning. Several studies have applied network theory to evaluate resilience. In [3], the authors developed a methodology for restoring road network connectivity after natural hazards, using topological simulations and Monte Carlo analysis. A similar approach is used in [4], where a complex-network model guides the prioritization of recovery strategies through a range of connectivity metrics.

Urban rail transit systems (URTSS) have also been evaluated for their resilience under natural hazards. For instance, [5] introduces a framework that integrates physical attributes and flood return periods with network analysis, while [6] proposes a multi-layered approach combining topology, spatial data, and passenger flows to assess the resilience of the London metro.

Going beyond purely structural models, [7] presents a stochastic microscopic simulation that includes operational dynamics and passenger movements, offering deeper insight than traditional metrics. Similarly, [8] introduces a model that integrates robustness, adaptability, and recoverability into a single resilience score.

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Authors in [9] and [10], focus on how different network layouts and diversity metrics influence resilience. Large-scale simulations conducted in [10] examine how canonical network structures respond to disruptions, highlighting the role of topology in shaping resilience outcomes.

All the above-mentioned papers employed network theory to simulate resilience and characterize the structure of transport networks. Most of them integrate passenger demand patterns and operational timetables into their resilience simulations. In contrast, this study is limited to a topological analysis, as such data are not yet available for the planned Belgrade metro system.

3 Methodology

The methodology adopted in this research is designed to evaluate the structural resilience of the planned Belgrade metro and BG voz network. Since the physical system is not yet operational and no data on passenger flows or operations is available, the analysis is based entirely on the topological characteristics of the network. The procedure relies on the application of network theory and consists of four main stages: (1) construction of the network model; (2) definition of resilience indicators; (3) generation of disruption scenarios; and (4) simulation-based measurement of resilience by tracking changes in indicator values before and after each disruption.

The Belgrade metro and BG voz transportation network is constructed as an undirected graph, $G(N,M)$, where stations correspond to nodes ($n \in N$) and the tracks connecting them represent edges ($m \in M$). The graph is assumed to be unweighted and static, and all stations are treated as equally important in the baseline configuration.

Each simulation scenario is executed using custom developed scripts in MATLAB R2024b.

3.1 Resilience Metrics

In order to evaluate the resilience of the Belgrade metro and BG voz network under disruptions, we select two commonly used metrics. The first is the *giant component*, which indicates the proportion of stations that remain mutually reachable after the removal of stations or links between them. This measure reflects the network's ability to preserve overall connectivity despite disruptions. The second metric is *global efficiency*, which captures the extent to which the network maintains short routes between stations, even in degraded conditions. Together, these metrics provide insight into both the connectedness and functional accessibility of the network during disruption events.

For the complete mathematical formulation of the giant component, we refer to [11], and for global efficiency [12].

Resilience indices are calculated as the areas under the corresponding resilience curves, as proposed in [13]:

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$$R_{gq} = \int_{t_0}^{t_i} [(t_{i+1} - t_i) - r_{gq}] dt, \quad (1)$$

$$R_{ge} = \int_{t_0}^{t_i} [(t_{i+1} - t_i) - r_{ge}] dt. \quad (2)$$

In Eq. 1 and Eq. 2, t_0 and t_i represents time intervals before and after disruption occur, respectively. Values of r_{gq} and r_{ge} are calculated as resilience costs (as proposed in [14]) for the giant component and global efficiency, respectively:

$$r_{gq} = \sum_{i=0}^{|D|} \frac{F_0^{gq} - F_{dis}^{gq}}{F_0^{gq} - F_{min}^{gq}} \cdot (t_{i+1} - t_i), \quad (3)$$

$$r_{ge} = \sum_{i=0}^{|D|} \frac{F_0^{ge} - F_{dis}^{ge}}{F_0^{ge} - F_{min}^{ge}} \cdot (t_{i+1} - t_i), \quad (4)$$

where F_0^{gq} and F_0^{ge} represent the performance indicators of the undisrupted system for the giant component and global efficiency, respectively. F_{dis}^{gq} and F_{dis}^{ge} are performance indicators that correspond to the values of the giant component and global efficiency at a given disruption phase, respectively. F_{min}^{gq} and F_{min}^{ge} are lower bound thresholds for the giant component and global efficiency, respectively. $|D|$ represents the number of disruption phases. The duration of each disruption phase is set to 2 hours. This value was chosen mainly to make the graphical presentation of results clearer, as the analysis at this stage is not affected by the actual duration of the disruptions.

The resilience curve is characterized by multiple disruption phases (“stairway” curve) until the network is recovered, as proposed in [14].

3.2 Disruption scenarios

To assess resilience, the disruption scenarios are categorized following common practice in the literature into three types [3-6]: random failures, targeted attacks, and nature-caused failures, such as flooding.

Random failure of a node or edge. In each simulation step, one network element is randomly selected and removed. This type of disruption is intended to simulate random failures, such as equipment malfunction, minor accidents, or technical issues that may occur without any specific spatial or structural pattern. Two separate simulation scenarios are generated within this disruption category: one based on random node removal and another on random edge removal.

Targeted attack on critical elements. In this disruption scenario, all nodes in the intact network are ranked based on their betweenness centrality, a measure that identifies elements most frequently located on the shortest paths between other nodes. The element with the highest betweenness value is removed first, followed by recalculation of betweenness scores before the next iteration. This removal process continues step by step, with each deletion targeting the currently most critical component. The procedure is designed to simulate targeted attacks or high-impact failures at transfer hubs, which are most essential for maintaining global connectivity. A single scenario

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is simulated for this case, focusing on node removal as the most structurally disruptive form of targeted attack.

Natural hazard with spatial clustering. To simulate flooding along the Danube and Sava riverbanks, a flood zone is drawn around the rivers' axes, and all stations and links that fall within that zone are removed simultaneously. Because all removals occur at once, this scenario produces a single spatial shock rather than incremental losses. A single scenario is simulated for this case.

For each scenario, the post-disruption graph is evaluated with the resilience metrics from Section 4.3.

4 Case study: Belgrade Metro

In this section, the Belgrade metro preliminary transportation network is constructed. The design network is combined with the existing Belgrade's BG voz network line. Combining the planned metro network with the BG voz network enables a more realistic assessment of connectivity and resilience, reflecting how these systems are expected to operate as an integrated urban transport framework. Figure 1 graphically illustrates the provision/layout and stations.

The design network has 70 stations and 80 sections, with the network density of 0.033, meaning that only about 3% of all possible connections between stations exist. In other words, the network is sparse compared to a fully connected graph.

An average node degree of 2.29 implies that a typical station is connected to only two neighboring stations, forming mostly linear routes with only a few transfer hubs (degree > 2). The degree distribution of the Belgrade metro and BG voz network (Figure 2) does not follow a clear power-law trend. As a result, the network does not exhibit scale-free properties typically seen in more complex systems (e.g. China railway and air transport network [10])

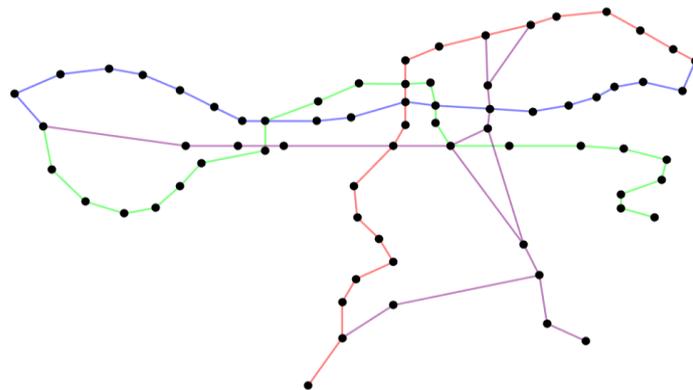


Fig. 1. Planned Belgrade metro and BG voz transportation network [15]. Red: First metro line; Blue: Second metro line; Green: Third metro line; Purple: BG voz line.

4.1 Simulated disruption scenarios

In the baseline configuration, the network forms a single giant component that contains all 70 stations, with a computed global efficiency of 0.196. Lower bound thresholds for the giant component and global efficiency are set to 35 and 0.12, respectively.

First scenario: Random failure of a node. The first disruption scenario captures unexpected technical faults that can disable any station with equal probability. In each phase, one station is chosen at random from the current graph, removed together with all of its incident links, and the resilience indicators are recalculated. This procedure is repeated 10 000 times in a Monte Carlo simulation. The process is repeated in ten successive phases so that the removed set grows from one to ten distinct stations.

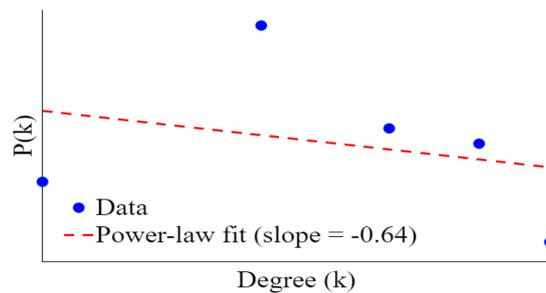


Fig. 2. Planned Belgrade metro and BG voz transportation network degree distribution

Second scenario: Random failure of a link. The second disruption scenario mirrors the procedure described in the first disruption scenario, with the exception that random failure is applied to track segments rather than stations.

Third scenario: Targeted attack. The third disruption scenario follows the same phase structure but removes stations in a deliberately adversarial order instead of at random. At the start of each phase, all remaining stations are ranked by betweenness centrality; the highest ranked station is then deleted together with its incident links, and the resilience indicators are recalculated. The procedure is carried out through ten phases.

Fourth scenario: Failure caused by flooding. In the fourth scenario, all stations and their connecting track segments that lie within the flooding zone of the Danube and Sava Rivers (identified from flooding hazard maps given in [16]) are removed in a single step. The resilience indicators are then recalculated on the remaining network to show the immediate impact of a severe flood event.

4.2 Results

Results from Table 1 show that random failure of up to ten distinct stations produces only moderate structural loss. After the first randomly chosen station is deleted, the giant component falls from 70 to 69 stations, yet subsequent phases remove mostly

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peripheral nodes, so the component shrinks stepwise to 48 stations, always well above the threshold. Global efficiency behaves similarly. It goes from 0.196 to 0.195 in phase 1 and declines in small increments to 0.140 after the tenth removal. The resilience cost grows gradually, while the resilience index drops from 0.971 to 0.371 for connectivity and from 1 to 0.267 for efficiency. The Belgrade metro and BG voz network remains reasonably resilient up to five random station failures. The results of the first scenario are illustrated in Figure 3.

Table 1. Results for the first scenario.

Disruption scenario phase	F_{dis}^{gq}	F_{dis}^{ge}	r_{gq}	r_{ge}	R_{gq}	R_{ge}
1	69	0.195	0.057	0	0.971	1
2	68	0.194	0.114	0.027	0.943	0.987
3	67	0.188	0.171	0.187	0.914	0.907
4	66	0.182	0.229	0.347	0.886	0.827
5	65	0.176	0.286	0.507	0.857	0.747
6	58	0.165	0.686	0.800	0.657	0.600
7	56	0.160	0.800	0.933	0.600	0.533
8	55	0.157	0.857	1.013	0.571	0.493
9	51	0.147	1.086	1.280	0.457	0.360
10	48	0.140	1.257	1.467	0.371	0.267

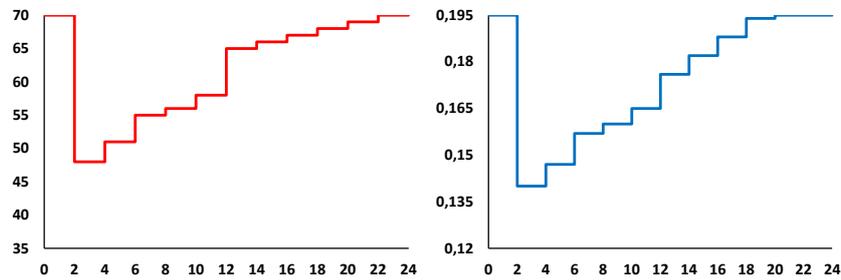


Fig. 3. Resilience curves for the first scenario (L: giant component; R: global efficiency)

Random failure of track segments proves even less disruptive than random station loss. As Table 2 results show, removing up to five randomly chosen links leaves the giant component completely intact at 70 stations, while global efficiency drops from 0.193 to 0.172. A sixth deletion finally breaks a single branch, trimming the giant component to 69 stations and lowering efficiency to 0.169. More visible effects appear only after seven to ten removals, when the component reaches 59 stations and efficiency reaches its lowest value of 0.134, still above the preset 0.12 threshold. The results indicate that the Belgrade metro and BG voz network tolerates unsystematic link failures at least as well as random station outages, and during the first five removed links, even more effectively. The results of the second scenario are illustrated in Figure 4.

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Table 2. Results for the second scenario.

Disruption scenario phase	F_{dis}^{gq}	F_{dis}^{ge}	r_{gq}	r_{ge}	R_{gq}	R_{ge}
1	70	0.193	0	0.053	1	0.973
2	70	0.190	0	0.133	1	0.933
3	70	0.186	0	0.240	1	0.880
4	70	0.181	0	0.373	1	0.813
5	70	0.172	0	0.613	1	0.693
6	69	0.169	0.057	0.693	0.971	0.653
7	62	0.160	0.457	0.933	0.771	0.533
8	62	0.152	0.457	1.147	0.771	0.427
9	62	0.145	0.457	1.333	0.771	0.333
10	59	0.134	0.629	1.627	0.686	0.187

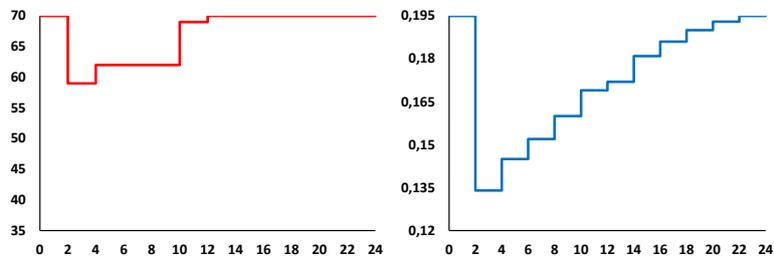


Fig. 4. Resilience curves for the second scenario (L: giant component; R: global efficiency)

Results from Table 3 show that targeted removal of stations with high betweenness is much more damaging than random failure. After a single deletion the giant component falls from 70 to 61 nodes, and global efficiency drops from 0.195 to 0.162. A second deletion lowers the component to 60 and the efficiency to 0.140. The third hit is critical: the giant component drops to 45 nodes, efficiency falls below the 0.12 threshold, and both resilience costs rise sharply. From the fourth deletion onward, the giant component remains below 35 stations and global efficiency stays under 0.12, so the resilience index for connectivity collapses to zero, and the efficiency-based index also remains at zero. Results indicate that the Belgrade metro and BG voz network is highly vulnerable to deliberate attacks on most central stations. The results of the third scenario are illustrated in Figure 5.

Table 3. Results for the third scenario.

Disruption scenario phase	F_{dis}^{gq}	F_{dis}^{ge}	r_{gq}	r_{ge}	R_{gq}	R_{ge}
1	61	0.162	0.514	0.880	0.743	0.560
2	60	0.140	0.571	1.467	0.714	0.267
3	45	< 0.12	1.429	2	0.286	0
4,5,6,7,8,9,10	< 35	< 0.12	2	2	0	0

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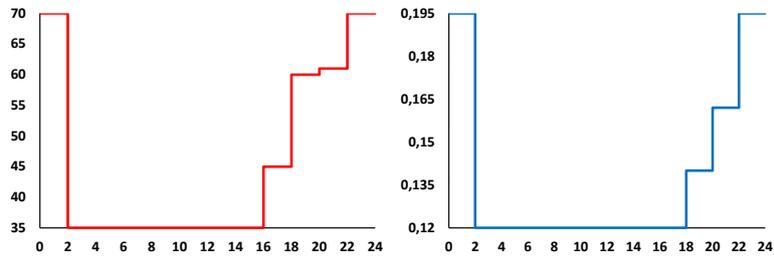


Fig. 5. Resilience curves for the third scenario (L: giant component; R: global efficiency)

Results from Table 4 show that a severe flood of the Danube and Sava rivers is immediately catastrophic for the proposed system. In a single step, the giant component collapses from 70 to only 12 stations, while global efficiency falls to 0.076, far below the threshold of 0.12. Both resilience costs reach the upper limit of two, and the resilience indices for connectivity and efficiency drop to zero, indicating a complete loss of acceptable service. Results indicate that the Belgrade metro and BG voz network is highly vulnerable to severe flooding along the Danube and Sava rivers. The results of the fourth scenario are illustrated in Figure 6.

Table 4. Results for the fourth scenario.

Disruption scenario phase	F_{dis}^{gq}	F_{dis}^{ge}	r_{gq}	r_{ge}	R_{gq}	R_{ge}
1	12	0.076	2	2	0	0

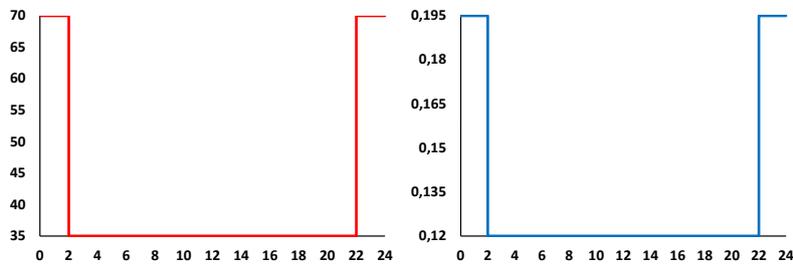


Fig. 6. Resilience curves for the fourth scenario (L: giant component; R: global efficiency)

5 Conclusions

This paper quantifies the resilience of the Belgrade Metro and BG voz network under four disruption categories: random station failure, random link failure, targeted attack, and flooding. For each scenario, the affected nodes or edges are removed, after which the resilience metrics are recalculated. Network resilience was measured based on the size of the area under the resilience curve for each individual scenario.

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Simulation results show a clear gradient in the vulnerability of the Belgrade metro and BG voz network across the four disruption categories. When stations are removed at random, the network retains a single giant component and loses only modest efficiency through the first five deletions. Even after ten random removals it still binds 48 of its 70 original stations and keeps global efficiency just under 0.140, so both resilience indices remain well above the imposed thresholds. Random removal of track segments has shown to be less harmful. Five link failures leave the network completely intact, and only when seven or more links are removed, the giant component shrinks below 60 stations and efficiency approaches the threshold. By contrast, targeted deletions focused on high betweenness stations prove severe. A single strike reduces the giant component to 61 stations and a third strike pushes both efficiency and connectivity below their limits, causing the two resilience indices to collapse to zero from the fourth deletion onward. The most drastic losses arise under the flood scenario, where the removal of every station within the Danube and Sava floodplain in a single step interrupts the cohesive structure, leaving only 12 connected stations and driving efficiency to 0.076. In short, the network is reasonably robust to unsystematic station and link failures, vulnerable to deliberate attacks on its busiest transfer hubs, and extremely sensitive to severe river flooding that strikes stations and links simultaneously.

The paper has several limitations. First, the duration of each disruption phase is fixed at two hours, whereas real incidents vary in length and recovery time. Second, because the metro system is still at the planning stage and no passenger data exists, the model does not consider passenger flows and train schedules. Finally, the assessment focuses solely on the topological properties of the network (connectivity and path length).

Future research directions should aim to incorporate demand data into the resilience assessment. This includes mapping passenger flow patterns from existing public transportation services onto the projected metro network to simulate realistic usage conditions. Additionally, an artificial train timetable could be developed to approximate operational dynamics and enable the integration of system-oriented resilience metrics.

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Analysis of Rail Transportation Services and Accessibility from the aspect of Persons with Disabilities: Serbian Railway Network

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Abstract. This study represents a continuation of monitoring the support provided to persons with disabilities using railway transport to improve service quality and accessibility in the Republic of Serbia by 2025. A questionnaire related to services and accessibility in passenger rail transport was used to gather the user opinions. This approach is considered effective for obtaining feedback from passengers on various aspects of train travel and the use of railway stations. The goal of the questionnaire is to ensure continuous monitoring in line with Eurobarometer, the EN13816 standard, and best practices. Presenting this data to railway operators is of great importance, especially since these operators do not currently conduct such specific surveys. Additionally, all the results presented in this paper are considered highly important as a basis for identifying gaps, which will help decision-makers reduce problems related to the use of railways.

Keywords: Railway, Service, Accessibility.

1 Introduction

The observation and response of users to the use of a service is considered one of the basic data that needs to be collected. System performance can also be monitored by examining the service provided, regardless of the type of service. Finding new users around service provision, adaptation, and understanding of needs is considered very important.

People with limited mobility or disabilities can be considered a special group of public transport users. Recognizing this part of the population as a group that is generally in a less favorable position and, in many cases, discriminated against, certain steps are taken to minimize both the impact of external access and the services provided.

This kind of data can help the service provider to improve its services or find its weak points and provide ongoing support for a better understanding of the problems that PWD faces in railway traffic.

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2 Literature review

Different approaches can be applied for better quality service. In the analysis of TV users, especially in the selection of the number of channels, different platforms, and price, a comprehensive analysis of the choice and provided service was carried out of the system use [8]. Therefore, it can be said that the use of the approach of observing the quality provided by users is not limited and is considered very favorable.

As a basis for observing social mobility as a unit of measurement, the functioning of transport is the basis for increasing social activities globally, as well as for certain groups and individuals. These observations can be carried out on a general basis that also includes a global approach for the entire public transport [4]. The correlation of the variables was observed, taking the user's satisfaction as a basis in the wider area of the Coast-Accra Route, Ghana.

In addition, around Cape Coast, Ghana, an individual observation of the provision of a specific taxi service was conducted, an analysis was conducted on several variables, and the detection of user satisfaction was conducted [5]. The general approach for observing the quality of service provided is also applied in transport analysis. In a study conducted on the bus transit system in Bogor, Indonesia, within the urban public transportation context, the emphasis was on analyzing the relationships between transportation performance, service quality, customer satisfaction, and reuse intention [16]. In paper [6], the relationship between service quality and customer satisfaction of public transport operations of Vancouver Lower Mainland in the Province of British Columbia, Canada, was observed for public transport users. An assessment was conducted along the lines of tangible and intangible for transport users to evaluate the service quality of the system and customer satisfaction when using buses. As an integral part of the analysis of the quality and accessibility provided, it is regularly conducted on railway transport as well. These analyses can be carried out for the classic observation of general service and accessibility or for certain specific areas.

Indian Railways has a good idea of improving its service quality. In the study, attempts were made to identify the gap that exists in the service level, and only internal aspects such as facilities (attributes) that make the journey comfortable were observed [9]. A special case study [3] identifies the components of service quality of Indian Railways at railway platforms to determine the most important factors for offering quality service. A comprehensive psychological model [15] was used to integrate methodology and models to understand and analyze passengers' travel intentions through Customer Satisfaction theory. They attempted to better understand the psychological factors shaping passengers' decisions and enhance service provision accordingly. To analyze the status of service quality and passenger satisfaction of light rail transit service in Addis Ababa, passengers' expectations of the service quality and perceptions of the service delivered by AA-LRT [10] were observed. The survey concluded that there is a need to improve the quality of services in all dimensions, including for people with disabilities (PWD). In examining the advancement of accessibility within urban planning, Thailand has committed resources to the development of railway initiatives and the refinement of design standards for transportation infrastructure

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to accommodate the needs of diverse users [7]. This strategy has advantages when comparing regulations and recommendations for railway stations and amenities crafted for everyone. Enhancing accessibility is likely one of the primary factors for the effectiveness and sustainability of a transportation system. In this regard, the financial benefits for service providers were also noted, as an evaluation of successful practices related to access to infrastructure, vehicles, or information was conducted [2]. In the document [14] regarding the new railway infrastructure under construction in South Sulawesi, an investigation was conducted to determine if women and individuals with disabilities will have accommodations that cater to their requirements and promote their use of public transportation, as well as to identify issues related to accessing the stations. In a useful way, to make it simpler for everyone to use train stations, papers are made that relate to the services offered by train companies in Great Britain. [1]. These approaches could help those who run passenger trains and stations to make train travel easier for people with disabilities.

In the area of the Republic of Serbia, research was performed to find out how much people with disabilities use public transportation, particularly trains [13]. The document highlights that making things easier to access is a process that needs to be repeated and watched closely to see how well it is working and to ensure everyone understands it. To look at the situation and how well things work for people with disabilities, information from studies [11] and [12] was used. The accessibility of the buildings and services was examined from the perspective of wheelchair users, and it was noted that there are still some issues that remain even after improvements were made.

3 Study Area and Methodology

The regular surveys on population mobility conducted in the Republic of Serbia do not adequately address traffic needs for PWD population. All questionnaires were submitted to associations, which were later sent by e-mail. Due to the importance of this research and the comparability of the obtained results with other European countries, adapted questions from the Eurobarometer, the SRPS EN 13816:2012 standard and positive practices in the field were used as the basis for this questionnaire. This research involves 39 respondents from the PWD population, and the data was collected through a questionnaire survey conducted from March 8th to June 30th, 2025. The study participants had various disabilities. The questionnaire was structured as a combination of closed and open answer form, and an individual survey was conducted through a web-based survey.

The questionnaire was divided into three parts: Demographic characteristics of the respondents, including municipality of residence, gender, age, and work status (employed, dependent, pensioner), Satisfaction with the services in the stations, with train services and accessibility. The surveyed population covered urban and rural areas within the Republic of Serbia.

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4 Results

4.1 Socio-demographic characteristics

The classification of the PWD population was based on the collected databases- Key parameters of socio-demographic characteristics: Gender (Man:16, Female:23), Age (15-20: 1, 21-25: 3, 26-30: 3, 31-35: 10, 36-40: 2, 41-45: 5, 46-50: 3, 51-55: 2, 56+: 10), Mobility (Walks independently: 20, Walks with the help of aids: 5, Uses a wheelchair, drives independently: 11, He uses a wheelchair, another person drives: 3), Speech (Normal: 22, Not very difficult, understandable: 7, Unintelligible, passive speech: 1, Hardly understandable: 6, Does not speak, but communicates: 2, Does not speak and do not communicate: 1), Damaged senses (None: 21, Sight: 1, Hearing: 13, Combined: 4), Type of settlement (Village: 1, Small city: 12, Big city: 26), Level of education (No education: 1, Elementary school: 3, High school: 14, College or university (academy): 21) Work status (Dependent: 4, Employee: 24, Pensioner: 11).

4.2 Number of railway users and reasons prevent travelling by train

A considerable number of PWD population in this survey is that 56% use and 44% do not use the railway. The main reasons given by respondents, which do not use railways, are a combination of answers which contain lack of information regarding accessibility and general service, inaccessible roads and sidewalks and the lack of specialized public transport leading to the station, inaccessible stations and lack of specific staff and assistance. Some specific ones are that trains do not operate or rarely operate near homes, that trains have long travel times, that there is no information adapted for the blind and visually impaired, and that, for some people, the very organization of getting to the station and using the train is very complicated.

4.3 Railway users' basic data

For the PWD population, significant information is: the benefits do not use 63% answered in the affirmative, getting to the station most transport mode is car/taxi use 50%, time to get station from home for 50% is between 10 and 20 min, the reason for traveling for 41% is rest/recreation and frequency of using train for 45% is several times per year. Most used railway stations: Prokop (Belgrade main station) and Novi Sad on the new reconstructed line, Valjevo, Kruševac, Čačak, Kraljevo, Raška, Niš, Zaječar on the rest of the network. Further analysis was conducted only with the responses of railway users.

4.4 Satisfaction with the services in stations and trains

Service received a significant response, with 55% of those in stations being dissatisfied with Pollution exhaust gases, and 41% on trains reporting that they were neither satisfied nor dissatisfied with Train departures, Travel time and speed (these answers are more connected with reconstructed and modernized lines), within specific groups

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of questions and special equipment. The images (1. and 2.) display more information about individual responses for stations and trains separately.

Station



Fig. 1. Service satisfaction in the Station for the Arrival-station square, Service, Information and navigation throughstation, Tickets, Comfort and Ambience, Security, Staff, Cleanliness and maintenance

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Train



Fig. 2. Service satisfaction on the Train for the Train movement, Service, Information, Comfort and ambience, Safety, Staff, Maintenance and cleanliness, and Environment

4.5 Satisfaction with accessibility in stations and trains

Accessibility received a significant response, with 45% of those in stations and 55% on trains reporting that they were neither satisfied nor dissatisfied with Braille signage accessibility, within specific groups of questions and special equipment. The images (3. and 4.) display more information about individual responses for stations and trains separately.

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Station



Fig. 3. Accessibility satisfaction in the Stations for Physical barriers, Staff and services, and Special equipment

Train

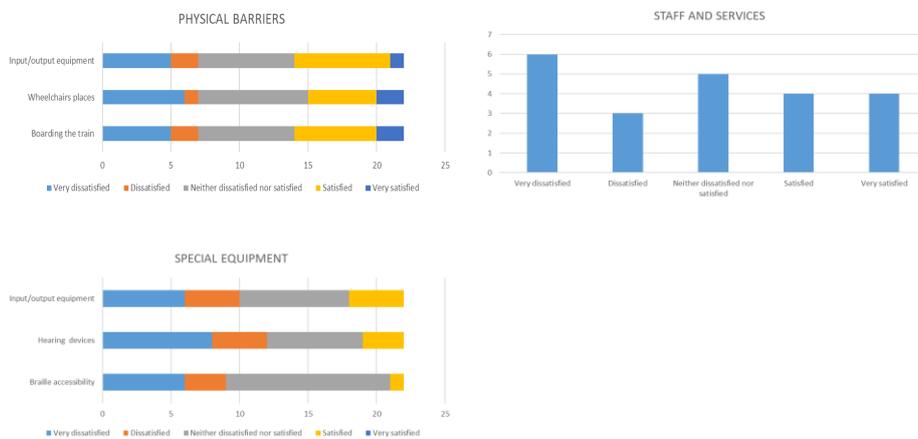


Fig. 4. Accessibility satisfaction on Trains for Physical barriers, Staff and services, and Special equipment

5 Conclusions

In general, in the study [17] service satisfaction is over 50%, for some process about accessibility is between 40 and 50%. In the same study on only for PWD population reason for not travelling by train is difficulties travelling to the station (16%), while

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12% mention the inaccessibility of stations or platforms, and 10% mention the lack of pre-journey information about stations and accessible services. According to a study [18], only a third of PWD passengers experience problems during their journey, while two thirds do. Problems experienced during any of the following journey stages on the train are less than 25% (although some types of PWD population may experience higher values). The PWD population in Serbia experienced worse results when compared to previous studies in relation to the conducted survey.

Despite the negative experience, there is also satisfaction among respondents who see Serbian Railways through ticket sales staff, the call center, and conductors, and this case is mostly on the reconstructed network. Apart from the part of the network that was reconstructed for people who do not use the train, this type of questionnaire is considered very ambitious. There is insufficient accessibility of both vehicles and infrastructure; train use is unreliable, and there are not enough trains, as they rarely operate. For certain types of disabilities, it is not possible to determine what type of travel benefits are available. The problem of moving platforms and the maintenance of elevators that are not always in operation is, based on comments, one of the more significant issues, especially for wheelchair users. People with hearing impairments have significant problems communicating and exercising their rights while traveling. As for blind and visually impaired people with disabilities, in addition to the reconstructed and newly built infrastructure, tactile paths on the floor are blocked by certain obstacles. Planning a trip under these conditions could be very difficult.

By monitoring data through surveys in the last few years, there has been great progress in improving the position of PWDs in the regulatory framework, but not completely in the implementation. It can still be said that these people "suffer" to a certain degree from discrimination because they are not provided with full mobility, which can be limited even with the services and accessibility provided. This research's limitations also highlight the problem of engaging a larger number of respondents in associations of PWDs, which, despite a certain number of responses, does not yield a sufficient sample. In addition to the identified problems, it is still necessary to carry out intensive additional education for academic communities, engineers who plan, design, and perform works, as well as executive authorities, traffic service providers, and the general population in the long term. An important next step is to establish a regular survey for people with disabilities and to create a complaints system to improve the service provided.

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Regulatory Frameworks for the Mutualization of Railway Resources in Freight and Passenger Transport

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Abstract. The mutualization of resources in railway transport is emerging as a key strategy to enhance the efficiency, sustainability, and interoperability of rail systems across Europe. This paper explores the evolving models of resource sharing in both freight and passenger railway sectors, with particular attention to the regulatory frameworks that shape their implementation. Drawing on European Union directives, agency reports, and recent academic research, it investigates how liberalization, infrastructure governance, and digitalization are transforming operational aspects. The study highlights the opportunities and constraints posed by technical specifications, market fragmentation, and national regulatory differences, particularly in cross-border contexts. Special emphasis is placed on the role of the practices, initiatives, and data governance mechanisms in enabling mutualization. By comparing internal practices with broader European models, the paper aims to identify feasible pathways for greater coordination, reduced redundancy, and improved service quality. The findings may contribute to the ongoing debate on balancing competition and cooperation in rail transport, offering preliminary insights for policy makers, infrastructure managers, and operators seeking to optimize resource allocation while aligning with European Union sustainability and digitalization goals.

Keywords: Resource Mutualization, Regulations, Railway Operators.

1 Introduction

Railway transport is increasingly recognized as a key component in both freight and passenger mobility due to its significant contribution to sustainable development. A well-developed rail system not only supports environmental objectives, particularly the reduction of greenhouse gas emissions, but also provides competitive transport services that can serve as viable alternatives to more polluting modes of transport. Given its strategic role in advancing sustainability goals and aligning with current regulatory frameworks, it is essential to examine the potential for further development and optimization of railway systems. Enhancing their performance is crucial to ensuring their attractiveness and reliability for enterprises and transport service operators.

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Improving rail transport services, as well as the performance of rail freight or passenger transport, is a problem in the current context, since an efficient development of the transport system requires a delicate analysis of a series of factors that influence or even limit the possibilities of streamlining the system's performance.

The concept of mutualization of resources in the railway sector refers to strategies and arrangements through which different stakeholders, whether infrastructure managers, train operators, or service providers, share critical assets, systems, or data to achieve greater efficiency, cost-effectiveness, and operational coherence. Unlike simple coordination agreements, mutualization typically involves structured, often formalized mechanisms that allow participants to access or collectively manage resources that would otherwise require duplicative investment or lead to fragmented operations.

In the European railway context, mutualization is particularly significant given the diverse national systems that must coexist within a single market framework. It manifests through various practices, ranging from joint use of rolling stock and interoperable signaling systems to shared maintenance facilities and collaborative data platforms. These approaches aim to reduce idle capacities, streamline cross-border operations, and mitigate the financial and administrative burdens that individual actors would face if they operated entirely independently.

At its core, mutualization of resources serves as a response to multiple pressures, such as the need for capital efficiency, the imperative of aligning with European Union objectives on interoperability and sustainability, and the practical challenges of managing complex, transnational traffic flows. It allows railway undertakings and infrastructure managers to balance autonomy with shared responsibility, ideally leading to a system that is more resilient, adaptable, and capable of delivering higher quality services across both freight and passenger segments.

Cooperation agreements in the railway sector are formed for a variety of strategic and operational reasons. As in other industries, such collaborations aim to enhance service quality and address discrepancies between divergent market demands. Often, competitive pressures, along with the specific strengths and limitations of individual companies, serve as primary drivers for initiating cooperation. However, the mutualization of resources does not follow a uniform model, as there is no standardized implementation criteria, designated organizational structure, or fixed area of application. Consequently, cooperative arrangements vary significantly between operators. This variability raises the recurring question of how best to structure cooperative efforts at the national level [1]. In the absence of a universally accepted solution, the most important goal becomes providing strategic guidance to railway operators considering cooperation. This is typically achieved through an analysis of the relevant regulatory and operational conditions, coupled with the development of innovative business models aimed at fostering effective collaboration among stakeholders. Particular emphasis is placed on evaluating the current state of cooperation within the railway sector and identifying both past successes and remaining challenges. In order to fully understand the dynamics of mutualization in the railway sector, it is essential to examine the regulatory frameworks that govern both technical and operational aspects of railway activity.

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The regulatory framework affects freight and passenger transport differently, reflecting the distinct operational models, market pressures, and service expectations inherent to each segment. Freight operators typically prioritize flexibility in scheduling, access to cross-border corridors, and interoperability of wagons and terminals, while passenger service providers must comply with strict safety, punctuality, and comfort standards, often under public service obligations. Consequently, mutualization strategies must adapt to these divergent priorities, balancing the operational autonomy of each operator with the technical compatibility required for shared use of rolling stock or infrastructure. Moreover, regulations extend beyond high-level legal mandates to include detailed technical specifications related to vehicle authorization, track gauge compatibility, braking systems, coupling interfaces, and digital communication protocols. At the same time, they also encompass operational aspects such as staff certification, timetable coordination, traffic management, and the use of shared maintenance facilities.

2 The Role of Regularization in Enabling Mutualization in the Railway Sector

As stated above, the effective mutualization of resources in the railway sector, particularly between freight and passenger transportation, relies heavily on a well-structured regulatory framework that addresses both technical interoperability and operational coordination. A regulation functions as the base mechanism through which diverse railway operators can access and utilize shared infrastructure and rolling stock without compromising safety, efficiency, or market fairness. In the European context, this is primarily achieved through a dual-layered regulatory approach: technical harmonization through binding standards and operational alignment through competition and rules of access.

At the technical level, regulations such as the European Union's Technical Specifications for Interoperability (TSIs), complemented by international frameworks provided by the International Union of Railways (UIC), standardize critical aspects of rolling stock, signaling, braking systems, and train control mechanisms. These regulations facilitate the compatibility of vehicles across different national networks and operators, thereby reducing barriers to resource sharing [2]. Without such harmonization, the interoperability required for mutualization, especially in cross-border freight corridors, would be severely limited [3].

Operationally, the regulatory landscape provides the basis for fair access to infrastructure, timetable allocation, and cost transparency. This is especially important in systems where both public passenger services and commercial freight operators compete for limited track capacity. The European regulatory framework, particularly through the 2012 directive [4], establishes principles of non-discriminatory access to railway infrastructure and transparent track access charges. These provisions are essential to ensure that mutualization does not lead to structural disadvantages for smaller or new entrants, particularly in the freight sector.

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The complexity of mutualization is compounded by the divergent needs of freight and passenger transport. Passenger services are often governed by public service obligations and prioritize punctuality and frequency, while freight operators require flexible routing, longer train lengths, and cost-effective access [5]. Therefore, mutualization must be mediated by regulations that are sensitive to these operational asymmetries. According to the study, the European rail freight market illustrates the limitations of regulation: while liberalization has been legally enacted, real-world outcomes are constrained by legacy infrastructure, incumbent operator dominance, and weak intermodal competitiveness. This highlights that regulatory design must extend beyond formal liberalization and actively support conditions for cooperation, interoperability, and shared innovation.

The liberalization of railway markets within the European Union has been a cornerstone policy aimed at increasing competition, improving efficiency, and enhancing service quality across both freight and passenger transport sectors [6]. Moreover, liberalization often exposes tensions between incumbent operators and new entrants, especially regarding access to scarce infrastructure resources and the balancing of freight and passenger priorities.

Therefore, the success of mutualization efforts depends on complementing liberalization with targeted regulation that not only guarantees fair and non-discriminatory access but also promotes collaboration and joint investment. In table 1, various regulations in the European Union are presented, highlighting the relevance to the mutualization of resources in the railway transport.

Table 1. Key regulations relevant to mutualization of railway resources.

Regulation	Main focus/summary	Relevance	Reference
Directive 2012/34/EU – Single European Railway Area	Establishes a unified regulatory framework for access to railway infrastructure, transparency in charges, and fair competition.	Enables multiple operators to access and use infrastructure equitably, essential for shared (mutualized) use.	[5]
TSIs (Technical Specifications for Interoperability)	Set of EU-mandated standards for subsystems (rolling stock, infrastructure, signaling, etc.) to ensure cross-border compatibility.	Critical for technical mutualization, ensures different operators can use common rolling stock and tracks.	[2]
UIC Leaflets & IRS (International Railway Standards)	Technical and operational guidelines (non-binding but widely adopted) for interoperability, maintenance, and design.	Facilitate harmonization beyond EU borders; commonly used in Europe to align national systems for shared use.	[3]
Regulation (EU) No 913/2010 – Rail Freight Corridors	Establishes governance and coordination rules for international rail freight corridors; prioritizes freight paths.	Enhances freight mutualization by coordinating cross-border paths and simplifying access for freight operators.	[7]
Directive 2008/57/EC (super-	Early directive on interoperability of the trans-European	Formed the legal basis for technical harmonization	[8]

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seded by 2016/797)	rail system (passenger and freight).	that supports mutual use of infrastructure and vehicles.	
Regulation (EU) 2016/796 – ERA Regulation	Establishes the European Union Agency for Railways (ERA), which develops and oversees implementation of TSIs.	Supports uniform rules and certification, essential for cross-acceptance of vehicles and operators.	[9]
UIC – Rolling Stock Mutualization Guidelines	UIC guidance on pooling and leasing rolling stock across operators.	Directly supports technical and operational mutualization—reduces costs and increases flexibility.	[3]

In summary, regulatory frameworks play a key role in shaping the landscape of railway transport by legally enabling market liberalization and establishing essential standards for infrastructure access, safety, and interoperability. Such regulations facilitate the entry of new operators by lowering legal barriers and promoting transparency, thereby aiming to foster a more competitive environment. With regard to the mutualization of resources within the railway sector, regulation provides an indispensable legal framework but does not, in isolation, guarantee effective cooperation. Successful mutualization requires active coordination mechanisms that extend beyond formal access rights to encompass organizational agreements, technical interoperability, and aligned business models.

While established western markets often benefited from mature regulators with the autonomy to enforce neutrality and transparency in access regimes, many of the newer markets struggled with limited institutional capacity, ongoing political influence, and dominant incumbents who resisted meaningful market restructuring. This imbalance undermines the potential benefits of both liberalization and mutualization, reinforcing the idea that regulation must go beyond legal access to include enforceable standards for cooperation, resource sharing, and technical compatibility. Without regulatory structures that actively promote interoperability, fairness, and trust among operators, the mutualization of railway resources remains unlikely or ineffective. With these ideas in mind, it is essential to acknowledge the importance of different types of mutualization and where they apply, as they will be presented in the following chapters.

3 From Regulation to Practice: Concepts and Applications of Mutualization in European Railway Transport

Considering the current context of the cooperation in the railway sector, it is important to bridge the gap between regulatory frameworks and their practical implications by exploring how mutualization models are implemented across the European railway sector. While certain models have established the importance of regulation in enabling cooperation and market liberalization, other approaches focus on the tangible organizational and operational arrangements that railway operators adopt to share resources effectively.

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Mutualization in the railway sector encompasses a broad spectrum of shared resources and collaborative arrangements aimed at optimizing infrastructure use and operational efficiency. Key areas of mutualization include track and infrastructure sharing, station facilities, rolling stock leasing, scheduling, and traffic management. Track and infrastructure sharing involves multiple railway operators using the same railway lines and related assets. Regulatory frameworks play a vital role in ensuring non-discriminatory access, which promotes competition and enhances operational efficiency [5]. Effective mutualization in this domain requires harmonized technical standards to enable interoperability and coordinated traffic management to prevent conflicts between operators [10].

Station facilities also serve as important nodes for mutualization, where access and amenities are shared among passenger and freight operators. As multimodal hubs, stations benefit from coordinated use of platforms and services, relying on technical compatibility, such as platform lengths and signaling systems, and operational agreements concerning scheduling and service priorities [11]. Similarly, the leasing of rolling stock represents a form of mutualization that allows operators to share costly assets such as locomotives and wagons. These arrangements improve capital utilization and flexibility but demand strict compliance with interoperability standards and maintenance protocols to ensure safety and consistent performance.

Scheduling constitutes another critical element of operational mutualization, involving the coordinated planning of train paths and timetables. Through sophisticated algorithms and real-time traffic management, scheduling aims to maximize network capacity and minimize conflicts, balancing the punctuality demands of passenger services with the flexibility needs of freight operators [12]. Complementing this, traffic management governs train movements across the network with an emphasis on safety, efficiency, and conflict resolution. Mutualization in this area often consists of integrating control centers and operational protocols across multiple operators, supported by common technical systems and collaborative regulatory frameworks.

Underlying these various dimensions of mutualization are distinct but interrelated technical and operational aspects. The technical dimension encompasses the physical and technological standards governing railway infrastructure and assets, including interoperability requirements such as track gauge, signaling, vehicle compatibility, safety regulations, and maintenance standards. Technical mutualization ensures that shared infrastructure and rolling stock can function seamlessly across different operators and countries, overcoming practical barriers that might otherwise arise from incompatibility or safety concerns. In contrast, the operational dimension involves the real-time management of railway services and traffic, including the scheduling of train movements, allocation of capacity, dispatching, incident management, and the coordination of freight and passenger operations with often competing priorities. Operational mutualization relies heavily on collaborative decision-making processes, regulatory oversight, and digital platforms that enable efficient and equitable use of shared resources.

In essence, the success of mutualization in the railway sector depends on the seamless integration of these technical and operational aspects. While technical harmoniza-

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tion provides the necessary foundation for compatibility and safety, operational coordination ensures that shared resources are managed effectively on a daily basis, balancing the needs of diverse stakeholders and maximizing the overall efficiency of the railway system [13]. By synthesizing regulatory intent with industry practice, this section provides a comprehensive understanding of the evolving landscape of resource mutualization in European rail transport.

The ability to engage in mutualized arrangements depends heavily on whether governance frameworks are sufficiently robust to prevent strategic obstruction, cross-subsidization, or implicit discrimination, particularly in infrastructure scheduling and depot allocation. Economic principles and regulatory frameworks profoundly shape the practical implementation of mutualization in the railway sector. The economic viability of resource sharing is decided upon well-designed incentive structures and clear regulatory signals [14]. Specifically, it is that economic regulation must balance promoting competition with ensuring the sustainability of infrastructure investments, which are often characterized by high fixed costs and natural monopoly features. This dual imperative influences how mutualization models develop, particularly in allocating infrastructure capacity and coordinating rolling stock usage.

A recurring theme is the critical role of independent regulatory bodies in ensuring transparent, non-discriminatory access to railway infrastructure. The issue stresses that mutualization efforts depend on the regulator's capacity to enforce access rules impartially, resolve disputes, and monitor market behavior. Without this oversight, dominant parties can exploit vertical integration and control over infrastructure to hinder cooperation and resource sharing.

Operational regulation also plays a pivotal role, particularly in capacity allocation and timetable coordination. The issue highlights that these operational rules must be designed to balance the conflicting demands of freight and passenger services, reflecting their distinct priorities for punctuality, flexibility, and cost-efficiency. Regulatory frameworks that incorporate stakeholder consultation and flexible allocation mechanisms have shown greater success in enabling effective mutualization. Overall, the models affirm that successful mutualization in the railway sector hinges on a regulatory ecosystem that integrates economic oversight, technical harmonization, and operational governance. Such a system ensures that shared resource models are not only legally permissible but also practically feasible and economically sustainable.

The concept of mutualization in the railway sector also extends to the digital transformation of rail networks, which increasingly influences both technical and operational dimensions. Digitalization enables advanced traffic management systems that optimize network capacity and improve safety through real-time data exchange and predictive analytics [15]. This technological evolution facilitates more dynamic mutualization by allowing multiple operators to share infrastructure usage more flexibly and respond rapidly to disruptions or demand fluctuations. The deployment of the European Rail Traffic Management System (ERTMS) exemplifies how common digital standards can enhance interoperability across national borders, streamlining both passenger and freight services [16]. Such digital mutualization reduces fragmentation and fosters a more integrated European rail system.

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Another important dimension relates to the economic and financial mechanisms related to mutualization. Shared investments in infrastructure and rolling stock often require complex funding models involving public-private partnerships, European Union grants, and operator contributions [17]. Effective mutualization is thus closely linked to the design of incentives that encourage cooperation while ensuring equitable cost and benefit allocation among stakeholders. Without proper economic frameworks, operators may hesitate to share resources due to perceived risks or unequal returns. This highlights the need for regulation not only to set technical standards and operational rules but also to create market conditions that facilitate joint investment and long-term planning [18].

Furthermore, governance structures play a critical role in enabling and sustaining mutualization in railways. Multi-level governance, combining European Union parties, national regulators, infrastructure managers, and operators, can help balance competing interests and coordinate complex resource-sharing arrangements [19]. However, the diversity of regulatory environments and strategic objectives among member states poses challenges to harmonizing mutualization practices. Lessons can be drawn from regional collaborations that implement common frameworks for access, pricing, and quality standards, which help overcome fragmentation and foster trust between partners [20]. Thus, governance models that emphasize transparency, stakeholder engagement, and dispute resolution are crucial to operationalizing mutualization.

While mutualization in railway transport has been discussed in various regulatory, operational, and technical studies, existing analyses are often fragmented, focusing on isolated aspects of either freight or passenger transport, or limited to single-country case studies. This paper contributes by consolidating these scattered insights into a coherent comparative framework that spans both freight and passenger sectors at the European level. By linking regulatory provisions to concrete operational practices, the study offers an integrated perspective aimed at supporting decision-makers, infrastructure managers, and operators in identifying actionable pathways for resource sharing. This synthesis, while grounded in established knowledge, provides added value through its cross-sector and cross-border scope, which is rarely presented in a unified format.

The analysis of mutualization models across Europe reveals a rich and uneven landscape. While some countries, such as Sweden and the Netherlands, have embraced full or partial open access frameworks supported by strong regulatory institutions, others, like France, continue to wrestle with the inertia of vertical integration and limited interoperability. The United Kingdom's leasing model and Italy's competitive high-speed market demonstrate how distinct mutualization strategies can foster greater access and innovation, even in liberalized environments. These comparative insights show that while regulation provides the blueprint, local governance structures, operator behavior, and historical context critically shape the realization of mutualization.

4 Future Perspectives and Conclusions

In order to properly analyze the opportunity of mutualization in the railway sector, it is necessary to have insights on the regulatory, operational, and technical aspects shaping mutualization in European rail transport. To fully understand this concept, several strategic directions emerge. First, harmonizing regulatory frameworks across countries is essential to facilitate cross-border cooperation and reduce administrative burdens. Greater alignment of national regulations, safety standards, and licensing procedures would promote smoother resource sharing and interoperability among operators, paving the way for more extensive mutualization initiatives.

At the same time, regulators must find the right balance between fostering competition and enabling cooperation. Adaptive regulatory frameworks should recognize collaborative arrangements such as joint ventures, resource pooling, and data sharing, ensuring these do not distort competitive markets but rather enhance overall efficiency. Transparent, open data platforms are also critical, enabling all operators access to real-time network information and standardized data-sharing protocols can significantly improve capacity allocation and traffic management. These measures reduce information asymmetries and encourage operational coordination.

Investment incentives play a crucial role in encouraging mutualization. Public policies and funding mechanisms should promote joint investments in infrastructure upgrades and interoperable rolling stock. By sharing the financial burden, operators can avoid duplication of resources, leading to cost savings and improved network performance. Moreover, mutualization policies must be sensitive to sector-specific differences. Passenger transport, often subject to public service obligations, requires frameworks that allow resource sharing without compromising service quality and punctuality. Freight transport, with its emphasis on flexibility and efficiency, demands flexible access arrangements and optimized traffic management solutions. Institutional cooperation and trust-building mechanisms are equally vital. Mutualization relies heavily on strong collaboration among infrastructure managers, operators, and regulators. Formal cooperation bodies and joint governance frameworks can help align incentives, manage conflicts of interest, and foster transparency, thereby overcoming cultural and strategic barriers that often hinder resource sharing.

This synthesis of regulatory provisions and operational practices, spanning both freight and passenger sectors across the EU, offers an integrated perspective that is rarely presented in a unified format and is intended to support both policymakers and railway operators in advancing mutualization.

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Optimization of Human Resources in the Railway Sector: A Case Study of HŽ Infrastruktura

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Abstract. Human resources remain one of the key strategic assets of railway transport companies in the 21st century. The focus of human resource management is increasingly shifting from a quantitative approach—centered on workforce numbers—to a qualitative approach that emphasizes employee competencies, efficiency, and adaptability. This paper analyzes the specific characteristics of human resources in the railway sector and explores possibilities for their optimization using the case study of HŽ Infrastruktura (HŽI). HŽI is a state-owned company responsible for the management, maintenance, and development of the railway infrastructure in the Republic of Croatia. The research is based on a SWOT analysis of human resources within HŽI and includes the proposal of a computer-supported model for human resource optimization. The main conclusion of the paper is that a model-based approach to human resource management enables HR managers to make informed and optimal decisions, as well as to conduct simulations that allow adaptation to internal and external constraints and challenges.

Keywords: Railway transport, human resources, HŽ Infrastruktura, optimization.

1 Introduction

HŽ Infrastruktura (HŽI) is a state-owned company responsible for managing, maintaining, and developing the railway infrastructure of the Republic of Croatia. The company employs around 5,000 people. Workforce size in the railway industry is shaped by several factors: deregulation of railway traffic, the degree of automation in traffic management, the availability of railway-specific education, trade union influence, and state regulation. Deregulation tends to prioritize labor productivity, cost reduction, and ultimately, downsizing [1]. Similarly, transitioning from conventional to automated traffic management significantly reduces staffing needs [2]. Both factors directly affect labor demand in the sector. Additional constraints arise from state-imposed wage controls, employment bans, and trade union demands to retain positions, even if unproductive. On the supply side, negative demographic trends and a

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declining interest in railway professions have reduced enrollments in specialized programs, further shrinking the pool of qualified candidates. These trends create a pressing challenge for HŽI's Human Resources (HR) Department: ensuring operational efficiency and sustainability under simultaneous pressure to downsize and upgrade skills.

The objective of this research is to develop and test a computer-supported optimization model for quantitatively and qualitatively reorganizing HŽI's workforce at minimal cost while respecting real-world constraints such as labor market supply, severance pay rules, education costs, and strategic staffing goals.

This study addresses the following research questions:

RQ1. What are the key HR functions in the railway sector?

RQ2. What are the specifics of HR management in railway transport?

RQ3. How is the HR department in HŽI organized?

RQ4. What are the strengths and weaknesses of HŽI's workforce?

RQ5. How can workforce size and structure be optimized quantitatively and qualitatively within given constraints?

The research uses secondary data from HŽI Statistical Reports [3], the 2025 Business Plan [4], and the Ordinance on Job Systematization [5]. The main contributions of this work are: 1) applying optimization modeling to HR management in a state-owned railway infrastructure company — a context rarely addressed in the literature; 2) demonstrating how Excel Solver can be used as a transparent, replicable decision-support tool for HR restructuring; 3) providing scenario simulations to assist management in budget-constrained decision-making.

2 Literature Review

Human resources in the railway industry have become a strategic production factor and simultaneously, the main component of performance in an organization [6–8]. Human resources (HR) in the railway industry plays a pivotal role in ensuring the sector's operational efficiency, safety, and ability to adapt to evolving business and technological demands. Human resource management (HRM) is the utilization of human resources to achieve organizational objectives [9]. Ivancevich and Glueck [10] defined the HRM as the function performed in organizations that facilitates the most effective use of people (employees) to achieve organizational and individual goals. The HR function is responsible for a wide range of activities, from workforce planning and recruitment to employee relations and compliance with regulatory standards. So, HR function provides a service for the operational functions [11]. No, today that is not enough. Employers increasingly want the human resources department to have not only a service role but also an advisory function, assisting top management in developing and implementing their long-term plans and strategies [8, 12]. The objective of a human resource strategy is to manage labor and design jobs so people are effectively and efficiently utilized [13].

Key functions of HR in the railway sector include [14]:

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- **Workforce Planning and Organizational Development.** Forecasting future staffing needs, designing organizational structures, and ensuring the right mix of skills and roles to meet operational requirements [15, 16];
- **Recruitment and Talent Acquisition.** Attracting, selecting, and onboarding new employees, often in a highly competitive labor market with specialized skill requirements [17];
- **Compensation and Benefits.** Managing pay structures, employee benefits, and ensuring competitive remuneration to retain talent;
- **Performance Management.** Setting objectives, evaluating employee performance, and linking individual contributions to overall business goals;
- **Training and Development.** Identifying skill gaps, implementing training programs, and supporting career development and succession planning
- **Employee and Labor Relations.** Handling grievances, negotiating with trade unions, and maintaining constructive industrial relations to prevent disputes and ensure smooth operations;
- **Health, Safety, and Compliance.** Promoting a culture of safety, ensuring regulatory compliance, and managing drug testing and security clearances [18];
- **Diversity, Equity, and Inclusion.** Fostering an inclusive workplace that attracts and retains a diverse workforce, which is crucial for innovation and public reputation.
- **The railway industry presents several distinctive HR challenges [19]:**
- **24/7 Operations.** Managing shift work, scheduling, and fatigue among staff due to round-the-clock service requirements;
- **Geographically Dispersed Workforce.** Coordinating employees across multiple locations and environments, from urban stations to remote tracks;
- **Safety-Critical Roles.** Ensuring all staff are adequately trained and fit for duty in roles where safety is paramount;
- **Technological Evolution.** Adapting workforce skills to new technologies, automation, and digital systems that are increasingly integrated into railway operations [2];
- **Industrial Relations.** Navigating complex relationships with trade unions and balancing the need for flexibility with established employment terms.

Moreover, research in railway HRM highlights key factors affecting productivity, such as organizational culture, leadership style, and employee ergonomics [20]. Studies in large public-sector rail organizations like Indian Railways reveal how HR practices such as recruitment, training, compensation, and welfare are crucial to performance improvement, despite legacy system constraints [21, 22].

3 Organization of the Human Resources Department in HŽ Infrastruktura

The Human Resources Management (or HR) Department in HŽ Infrastruktura is part of the broader organizational structure of this state-owned company, which is respon-

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sible for the management, maintenance, and development of the railway infrastructure of the Republic of Croatia. The Human Resources Management Department is located among the so-called support departments, together with the departments for IT, finance, procurement, real estate, legal affairs, management support and communications, corporate security, and mechanization (Fig. 1).

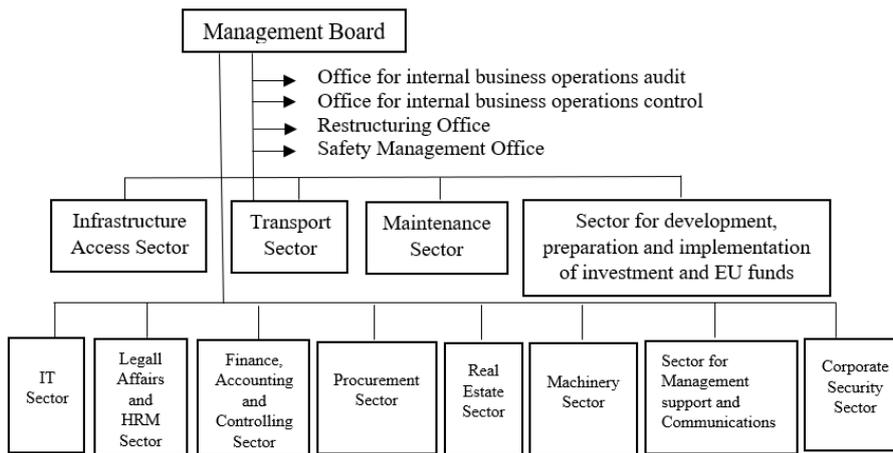


Fig. 1. Organization chart of HŽ Infrastruktura d.o.o. [10]

Based on figure 1, it is clear that the Human Resources Department is part of the Legal Affairs and Human Resources Management Sector and that the sector is subordinate to the Company's Management. Within a sector, departments (such as the human resources department) have clearly defined tasks and responsibilities, and employees within the department report to the head of the department, who further communicates to the director of the sector. The human resources department is organized as shown in Fig. 2.

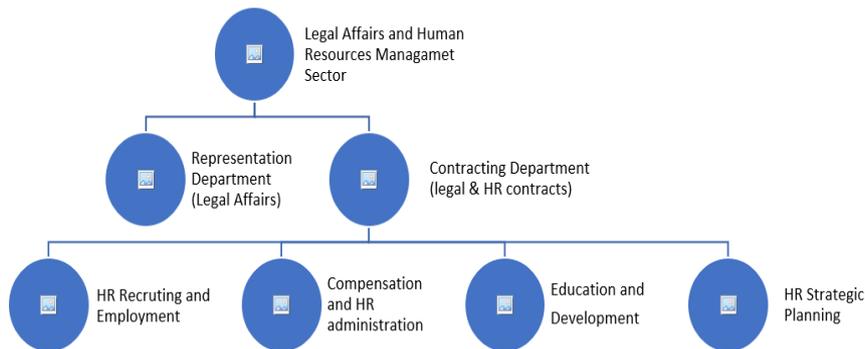


Fig. 2. Organization of the HŽI human resources department [10]

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The Human Resources Department of HŽI is organized vertically through a clearly defined hierarchy within the sector and the company, while horizontally it cooperates with other sectors, departments, and external partners, thus ensuring effective human resources management and support for the company's business goals. The department's responsibilities are focused on developing and retaining quality staff, increasing the company's efficiency and competitiveness, and ensuring compliance with relevant legislation and standards.

4 Research data and methodology

Based on the data collected in this way, a SWOT analysis of HŽI human resources will be compiled. After that, a computer-supported model will be developed in the MS Excel spreadsheet for the purpose of optimizing human resources in the railway infrastructure company. The model should ensure quantitative and qualitative harmonization of human resources with minimal costs, and will be developed and tested based on the data listed below.

The railway infrastructure company employed 5,080 workers in 2024. The planned number of employees for the end of the next planning period (2025-2029) is 4,620. In addition to laying off redundant employees, the railway infrastructure company also wants to reorganize the qualification structure in a way that ensures a transition to a higher level of the qualification structure. The current qualification structure consists of employees with higher education (1,200), secondary education (3,080) and employees with education below secondary education (800). The task of the human resources department is to carry out the necessary reorganization with minimal costs. The unions have reached an agreement with the company's management that employees whose employment contracts are terminated will be paid severance pay in the amount of €30,000 if they have a higher education, or €20,000 for other employees. The human resources department estimates the costs of hiring new employees at €1,250 for candidates with higher education, €750 for candidates with secondary education, and €100 for candidates with lower education. The situation on the labor market is such that on average, 30 candidates with higher education, 55 candidates with secondary education and 70 candidates with lower education can be found annually. The cost of acquiring a higher education qualification for a company was estimated as follows: lower secondary education to secondary education €1,400, secondary education to higher education €5,000 per person. Since the high age of employees was noted, i.e. the lack of young staff, it was decided to hire 50 secondary education trainees in the observed period, namely: 10 immediately during 2025, an additional 15 by 2027, and an additional 20 by the end of 2029.

5 SWOT analysis of human resources of HŽ Infrastruktura

SWOT analysis assumes that the analysis and identification of strengths, weaknesses, threats, and opportunities from the environment will be a useful strategy for achieving

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organizational goals [23]. It is an analysis of the organization's microenvironment. SWOT analysis in the area of human resources is used to identify strengths and weaknesses within the organization (internal factors), as well as opportunities and threats from the environment (external factors). This kind of analysis helps human resource managers develop strategies to improve employee performance, attract and retain talent, and adapt to changes in the labor market. The results of the analysis are shown in Table 1.

Table 1. SWOT analysis of HŽI human resources

STRENGTHS	WEAKNESSES
<ul style="list-style-type: none"> • Experienced staff and expertise in technical sectors • Employment stability and regular income • Internal operational and tacit knowledge • Active attractive infrastructure projects (modernization) 	<ul style="list-style-type: none"> • Aging workforce and lack of knowledge transfer • Lack of professional staff and low attractiveness • Outdated training and education systems • No strategic HR planning (succession, talents) • Low motivation, limited advancement
OPPORTUNITIES	THREATS
<ul style="list-style-type: none"> • EU funds and the National Recovery and Resilience Plan for education and digitalization • Cooperation with educational institutions • Automation and digital transformation • Development of competence centers for new professions • Investments in sustainable transport and new employment 	<ul style="list-style-type: none"> • Mass retirements without replacement • Outflow of young experts abroad/private sector • Administrative rigidity of the public sector • Negative perception of the railway sector • Insufficient readiness for changes

Source: Authors

6 Computer-supported model in the function of human resource management in a railway infrastructure company

A model for the optimal quantitative and qualitative reorganization of human resources in a railway infrastructure company is set up in an MS Excel spreadsheet (cf. Fig. 3). The model consists of four interconnected parts. The first part contains information related to the costs of firing employees (severance pay) – B9:B11, the supply of railway experts on the labor market – C9:C11, employment costs D9:D11 and costs of additional education per employed worker. The second part contains information on the number of current employees by qualification structure and the desired dynamics of the structure of employees in the planning period. The third part refers to the

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decision-making variables, namely: the number of persons who will be sent to additional education, the number of trainees who should be employed, and the number of persons whose employment contracts will be terminated. The fourth part contains the number of employees by qualification structure in the planning period and the total costs of the reorganization of human resources.

	A	B	C	D	E	F	G	H
6								
7	Employee information							
8		Cost of lay-off	Available to be hired per year	Cost of hiring	Additional training of employees			Cost
9	High school	\$30.000	30	\$1.250	Less than secondary school -> secondary school			\$1.400
10	Secondary school	\$20.000	55	\$750	Secondary school-> High school			\$5.000
11	Less than secondary	\$20.000	70	\$100				
12								
13	Estimated number of employees that are required.							
14		Current	Year 2025	Year 2027	Year 2029			
15	High school	1200	1210	1215	1220			
16	Secondary school	3080	3030	2950	2900			
17	Less than secondary	800	750	600	500			
18	Number of employees	5080			4620			
19	Number of employees that are trained, hired or laid off.							
20	<i>Number of employees trained</i>							
21			Year 2025	Year 2027	Year 2029		Cost	
22	Less than SS -> Secondary school		0	0	0		50	
23	Secondary school-> High school		0	0	0		50	
24	<i>Number of employees hired</i>							
25			Year 2025	Year 2027	Year 2029		Cost	
26	High school		0	0	0		50	
27	Secondary school		0	0	0		50	
28	Less than secondary school		0	0	0		50	
29	<i>Number of employees laid off</i>							
30			Year 2025	Year 2027	Year 2029		Cost	
31	High school		0	0	0		50	
32	Secondary school		0	0	0		50	
33	Less than secondary school		0	0	0		50	
34								
35		Total number of employees laid off					0	
36								
37	<i>Number of employees working</i>							
38			Year 2025	Year 2027	Year 2029			
39	High school		0	0	0			
40	Secondary school		0	0	0			
41	Less than secondary school		0	0	0			
42								
43	Total cost of reorganizing							50

Fig. 3. Model for the optimal quantitative and qualitative reorganization of human resources in a railway infrastructure company

After the model has been formed in this way, it is necessary to enter formulas in the appropriate address fields. In address field F22, the formula =H9×SUM (C22:E22) is entered, which is then copied to address field F23. In this way, the costs of sending employees to additional education are calculated. In address field F26, the formula =D9×SUM (C26:E26) is entered, which is then copied to address range F27:F28. In this way, the costs of hiring new employees are calculated. In address field F31, the formula =B9×SUM (C31:E31) is entered, which is then copied to address range F32:F33, and in this way the costs of laying off employees are calculated. The total number of employees to be laid off is calculated in the address field E35, where the formula =SUM (C31:E33) is pasted. The dynamics of the qualification

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structure of the number of employees in the observed period is shown in address range C40:E42. The formula =B15+C23+C26-C31 was entered in the address field C40 and then copied to the address range C41:C42. The formula =C40+D23+D26-D31 was entered in the address field D40 and then copied to the address range D41:D42 and the formula =D40+E23+E26-E31 was entered in the address field E40 and copied to the address range E41:E42. The total costs of reorganizing human resources in a railway infrastructure company were calculated in the address field F43 using the formula =SUM (F31:F33; F26:F28; F22:F23). The address field F43 denotes the objective function, which is to minimize the total costs. The total costs are the sum of the costs of sending employees to additional training, the costs of hiring new employees and the costs of terminating employment contracts.

The Solver program is called from the Tools menu and data entry is accessed in the Solver Parameters tab.

Set target cell: Min F43

Variables: C22:E23; C26:E28; C31:E33

Constrains:

C22 <= B17

C23 <= B16

C27 ≥ 10

C26:C28 <= C9:C11

C31:C33 <= B15:B17

C40:E42 = C15:E17

D22 <= C41

D23 <= C42

D26:D28 <= C9:C11

D27 ≥ 15

D31:D33 <= C40:C42

E22 <= D41

E23 <= D42

E26:E28 <= C9:C11

E27 ≥ 20

E31:E33 <= D40:D42

Once all parameters have been entered, the Solve button on the Solver Parameters form is clicked, which activates the Solver program, which calculates the values of the decision variables. The decision variables defined the optimal solution. Fig 4. shows the optimal solution to the problem using MS Excel.

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	A	B	C	D	E	F	G	H
7	Employee information							
8		Cost of lay-off	Available to be hired per year	Cost of hiring	Additional training of employees			Cost
9	High school	\$30.000	30	\$1.250	Less than secondary school -> secondary school			\$1.400
10	Secondary school	\$20.000	55	\$750	Secondary school-> High school			\$5.000
11	Less than secondary school	\$20.000	70	\$100				
12								
13	Estimated number of employees that are required							
14		Current	Year 2025	Year 2027	Year 2029			
15	High school	1200	1210	1215	1220			
16	Secondary school	3080	3030	2950	2900			
17	Less than secondary school	800	750	600	500			
18	Number of employees	5080			4620			
19	Number of employees that are trained, hired or laid off							
20		Number of employees trained						
21		Year 2025	Year 2027	Year 2029		Cost		
22	Less than SS -> Secondary school	0	0	0		\$0		
23	Secondary school-> High school	10	5	5		\$100.000		
24		Number of employees hired						
25		Year 2025	Year 2027	Year 2029		Cost		
26	High school	0	0	0		\$0		
27	Secondary school	10	15	20		\$33.750		
28	Less than secondary school	0	0	0		\$0		
29		Number of employees laid off						
30		Year 2025	Year 2027	Year 2029		Cost		
31	High school	0	0	0		\$0		
32	Secondary school	50	90	65		\$4.100.000		
33	Less than secondary school	50	150	100		\$6.000.000		
34		Total number of employees laid off			505			
35								
36		Number of employees working						
37		Year 2025	Year 2027	Year 2029				
38	High school	1210	1215	1220				
39	Secondary school	3030	2950	2900				
40	Less than secondary school	750	600	500				
41		Total cost of reorganizing			\$10.233.750			
42								
43								

Fig. 4. Optimal solution

Based on the data in Fig.4., it is clear that all the set constraints have been met and that the planned human resource structure has been achieved. According to the optimal solution, it will be necessary to additionally educate 20 people. Only employees with secondary education will be sent for additional education. Their additional education will cost €100,000. In the observed period, 45 interns will be hired at a cost of €33,750. A total of 505 employees will be laid off, 205 employees with secondary education and 300 employees with less than secondary education. The cost of layoffs is €10,100,000. The total minimum costs of human resource restructuring are €10,233,750. The obtained optimal solution is 3.22 times better than the empirically most unfavorable solution obtained when the function is solved at the maximum.

The set model allows for various simulations. For example, in almost always limited financial conditions, the results of such constraints can be simulated. For example, if a railway infrastructure company had seven million euros to restructure, the question arises whether the necessary restructuring could be carried out. The answer is no. In that case, 20 employees with secondary education would be sent to acquire higher education, 45 trainees would be hired, while 343 employees would be laid off, 140 of them with secondary education and 203 with less than secondary education. A comparison of the planned and achieved qualification structure of employees with a budget limit of 7 million euros is given in Fig. 5.

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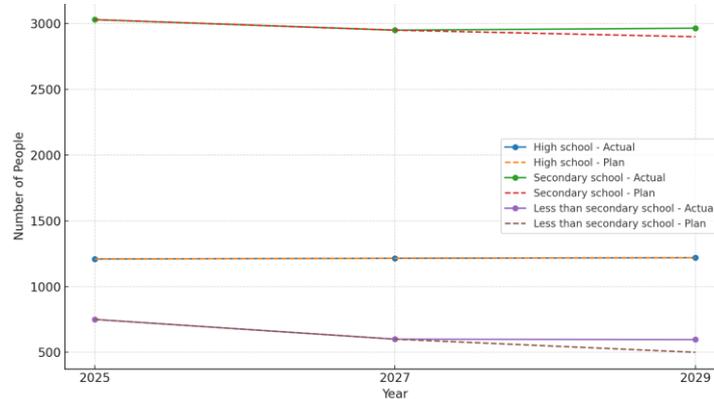


Fig. 5. Comparison of the planned and achieved qualification structure of employees with a budget limit

Fig. 5. clearly highlights that high school numbers match the plan, while secondary and less-than-secondary school numbers exceed the plan in 2029. The graph shows that the required reorganization would be completed as planned until 2027, and then, due to a lack of financial resources, there would be a deviation from the plan. Under a budget constraint of seven million euros, the workforce composition would exceed planned staffing levels by 65 employees with secondary education and 97 employees with less than secondary education. The model also allows for numerous other simulations. For example, if the limitation on the obligation to employ interns were removed from the model, 460 employees would have to be laid off, with a total cost of 9.3 million euros. It is also possible to find an optimal solution by setting the limitation to the maximum number of employees who can be laid off, etc.

7 Conclusion

This research demonstrates that optimizing human resources in the railway sector - particularly within complex, regulated systems like HŽI - requires a systematic, data-driven, and strategic approach. The developed Excel-based optimization model enables the company to minimize restructuring costs while aligning the workforce's quantitative and qualitative structure with operational and strategic goals. The model serves as a practical decision-support tool, enabling management to simulate restructuring scenarios, assess budget feasibility, identify the most cost-effective qualification upgrades, and provide objective data to guide negotiations with labor unions. Future research could apply the model to other railway undertakings, integrate demographic forecasting, develop dynamic simulations, link restructuring to performance metrics, and conduct cross-country comparisons to assess regulatory impacts across the EU.

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Design Recommendations for Level Crossings Located on Track Curves

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Abstract. Level crossings remain a critical safety concern, especially as railway networks are upgraded for higher speeds and increased traffic volumes. Although significant efforts are made to reduce the number of level crossings, many of them will remain in operation due to different local constraints. With the rise in operational speeds, the risks associated with level crossings become more severe, requiring the application of stricter safety standards and improved design practices. This paper presents the main principles for the design of level crossings. Although it is recommended for level crossings to be located in straight track, sometimes it is not possible to avoid locating them in curved track, even in the case of curves with high cant and narrow radius. Authors draw special attention to this type of level crossings, especially those located on double track railway lines due to their complex geometry. Additionally, authors recommend appropriate measures to improve road alignment while maintaining rail safety and operational efficiency. Implementing such solutions can significantly enhance the overall safety and functionality of level crossings in challenging track geometry.

Keywords: Railway, Infrastructure, Level Crossing, Curve, Design, Safety.

1 Introduction

Level crossings represent a long-standing safety issue for both road and rail transport systems worldwide. As the existing railway network is reconstructed to accommodate higher speeds and increased traffic volumes, the risks associated with level crossings, particularly in complex track geometry, become more pronounced. Notably, level crossing accidents are the second most common type of railway accident in the EU, with 224 fatalities and 186 serious injuries recorded in 2023 [1].

To address these safety challenges, the International Union of Railways (UIC) has developed a series of technical leaflets to guide infrastructure planning and safety practices. UIC Code 762 [2] serves as a critical reference for the design and operation of level crossings on railway lines with train speeds from 120 km/h to 200 km/h. Published as a supplement to UIC Code 761 [3], which outlines general principles for automatic level crossing systems, UIC Code 762 [2] provides targeted recommendations to address unique risks posed by higher-speed rail operations. These include enhanced warn-

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ing systems (as discussed in [4]), optimized barrier designs, and improved integration with centralized train control. The code emphasizes the minimization of the number of level crossings and, where they remain necessary, applying stringent safety standards to ensure reliable protection for both road and rail traffic [5].

Despite these guidelines, a notable gap exists in addressing level crossings located in track curves, particularly those featuring high cant and narrow radii. These configurations pose significant challenges due to their complex geometry and reduced visibility. Current standards provide limited practical guidance for such scenarios.

This paper aims to bridge that gap by presenting engineering solutions and safety measures specifically tailored to level crossings in curved track segments. The paper briefly outlines the core principles of level crossing design, and then focuses on crossings located in track curves, analyzing their specific risks and design constraints. Moreover, it presents engineering solutions that could be implemented in such cases. Finally, the last section presents key conclusions and recommendations.

2 Main principles for design of level crossings

An ideal level crossing assumes that both the railway track and the road are straight, with an intersection angle of 90° . Since road design parameters generally offer greater flexibility, the railway alignment should be prioritized in the design process whenever possible. Afterwards, the road alignment should be adjusted to conform to the railway design. When the railway is straight within the level crossing area, its grade should coincide with the road cross-level to ensure smooth and safe transport.

According to [6,7], level crossings should preferably be designed with a 90° intersection angle or less, but not below 60° (Fig. 1). In contrast, Handbook [8] prescribes a minimum intersection angle of 70° . Careful consideration of these geometric parameters is essential for maintaining transport safety and minimizing the risk of accidents.

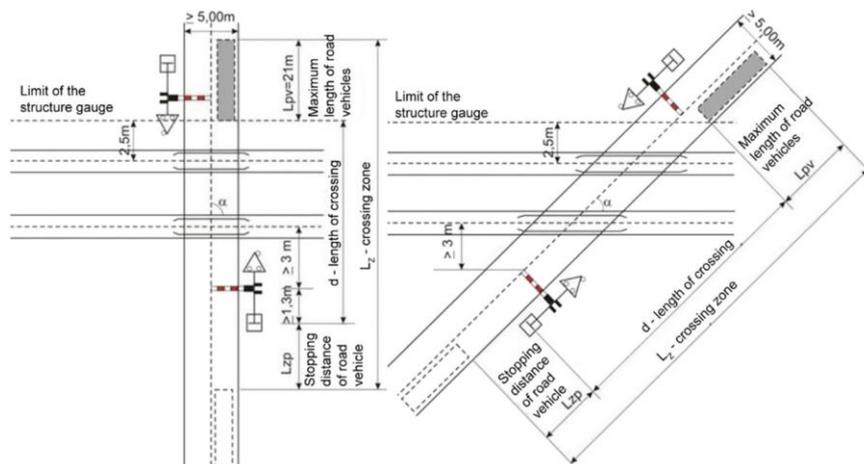


Fig. 1. Level crossing with intersection angle: $\alpha = 90^\circ$ (left) and $\alpha < 90^\circ$ (right) [6,7].

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The presence of a road curve in the vicinity of a level crossing compromises the available sight distance, potentially diverting the driver's focus to curve negotiation [9]. Furthermore, any road intersections near the level crossing should be located at a sufficient distance to mitigate the risk of collisions resulting from a vehicle being unable to clear the tracks prior to train passage (Fig. 2). This represents an issue that is often overlooked in the design of level crossings [10].

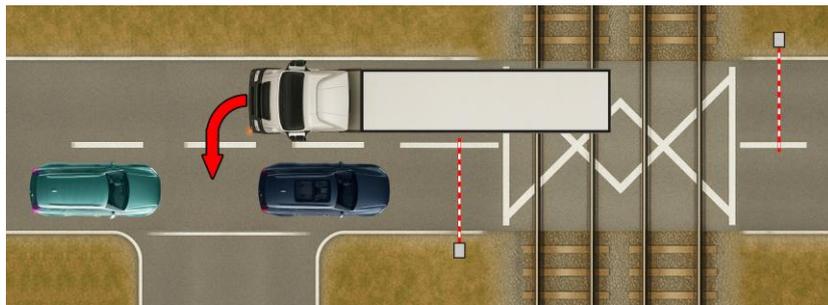


Fig. 2. Potential risk of a vehicle failing to clear the track at a level crossing.

In general, level crossings should not be located in track curves. In curved sections of a railway line at a level crossing, road vehicles approaching from the outer side of the curve have an advantage in sight distance over those approaching from the inner side. When avoiding a level crossing within a curved segment is not possible, the road gradient must be designed to correspond with the track cant. For railway lines with multiple tracks, maintaining a straight alignment at the level crossing is recommended. If a curve is unavoidable, the track should be designed without cant [11,12]. However, there are level crossings on existing double track lines in narrow radius curves, which cannot be replaced with an overpass or underpass in the near future.

The vertical alignment of the road at a level crossing shall match the elevation of the railway running surface over a 3.0 m distance measured from the track centerline on each side for single-track lines, or from the outermost track centerline for multi-track lines [6,7]. The longitudinal gradient of the road shall not exceed 3% over a minimum length of 20 m immediately preceding and following the level crossing (Fig. 3).

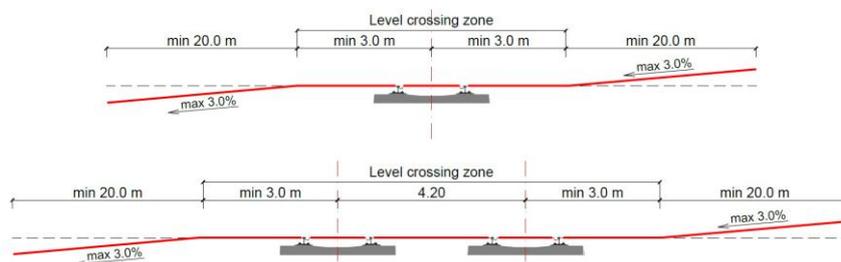


Fig. 3. Longitudinal profile of the road in the area of the level crossing on a single-track (up) and double-track (down) railway.

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Vertical curves on both approaches to a level crossing should comply with the requirements for road vehicle with the longest axle distance, in order to prevent vehicles from becoming stuck at the crossing and to avoid damage to both the pavement and the vehicle when passing over the vertical curve [11-13].

3 Level crossing in track curve

Fig. 4 presents the longitudinal road profile at a level crossing where the single-track and double-track railways are located in horizontal curves. In particular, Fig. 4 (down) displays complex vertical alignment of the road in the case of a double-track railway in a horizontal curve.

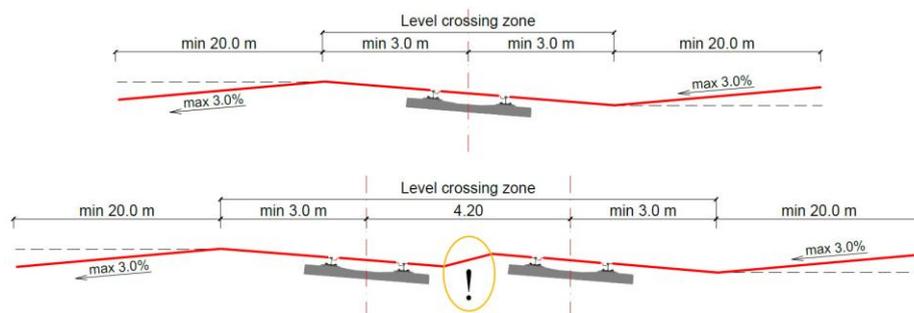


Fig. 4. Cases of longitudinal profile of the road at a level crossing in a track curve.

Minimum curve radius in the vicinity of level crossings is not explicitly defined by technical regulations. Nevertheless, certain recommendations can be derived based on allowable track cant values. For curves with the minimum radius, the upper cant limit is 150 mm, which corresponds to a maximum track cross-level of approximately 10%, given the standard track gauge of around 1500 mm.

Steep longitudinal gradients of the road surface at level crossings are generally discouraged due to the following concerns:

1. Safety risks: vehicles may experience difficulty stopping or starting on steep inclines, particularly under wet or icy conditions, thereby increasing the likelihood of collisions with trains;
2. Vehicle control issues: larger or heavier vehicles, such as trucks and buses, may stall or roll backward when attempting to cross uphill;
3. Traffic flow disruption: reduced crossing speeds on inclined approaches can lead to congestion, prolonging vehicle presence within the track zone and increasing the risk of incidents.

If a level crossing needs to be located in a track curve with a minimum radius due to significant constraints in the surrounding area, then one should first analyze the possibility of reducing the value of track cant. Value of track cant can be reduced, which im-

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plies an increase of cant deficiency and, consequently, increase of uncompensated lateral acceleration for the observed track curve. National technical regulations [14] allow three levels of uncompensated lateral acceleration: normal (0.65 m/s^2), minimum (0.75 m/s^2) and exceptional (0.85 m/s^2) value. Accordingly, Fig. 5 shows possible reduction of track cross level as function of uncompensated lateral acceleration.

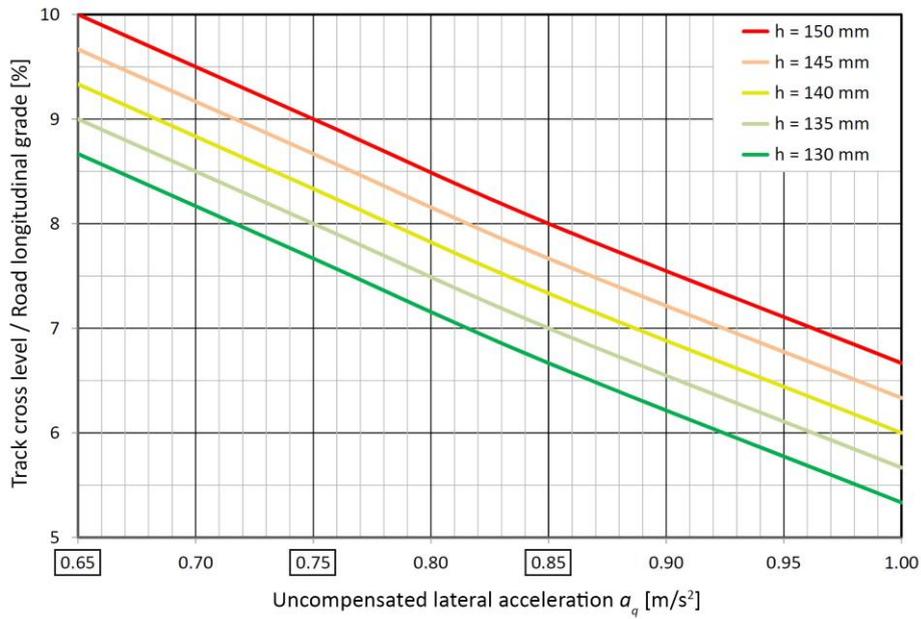


Fig. 5. Correlation between uncompensated lateral acceleration and track cross level.

According to Fig. 5, it can be concluded that the minimum value of uncompensated acceleration corresponds to a decrease in track cross level by 1% (15 mm lower cant), while the exceptional value of acceleration corresponds to a decrease in track cross level by 2% (30 mm lower cant). Therefore, for a minimum radius curve with 150 mm cant, it would be possible to reduce track cross level from 10% to 8% i.e. to reduce cant to 120 mm. Considering the maximum value of cant deficiency prescribed in [15], track cant could be reduced to 100 mm in a curve with a minimum radius, which coincides with uncompensated lateral acceleration of 1.00 m/s^2 and track cross level of 6.67%.

However, changing track cross level on a double-track railway would not solve the issue with the complex geometry of the road surface (Fig. 4, down). Therefore, the abrupt change between two tracks still remains the main concern. In case of track axial distance of 4.2 m, there would be height difference of 0.26 m on 1.02 m length, which equals to 25.5% (Fig. 6b). In this case, authors recommend changing the vertical alignment of either left or right track, depending on the local conditions, in order to achieve both track running surfaces in approximately the same plane (Fig. 6c). This

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solution provides uniform pavement geometry in level crossing thus enabling vehicles with large axial distance to traverse safely.

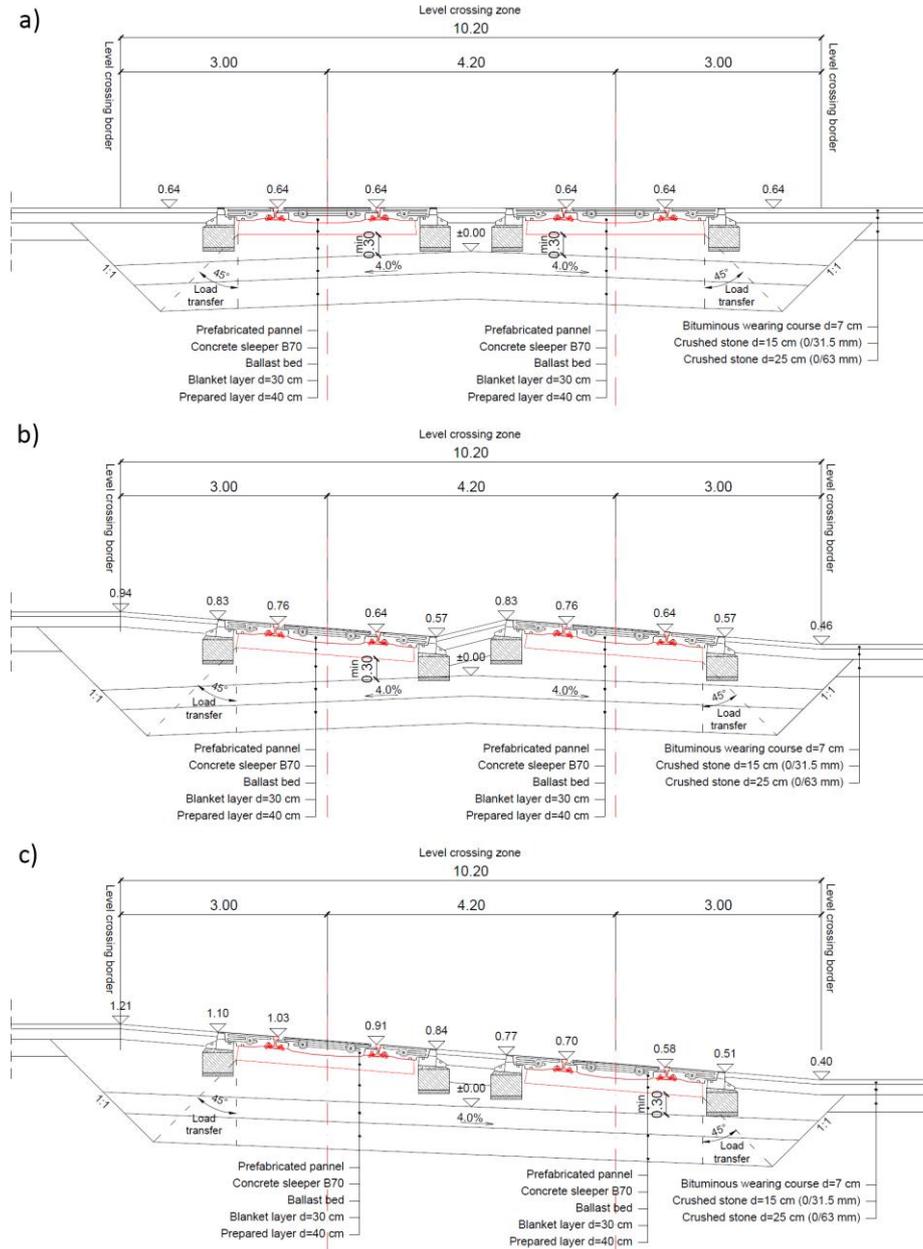


Fig. 6. Typical cross-sections of level crossing in case of: (a) straight track, (b) curved track, and (c) modified vertical alignment in the curved track.

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Authors recommend using Fig. 6a and Fig. 6c as typical cross-sections of level crossing on a double-track railway line for straight and curved track, respectively. On the other hand, the typical cross-section in Fig. 6b represents the solution that should be avoided due to significant traffic safety risks.

4 Conclusion

Level crossings continue to represent a critical point of vulnerability in modern rail transport, particularly as existing rail infrastructure is upgraded for higher speeds and increased traffic density. Consequently, efforts should be made to reduce the number of level crossings, while ensuring that those that remain are designed and maintained to meet the highest safety standards.

This paper outlines the main principles for the design of level crossings, with particular focus on level crossings located in track curves, especially those involving high cant and narrow radii on double-track railway lines. Such level crossings introduce additional traffic risks due to the complex vertical alignment of the road. Therefore, the authors recommend the application of appropriate engineering solutions to mitigate the specific risks associated with level crossings in curved track, which imply:

- reduction of track cross level, in accordance with permissible uncompensated lateral acceleration, in order to reduce the longitudinal grade of the intersecting road, and
- modifying the vertical geometry of either left or right track on double-track railway lines in order to achieve a simplified vertical profile of the road.

The implementation of the proposed recommendations is expected to enhance the safety and reliability of level crossings located on track curves. However, modifications to the vertical track geometry and the underlying substructure layers are only practical during the reconstruction of a substantial section of the railway line, including the road in the vicinity of the level crossing. Therefore, this approach is only feasible within the scope of upcoming railway modernization and reconstruction projects.

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RCF Irregularities on the Rail Head – Guidelines for Maintenance

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Abstract. The focus of the paper is on defining clear guidelines for the identification, monitoring, and management of these phenomena with the goal of extending the service life of both railway infrastructure and rolling stock, while also improving the overall efficiency of the maintenance system. The management of rail defects is approached as an integral part of both track superstructure and substructure maintenance systems. Modern non-destructive testing methods are recommended for rail inspection, including ultrasonic and eddy current techniques, which allow for the detection of internal and surface flaws without damaging the material. Control of defect development involves the use of grinding, rail head reprofiling, lubrication on curved track sections, and timely rail replacement in cases where the risk of fracture becomes critical. Special attention is given to dangerous combinations of multiple fatigue-related defects, which can significantly increase the risk of sudden failure. The paper contributes to the advancement of predictive and preventive maintenance strategies in modern railway systems.

Keywords: Railway, Rails, Rail Steel Fatigue, Rail Defects, Maintenance.

1 Introduction

Short-wavelength irregularities ($0 < \lambda \leq 1$ m) on the surface of the rail head within the wheel–rail contact zone have a significant impact on the reduction of rail service life in track. Managing their development remains an open issue, as there is still no unified maintenance strategy implemented by railway infrastructure managers (IMs) at the international level. The recommendations of the International Union of Railways (UIC) [1] and the European standards [2,3] provide only basic guidelines for managing the evolution of surface irregularities on rail heads.

The authors highlight the lack of consistent terminology in technical regulations related to rail defects caused by rolling contact fatigue (RCF) of rail steel in wheel–rail contact zones. This inconsistency may lead to misunderstandings and incorrect decisions by IMs during maintenance activities, potentially resulting in increased maintenance costs for infrastructure and rolling stock, as well as compromising railway traffic safety. A mismatch in terminology is observed between the most recent UIC recommendations [1] and European standards [2,3]. The authors emphasize the need to

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standardize the nomenclature of RCF rail defects, including the use of unambiguous numerical coding, without translating English defect names into national regulations.

This paper does not include an analysis of inspection methods, as the authors addressed this topic separately in [4], presenting modern non-destructive testing (NDT) methods that are effective for the inspection of RCF defects. A large number of studies report research results related to the management of RCF rail defects (Germany [5–9], the Netherlands [10–11], Sweden [12], Serbia [4, 13], Japan [14], etc.), highlighting the relevance and importance of this topic.

RCF is a fatigue process caused by rolling and sliding contact between wheels and the rail head. It results from the cyclic loading of rails and leads to fatigue-related damage, commonly referred to as RCF rail defects. Effective management of RCF and rail maintenance is essential to ensure the safety, reliability, and longevity of railway infrastructure. By clearly defining maintenance objectives, strategies, and plans, IMs can optimize resource utilization, reduce costs, and minimize the occurrence of rail defects, thereby maintaining optimal track performance throughout its service life. Rail maintenance involves a combination of technical, administrative, and managerial activities carried out over the rail's life cycle, aimed at preserving or restoring its condition to ensure that it continues to perform its intended function within the railway superstructure. Furthermore, maintenance management includes all managerial tasks that define maintenance objectives, strategies, and responsibilities, and ensures their implementation through tools such as maintenance planning, control, and the continuous improvement of both maintenance effectiveness and cost-efficiency. Maintenance objectives represent specific targets established and accepted for maintenance activities. These may include goals such as asset availability, cost reduction, environmental sustainability, and safety.

2 RCF rail defects – Guidelines for maintenance

RCF rail defects are observed on running rails across railway networks worldwide, including: (a) both conventional and high-speed lines, (b) heavy-haul, mixed-traffic, and passenger lines, and (c) rails in ballasted tracks as well as in slab track systems. A key feature in managing the occurrence and progression of RCF defects is that they develop in zones of high and complex contact stresses (Fig. 1). This enables the prediction of track sections that are particularly susceptible to RCF and allows preventive actions to be taken in advance, with the aim of delaying defect initiation and mitigating their growth rate.

Fatigue of rail steel in the wheel–rail contact zone involves a complex process of structural degradation, initiated by a subsurface micro-crack in the rail head that may lead to rail fracture under cyclic loading. For effective management of RCF defect development, the choice of appropriate NDT methods for in-track rail inspection is essential in order to identify defects at an early stage of development [4].

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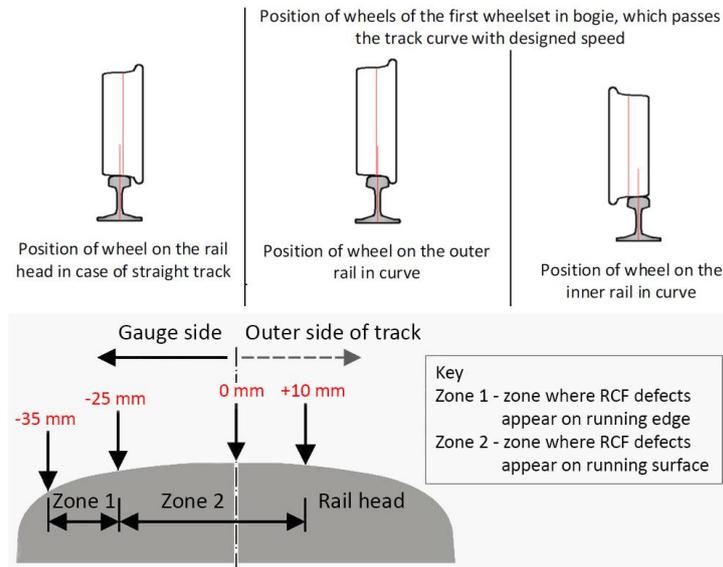


Fig. 1. Wheel/rail contact along the track and zones of RCF defect occurrence

The final and undesirable stage of RCF defect evolution is rail fracture. The fracture surface exhibits characteristic features (Fig. 2). The fatigue zone typically appears smooth and dark, with a clearly visible initiating crack that is linked to the running surface of the rail head, subjected to wheel contact. This specific appearance of the fracture cross-section enables simple visual identification of RCF defects (Fig. 2).

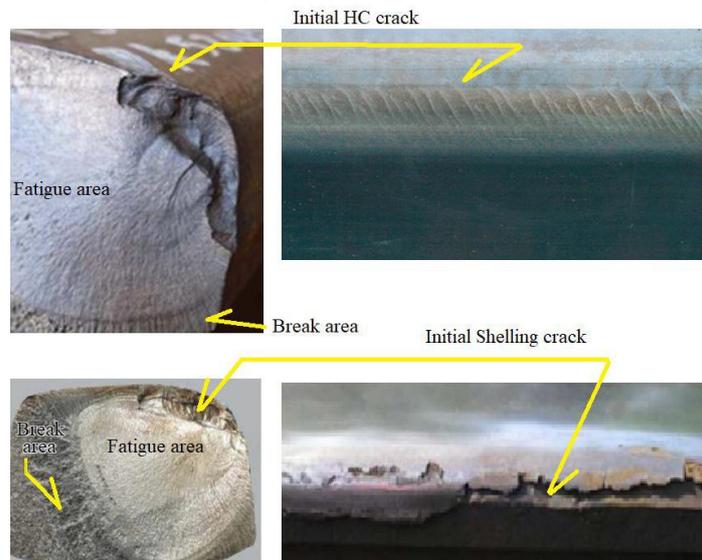


Fig. 2. Steel surface after break caused by RCF rail defects

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For comparison, Fig. 3 shows a defect caused by inclusions introduced during the rail manufacturing process. It is evident that the initiation point lies within the cross-section, in the fatigue zone of the steel, and is not connected to any surface cracking. This type of defect is extremely dangerous and unpredictable and its location can vary randomly. It may result in multiple sequential fractures. Such defects require a different maintenance approach, including urgent ultrasonic testing of rail volume, immediate rail replacement, and, if necessary, temporary securing with a fishplate.

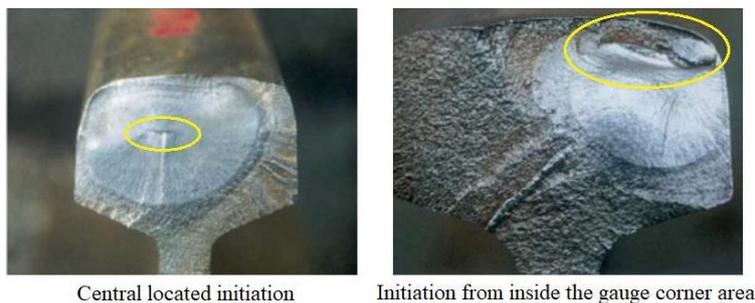


Fig. 3. Kidney-shaped fatigue crack due to internal inclusion (manufacturing defect)

Common types of RCF rail defects [13] include: head checking (HC), squat, bel-grospi, flaking, spalling, lipping, side cutting, and corrugation. Discrepancies in terminology, coding, and definitions between IRS 70712 and European standards EN 13231-5 and EN 16729-3 may cause misunderstandings and compromise safety. To mitigate this, IMs should standardize terminology, preferably adopting IRS 70712, and prepare a comprehensive rail defect handbook detailing defect locations, causes, detection methods, and maintenance practices. Particular attention is required for combined RCF defects (Figs. 4-7), which are often underrepresented despite their elevated fracture risk. Harmonization efforts by CEN/TC 256, combined with advances in inspection technologies and personnel training, are essential to ensure consistent and accurate defect identification across European railway networks.



Fig. 4. Combined corrugation and bel-grospi defects in the crossing zone (frog area) of a turnout on the Belgrade-Novı Sad railway line

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Fig. 5. The example of combined corrugation, squat and squat seed



Fig. 6. Squat cracking and local depression in aluminothermic welding



Fig. 7. Squat defect on the running edge affected by an HC defect

Defects appear with the formation of short wave corrugations having a depth of 0.03 mm. If these corrugations are not timely removed by grinding, belgrospi defects develop and can evolve into squat defects. The authors point out that a corrugation depth of 0.03 mm on the running surface of the rail head significantly increases the dynamic forces on the rail on high-speed lines. For this reason, this value is prescribed as the lower threshold for initiating rail head grinding activities. In urban environments, managing the development of this combination of defects is related to corrugation correction to reduce noise and vibration emissions. During a visual inspection of de-

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fects at Pančevo Varoš station, the presence of belgrospi-type defects was documented, appearing as so-called seeds for the development of future squat defects (Fig. 5).

Local heterogeneities of rail hardness in heat-affected zone of the aluminothermic weld can cause squat rail defect in weld zone (Fig. 6). Beside visual inspection, it is recommended to apply ultrasonic and eddy current testing in weld zone.

A particularly dangerous combination is the development of a squat defect on the running edge of the rail affected by HC defect (Fig. 7). This combination can lead to spontaneous rail fracture under a passing vehicle. When rail lubrication is used in curves, special attention must be paid to ensure that contamination does not mask surfaces infected by this hazardous combination of rail defects.

Since rails are a fundamental component of the track, their procurement, installation, and maintenance costs significantly influence the total life cycle cost (LCC) of the railway superstructure. IMs are increasingly driven to reduce expenses, making LCC considerations a crucial part of market strategies. This market-driven approach has led to improvements in existing rail steels and development of new steel grades.

Results from an international research project [15] demonstrate a correlation between curvature and rail degradation: wear predominates on curves with radii up to 1000 m, whereas RCF defects occur on curves with radii between 500 m and 5000 m. HC defect was considered the dominant type of RCF defect in this project.

Compared to standard R260 steel grade, R350HT with a thermally treated hard rail head exhibits approximately three times greater wear resistance and at least twice the resistance to RCF defects [15]. Many IMs have deviated from the 2005 UIC recommendations and developed their own steel grade selection strategies (Tab. 1).

Table 1. Overview of guidelines for steel grade selection on mixed-traffic railway lines

Radius [m]	<300	<400	<700	<800	<1500	<3000	>3000
UIC	R350HT		R350HT / R260		R260		
DB	R350HT ($\geq 30,000$ t/d)				R260		
DB new			R350HT ($\geq 50,000$ t/d)				R260
CH	R350LHT		R350LHT / R320Cr			R260	
AT	R350HT			R260			
SWE	R350HT			R260			
SWE (HH)			R350HT				R260
NOR		R350HT			R260		
UK				R260			
IT				R260			
BE, LUX		R350HT			R260		
NL	R350HT / R370CrHT			R370CrHT			R260
DK		R350HT			R260		
PL		R350HT			R260		
H		R350HT			R260		
RO		R350HT			R260		

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Rail support stiffness is a key factor influencing both the initiation and development of RCF defects. This correlation was confirmed through the inspection of squat defects at Pančevo Varoš station, performed by the authors.

Modern management of RCF defect progression primarily relies on rail reprofiling in the track. Different IMs adopt various reprofiling strategies based on their experience, expertise, and applicable technical regulations. Reprofiling extends rail service life, reduces maintenance costs, and enhances safety.

3 Conclusion

This paper examines the limitations of existing standards and emphasizes the necessity of harmonized terminology. A concept for a unified rail defect handbook, tailored to the operational framework of individual IMs is proposed. Further, it analyzes the role of systematic inspection, the application of advanced detection technologies, and the implementation of rail reprofiling as primary maintenance strategy.

Key findings in the paper include:

- Combined defects represent a critical safety risk due to their increased probability of rail fracture, but remain insufficiently addressed in current classifications.
- Steel quality and track substructure stiffness have a decisive influence on the initiation and propagation of RCF defects.
- Integration of defect characterization with structural and material considerations significantly improves the effectiveness of maintenance planning.

A harmonized classification system and a defect management framework are essential for improving the reliability and safety of railway infrastructure. The adoption of a unified rail defect handbook, supported by consistent terminology, systematic inspection, and advanced maintenance strategies, would provide IMs with a more robust toolset for RCF prevention and control. The authors particularly suggest:

- Collection of historical and current data on the rails within tracks, including structural characteristics, inspection and maintenance records, and documented defects.
- Analysis of these data to assess the current condition of the rails and to identify potential issues within the track, including the substructure.
- Development of interventions, repairs, or preventive measures aimed at maintaining or restoring the rails, the overall track structure, and rolling stock.

Conclusions of this paper should be implemented in technical regulations for railway infrastructure maintenance.

Acknowledgment

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Logistics and supply chain management

Last-Mile Challenges and Trends: Two-Way Impacts on Modern Supply-Chain Dynamics

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Abstract. Modern supply chains (SC) are rapidly transforming under digitalization, adapting to complex customer demands, and embracing sustainability imperatives. In this dynamic environment, optimization is shifting to the final distribution segment, where high customer expectations meet operational constraints. As a result, last-mile delivery (LMD) has become a major source of cost and risk across the logistics network. This paper analyzes the interdependencies between LMD practices and the broader SC. This paper aims to identify the main challenges and then examine the trends that mitigate them, specifically how these trends reduce costs, shorten delivery times, and enhance sustainability. Optimizing last-mile service increases customer satisfaction and overall supply-chain efficiency, while innovations in LMD delivery drive greater requirements for inventory, visibility, and flexibility across the network. Optimizing the LMD by reducing costs, greenhouse-gas emissions, and increasing customer satisfaction lowers inventory requirements and shortens order cycles. More accurate demand forecasting and greater end-to-end visibility, in turn, further enhance LMD, creating a bidirectional feedback loop that lifts overall SC performance. These findings offer actionable insights for practitioners seeking to develop integrated last-mile strategies that balance cost, service quality, and environmental impact.

Keywords: Last-mile delivery, supply chain, sustainability, challenges, trends.

1 Introduction

Last-mile delivery (LMD) represents the final stage, but also the most expensive, complex, and environmentally significant segment of the supply chain (SC). The importance of this segment is underscored by the fact that LMD accounts for approximately 41% of total logistics costs, which is significantly higher than the costs of storage and transportation [1, 2, 3]. This is largely driven by rising consumer expectations for delivery within two to three days, with nearly half of customers switching to another seller if this deadline is not met. These pressures have intensified with the growing share of e-commerce in total goods turnover. Consequently, optimizing

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LMD has become crucial for the profitability and sustainability of modern SC. However, meeting such expectations involves complex challenges, including urban congestion and CO₂ emission restrictions, fragmented demand (with an increasing number of small doorstep deliveries), a lack of warehousing space in urban areas, and the delicate balance between delivery speed and cost efficiency. At the same time, several transformative trends are reshaping how companies approach LMD. These include real-time shipment tracking, micro-fulfillment hubs located closer to end customers, electrification and micromobility of delivery fleets, and the deployment of autonomous vehicles and drones. While these trends offer potential solutions, they also raise new questions regarding regulation, interoperability, and investment priorities within SC [4, 5].

This research aims to systematically identify the key challenges of LMD in contemporary SC. To achieve this, a brief literature review was conducted to determine the direction and focus of the study. Several relevant papers from the past five years in the field of LMD were selected based on citation count and publication in reputable academic journals. Based on the challenges identified through the literature, the paper further analyzes how dominant logistics, technological, and sustainability trends affect the intensity and nature of these challenges. The contribution of this paper lies precisely in offering a deeper understanding of how modern LMD trends influence the transformation of SC under current business conditions.

The paper is structured as follows. After the introduction, Section 2 analyzes the LMD problem through a review of relevant literature. Section 3 presents in detail the key challenges of LMD in modern SC. Section 4 outlines the dominant trends in LMD. Section 5 provides a discussion of the identified challenges and trends, synthesizing their interrelation. Finally, the conclusion offers a summary of the entire paper and reflects on the role and complexity of LMD in today's SC landscape.

2 Literature Review

LMD represents the most demanding segment of the SC, as it generates a dominant share of operational costs, CO₂ emissions, and urban congestion, while simultaneously shaping the behavior and satisfaction of end users. In the academic literature, many authors have examined LMD from different perspectives. Accordingly, this section analyzes several relevant studies from the past five years that explore this topic. The goal of the literature review is to identify the main areas of interest, which aspects of LMD have been most extensively studied, and to determine the research direction of this paper accordingly.

Ghezzi and Cavallo [6] examine how agile business models influence the development and competitiveness of LMD, particularly in the context of same-day delivery services that have become prevalent in urban areas. The authors emphasize the increasing demand for fast deliveries, driven by digitalization and e-commerce. They conclude that agility has become a key competitive advantage in modern SC, espe-

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cially under unpredictable conditions such as those triggered by the COVID-19 pandemic.

Gatta et al. [7] explore the role of interactive decision-support tools in the development of city logistics strategies, with a particular focus on LMD. They argue that traditional strategies often fail to address the complex challenges of LMD because they neglect ongoing market changes. Their study shows that involving end users in the decision-making process increases the acceptance of proposed solutions, such as the introduction of micro-consolidation centers or vehicle access restrictions during specific time windows.

Mangiaracina et al. [8] analyze how sustainability influences user behavior and satisfaction in the LMD context. Their findings indicate that SC actors face growing pressure to improve the environmental performance of LMD, which (alongside high costs) is characterized by unfavorable working conditions, increased CO₂ emissions, and urban traffic congestion. The authors conclude that systemic changes in user behavior and preferences are essential prerequisites for implementing sustainable delivery solutions in the LMD phase.

Rai et al. [9] investigate the potential of crowd logistics as a sustainable solution to LMD challenges. They highlight how this model can reduce the need for additional vehicles and enhance the utilization of existing resources. The paper also outlines the benefits and limitations of crowd logistics in LMD, with a specific focus on sustainability aspects.

Yildizbasi and Felekoğlu [10] apply a hybrid multi-criteria decision-making (MCDM) model to evaluate various LMD options based on sustainable development goals. Their model ranks traditional fossil-fuel vehicle delivery, electric vehicles, consolidated deliveries, and bicycle or micromobility-based delivery. The MCDM approach incorporates all key sustainability dimensions. Results show that electric vehicles and consolidated deliveries receive the highest rankings.

Shaklab et al. [11] propose an experimental framework for artificial intelligence (AI) assisted autonomous delivery robots in the context of LMD. Their research integrates AI algorithms, the Vehicle Routing Problem (VRP), and safety technologies to demonstrate how advanced automation can enhance the efficiency and reliability of LMD. They conclude that the combination of autonomy and intelligent analytics enables faster, more accurate, and safer deliveries. However, they stress that legal frameworks, user acceptance, and implementation costs are critical factors for broader adoption.

Based on the reviewed literature, it is evident that LMD is explored from multiple perspectives. Researchers investigate user behavior and sustainability impacts, the development of alternative delivery models, and the application of advanced technologies and business models in LMD. Although their approaches vary, all studies recognize LMD challenges in terms of cost, efficiency, flexibility, and sustainable development. In the context of increasingly complex urban and digital logistics environments, authors seek efficient, sustainable, and user-centric solutions. As markets remain dynamic and consumer preferences constantly evolve, the literature affirms that LMD continues to be one of the key challenges of modern SC, both from the perspec-

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tive of operational optimization and concerning its social and environmental impact. Accordingly, this paper focuses on analyzing the contemporary challenges and trends in LMD.

3 Analysis of Key Challenges in LMD

LMD represents the final stage of the SC, during which goods are transferred from regional warehouses or distribution centers directly to the end user, whether to the customer's address or a designated pickup point. The LMD phase is critical, as it constitutes the first and only direct contact with the customer, which directly affects customer satisfaction. At the same time, LMD is the most expensive and participant-intensive part of the delivery process. LMD costs often account for a significant share of total delivery expenses due to the frequency of small shipments, unpredictable routing, urban parking difficulties, and the need for high flexibility and speed [4, 9, 12].

The demands of modern e-commerce for increasingly faster, cheaper, and more flexible delivery options further highlight the critical nature of LMD, which remains the most costly and challenging phase of the entire SC [6]. In this context, the analysis of relevant research reveals four key challenges that shape the future of LMD optimization: growing volume of shipments in LMD, sustainability and environmental impact of LMD, costs of LMD, and time constraints in LMD. Addressing these challenges is essential for achieving sustainability, efficiency, and customer satisfaction. Each of the identified challenges is explained in more detail below [6, 7, 9].

3.1 Growing Volume of Shipments in LMD

The first challenge is the increasing volume of parcels, directly influenced by the trend of urbanization. The expansion of urban areas and the growth of e-commerce continue to raise the number of customer demands, i.e., the number of packages requiring LMD. For example, parcel volumes in Germany rose from 1.69 billion in 2000 to over 4.4 billion in 2023, while Amazon's volume in the U.S. increased from 3.5 billion to 6.5 billion packages annually between 2019 and 2022. These changes require scalable and flexible logistics capacities that can absorb volume peaks and adapt to traffic, customer availability, and urban constraints [12, 13].

3.2 Sustainability and Environmental Impact of LMD

Sustainability (in its ecological dimension) has become a non-negotiable topic in modern business. The growing number of vehicles involved in LMD directly contributes to traffic congestion, air pollution, and noise in urban areas. As a result, regulators and consumers are increasingly demanding environmentally friendly solutions, ranging from the adoption of "green" vehicles and the establishment of micro-

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consolidation centers to the implementation of parcel lockers. Such solutions can reduce CO₂ emissions by hundreds of tons annually [6, 7, 12].

3.3 Costs of LMD

Cost optimization remains one of the most significant challenges in LMD. Operational costs include fuel consumption, vehicle maintenance, and labor. Overall costs are further increased by urban traffic congestion and limited parking availability. The average cost per delivery ranges from €2 to €6, and inefficient routing combined with high rates of failed first-attempt deliveries (ranging from 12% to 60%) places additional strain on logistics budgets, increasing operational expenditure and reducing profitability [12, 13].

3.4 Time Constraints in LMD

Modern consumer behavior increasingly demands same-day or next-day deliveries, often extending into evening hours, significantly shortening the timeframes for planning and execution. Weekly delivery loads peak at the beginning of the workweek, especially on Mondays, while seasonal peaks during holidays and sales periods create unpredictability in delivery flows. Therefore, LMD solutions must be highly flexible and scalable to quickly adapt to fluctuations in order volumes and traffic conditions.

The identified challenges illustrate the complexity of establishing an efficient, sustainable, and profitable LMD system. Understanding and overcoming these challenges is crucial for maintaining competitiveness in the dynamic e-commerce environment. Accordingly, the next chapter presents the key trends in LMD that offer innovative solutions and strategies for optimizing these identified challenges [6, 9, 12].

4 Contemporary Trends in LMD

The LMD market continues to experience significant growth, driven by the rapid expansion of e-commerce and increasingly dynamic consumer demands. The global market value of LMD, viewed here as the total annual revenue that carriers, fulfillment service providers, and technology providers generate for their services (i.e., the cost side, not the value of the goods), is projected to increase by more than USD 51 billion between 2025 and 2029 [14]. Nearly half of all companies are already investing in data collection and analytics to improve delivery efficiency and reduce costs, as 66% of consumers expect next-day delivery, while 50% expect same-day service [1, 14]. This trend not only reinforces the pressure to reduce costs, given that LMD accounts for 41 of total SC expenses, but also underscores the need for clean technologies to mitigate the environmental impact of delivery operations [1, 2, 3, 5].

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Simultaneously, technological advancements and shifting user behavior are shaping the main LMD trends, which can be grouped into five core categories. Below is a detailed overview of these emerging trends in LMD [1, 5, 14].

4.1 Micro-Fulfillment and Urban Consolidation Centers

Micro-fulfillment centers (MFCs) are small, automated facilities located in urban areas, whereas urban consolidation centers (UCCs) are positioned on city outskirts and consolidate shipments from various sources before distributing them via eco-friendly fleets into city centers. In the LMD context, MFCs enable same-day or next-day delivery by significantly reducing the distance to customers. UCCs reduce urban traffic congestion and emissions by consolidating a large volume of shipments into fewer delivery runs. As a response to growing demands for faster, more flexible, and more sustainable delivery services, these solutions are expanding rapidly through pilot “dark store” projects and increased investment in decentralized logistics infrastructure. Cities like Paris are testing these models in underground parking garages to ease peak-hour traffic [16].

4.2 Fleet Electrification

Fleet electrification refers to the deployment of electric light commercial vehicles (EVs) and cargo bikes in LMD to drastically reduce CO₂ emissions, comply with zero-emission zones, and lower operating “fuel” costs by using electricity instead of fossil fuels, all while generating less noise in urban environments. In LMD, EVs and cargo bikes allow for more frequent deliveries at lower maintenance costs, while complying with environmental regulations and consumer expectations for sustainable delivery options. This trend is gaining momentum due to stricter city regulations on pollution, subsidies for EV purchases, and public pressure on companies to adopt greener practices, thus ensuring competitive advantage and long-term operational sustainability. Companies such as DHL, Amazon, and FedEx are already transitioning to electric delivery vans, while European firms have collectively ordered 15,000 new EV vans from the joint venture between Renault, Volvo, and CMA CGM [15, 16].

4.3 Autonomous Vehicles

Autonomous delivery vehicles, including robotic couriers and drones, enable 24/7 operations and offer a solution to the growing shortage of delivery drivers. These technologies shorten delivery routes by going directly to the customer’s doorstep. With advanced sensors and navigation algorithms, these systems can independently plan optimal urban routes, avoid traffic congestion, and minimize human contact. This reduces operational costs, accelerates deliveries, and meets consumer expectations for faster and more reliable service. In Austin, Veho is testing robotic couriers that can climb stairs and doorsteps, while several drone-based pilot projects are already delivering prescriptions and parcels up to 5 kg [15, 17].

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4.4 Parcel Locker Networks and Click-and-Collect Points

Parcel locker networks and click-and-collect points enable consolidated deliveries to self-service lockers or designated pickup locations, virtually eliminating failed first attempts (with success rates close to 100%), reducing vehicle parking time, and lowering CO₂ emissions per parcel. In practice, couriers deliver a large number of packages to centralized locker networks or pickup points, allowing customers to retrieve their parcels at their convenience, thereby enhancing route efficiency and reducing urban traffic congestion. These systems are gaining traction as scalable solutions for handling growing shipment volumes, improving customer experience, and supporting sustainability goals by reducing door-to-door trips in densely populated urban zones. Automated lockers in London and Belgrade metro stations have shown CO₂ reductions of up to 30% per parcel [15, 18].

4.5 AI-Based Dynamic Routing and Gig-Crowd Fleets

AI-based dynamic routing uses real-time algorithms that integrate traffic data, weather conditions, and incoming orders to optimize delivery routes, reduce mileage, and maximize vehicle utilization. Gig-crowd fleets consist of independent drivers engaged “on demand” through digital platforms, allowing for flexible resource allocation and rapid adaptation to unexpected conditions. Studies show that such models can reduce total mileage by up to 15% and cut average delivery time by approximately 8% [15].

5 Discussion

Contemporary trends in LMD are no longer confined to the final segment of the SC; rather, they are generating systemic transformations that extend to demand planning, inventory management, and the overall design of the SC. The introduction of MFCs, fleet electrification, and AI-powered routing simultaneously enhances the operational efficiency of deliveries but also exerts pressure on storage capacities and increases the complexity of tactical planning in the upstream stages of the SC. At the same time, growing customer expectations for fast and environmentally friendly deliveries are driving the tightening of key performance indicators (KPIs), such as on-time, in-full (OTIF) delivery and CO₂ emissions per shipment, thereby establishing unified compliance standards across the entire SC.

Fleet electrification and the expansion of parcel locker networks require fine-tuned route optimization, coordination of charging infrastructure, and the strategic selection of locations, all of which significantly impact the design of LMD systems. On the other hand, the implementation of gig-crowd fleets and advanced AI-based routing algorithms demands costly infrastructure, high-quality real-time data, and flexible contracts with external service providers. As such, LMD increasingly acts as a driver of innovation across the entire SC, particularly in terms of sustainability and adaptation to dynamic market environments.

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Shifts in consumer behavior, especially the rise in small, frequent orders, are disrupting traditional distribution rhythms, resulting in lower vehicle utilization rates and increased congestion in urban areas. Logistics capacities must become agile and scalable to effectively manage seasonal demand fluctuations, which necessitates a redefinition of consolidation and micro-delivery strategies. Trends such as AI-based routing and parcel lockers can significantly improve OTIF rates through more accurate planning and a reduction in failed delivery attempts. Likewise, fleet electrification and the consolidation of shipments within urban micro-hubs can reduce CO₂ emissions per package. However, if procurement and ordering processes are not optimized (e.g., due to empty return trips or inefficient routing), both costs and emissions may rise despite the implementation of advanced technologies. An integrated approach that aligns data and objectives across all SC actors remains a fundamental prerequisite for sustainable improvement in these key performance indicators.

6 Conclusion

In modern SC, LMD is gaining increasing significance due to market dynamism, technological advancement, the rise of e-commerce, and shifts in consumer behavior. While LMD offers numerous advantages, such as faster deliveries and greater flexibility, its operational complexity, high costs, and sustainability challenges make it one of the most demanding phases in logistics [19]. Moreover, LMD has emerged as one of the most critical areas of innovation in logistics and a convergence point for various contemporary business challenges [15]. These benefits, alongside the complexity and limitations, illustrate the bidirectional nature of LMD's influence.

On one hand, trends such as micro-fulfillment centers, parcel locker systems, fleet electrification, and autonomous vehicles exert pressure on the rest of the SC. These developments require more precise planning, improved inventory coordination, enhanced communication among all stakeholders, increased costs, and more agile distribution models. On the other hand, changes within the SC itself, such as the rise in small orders, seasonal demand fluctuations, and supply instabilities, directly impact the efficiency and sustainability of LMD operations [20]. This interdependence demonstrates that LMD is no longer a passive component of the SC but an active agent influencing strategic decision-making, infrastructure development, and overall operational performance. These bidirectional effects are particularly evident through key performance indicators such as OTIF delivery and CO₂ emissions per shipment, which today serve as benchmarks for compliance and sustainability across the entire SC.

In this context, effective LMD management requires strong coordination and collaboration among all SC participants to ensure flexibility, accuracy, and environmental responsibility at every stage. LMD can no longer be viewed solely as an operational phase; it has become a strategic lever that shapes the entire SC. Its transformation necessitates a holistic, data-driven network design, flexible infrastructure, partnerships, and the integration of sustainability KPIs. Future research should focus on

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quantifying the synergistic effects of integrated solutions and identifying optimal transition points from traditional to digitally intensive distribution models.

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The Role of the South Caucasus in the Development of the Middle Corridor: Opportunities, Challenges, and Solutions

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Abstract. Located at the crossroads of Eastern Europe and Western Asia, Caucasus has long been a nexus for trade routes for millennia. Its position along the ancient Silk Road, connecting the Mediterranean world with the Far East, enabled a dynamic exchange of goods, ideas, and cultures. As a keystone of the Middle Corridor, the geographic significance of Caucasus extends beyond its borders, shaping global transportation links. The South Caucasian countries' strategic location between the Black and Caspian Seas establishes its role in international trade and transport networks. Batumi, Poti, and the under-construction Anaklia Port are major maritime trade hubs, handling cargo for Europe, Central Asia, and beyond. Looking ahead, Georgia faces both opportunities and challenges in strengthening its role in the Middle Corridor. Rapid globalization, technological advancements, and geopolitical dynamics present new trunk-roads for economic growth and integration. Georgia's route is a vital component of the Middle Corridor. Due to its geographic location, this transforms Georgia not only as a logistical hub but also as a critical Europe-Asia transport route and connecting corridor between China and Europe. This requires developing logistical infrastructure and implementing modern technologies. The primary objective in this direction is to establish a network of freight transportation centers within the corridor and to integrate them into the global system of intermodal transportation. Therefore, our goal is to study and master the scientific approaches to designing a network of freight transportation centers and a specific center, as well as the practical methods of planning and research techniques.

Keywords: Caucasus, Georgia, Middle Corridor, transport networks, globalization, Europe-Asia, logistical hub, freight flows, digital technologies.

1 Introduction

The landscape of global trade and commerce has undergone significant transformations, driven by technological advancements, shifts in consumer behavior, and

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evolving market trends. In this dynamic environment, logistics hubs play a key role in ensuring the seamless flow of goods and services. They serve as critical nodes within supply chain networks. In Georgia, a crucial gateway in the Middle Corridor, the development of a logistics hub is a timely and interesting field of study, given the complex interaction of trade routes and freight distribution. The location of the Caucasus countries on the Middle Corridor route is shown in Figure 1.



Fig. 1: The Middle Corridor Route

Located at the crossroads of Europe and Asia, Georgia has a unique geographical advantage that makes it a potential logistics hub. Given the country's growing importance in regional and international trade, it is crucial to understand the factors influencing the establishment and development of logistics centers within its borders. Furthermore, analyzing the structure of freight distribution within Georgia is essential for optimizing logistics operations, increasing supply chain efficiency, and promoting economic growth.

The purpose of this paper is to study the multifaceted dynamics of the formation of logistics centers in Georgia and their impact on freight distribution. By synthesizing theoretical frameworks with empirical evidence and case studies, the research aims to clarify the key factors that determine the location, design, and operational strategies of a logistics center in Georgia. The research also aims to identify the distribution of trade activities, logistical problems, and opportunities for improving transport links both within and beyond Georgia by studying the structure of freight flows. The research methods will include inductive and deductive approaches based on the study and analysis of the existing situation, as well as the method of processing research results with mathematical statistics. The study also uses a logistics process modeling method. The practical results of this research will allow us to develop valuable insights and practical recommendations that will pave the way for the countries of the Middle Corridor and Georgia toward a more efficient, sustainable, and interconnected logistics ecosystem.

The Middle Corridor project aims to ensure more efficient and reliable communication between the countries of Asia and Europe, as well as the safe and commercially profitable transportation of goods [1].

2 The Role of Freight Centers

Logistics centers, also known as distribution centers or freight hubs, are strategically located facilities that play a crucial role in the supply chain management process. These centers serve as key points for the storage, consolidation, and distribution of goods and materials, facilitating the efficient movement of products from suppliers to consumers [2]. The project includes:

- Study the parameters of traffic flows, analyze their patterns, assess the modes of transport movement, model traffic flows considering real road conditions, and develop methods for calculating pollutant emissions. Create maps of pollutant levels and evaluate environmental conditions on major highways.
- Create a map of the transport system's operation, identify workplaces, determine parameters, and assess technical and economic effects using modern automated and artificial intelligence (AI) based systems.
- Coordinate the loading and unloading of terminals and railways, select the location of transfer platforms, research and optimize their design parameters, and optimize network routes.
- Define the technical characteristics of modern terminal equipment and facilities, and plan infrastructure and digital communication systems in accordance with international standards and modern AI-based technologies.

The current geopolitical conditions necessitate political efforts. The control of transport policy can be managed at three different levels: transport regulation, transport infrastructure, and transport processes [3]. The effectiveness of logistics can be evaluated using several key indicators that help assess how efficiently a logistics system functions in a particular region [4]. In our research, we used the following indicators.

Key Indicators for Logistics Evaluation:

- Infrastructure Indicators: The development of roads, railways, ports, and airports; the accessibility of logistics hubs.
- Transport Efficiency: The speed and availability of transportation, as well as the cost and time of moving freight.
- Warehouse and Distribution Indicators: The availability of warehouse infrastructure and the efficiency of distribution networks.
- Connectivity and Integration: Regional and global connectivity, and the possibility of multimodal transport.
- Taxes and Customs Procedures: The transparency and flexibility of customs administration, and the duration of customs procedures.
- Technological Infrastructure: Digitalization, tracking and analytics systems, and data management platforms.
- Workforce Qualification and Labor Resources: The level of professional education and the availability of a qualified workforce.

Despite the progress made, many challenges remain before the Middle Corridor can become a fully-fledged regional transit and logistics hub. Work on improving

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transport infrastructure and services must continue until existing limiting factors are completely eliminated [5]. The challenges in implementing the Middle Corridor can be divided into three main categories: those stemming directly from technical operations, the competitive environment, and those resulting from a complex security situation [6].

The main land route of "TRACECA" is the most important part of the South Caucasus' "Middle Corridor." Thanks to its favorable geographical location, Georgia [7] has become a vital transport link—a bridge between Europe and Asia, connecting China and Europe. Accordingly, by developing transit and logistics infrastructure and technologies, the South Caucasus can gain significant economic benefits. This is because the Middle Corridor is a strategic transport route that connects China and East Asia with Europe via the Black Sea, the Caucasus, and Turkey. Its relevance is growing, and Logistics Performance Index (LPI) is a critical factor in strengthening the corridor's competitiveness. For the countries on this route, improving LPI indicators is essential to make the corridor a globally competitive and attractive option for freight transit [8].

Recommendations:

- Focusing on infrastructure investments.
- Promoting digital transformation in customs and logistics.
- Strengthening international cooperation with neighboring countries.
- Analyzing individual LPI sub-indicators for better political and economic decisions.

The Logistics Performance Index (LPI) published by the World Bank [9] is one of the most authoritative sources for comparing logistics systems between countries. It assesses six key components:

1. Customs Efficiency: 2.6 points
2. Quality of Infrastructure: 2.3 points
3. Ease of Arranging International Shipments: 2.7 points
4. Quality of Logistics Services: 2.6 points
5. Tracking and Tracing Capabilities: 2.8 points
6. Timeliness of Shipments: 3.1 points

Table 1. The Logistics Performance Indexes of the involved countries

Country	2007	2014	2018	2023
Georgia	-	2.51	2.44	2.7
Azerbaijan	2.29	2.45	-	-
Armenia	2.14	2.67	2.61	2.5
Turkey	3.15	3.5	3.15	3.4
Kazakhstan	2.12	2.7	2.81	2.7
Uzbekistan	2.16	2.39	2.58	2.6
Turkmenistan	-	2.3	2.41	-
China	3.32	3.53	3.61	3.7

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The Middle Corridor is a strategic transport route that connects China and East Asia with Europe via the Black Sea, the Caucasus, and Turkey. Its importance is growing, and Logistics Performance Index (LPI) is a crucial factor in strengthening the corridor's competitiveness. For the countries located on this route, improving LPI indicators is essential to make the corridor a globally competitive and attractive option for freight transit [9]. Therefore, it is necessary to design this network and specific freight centers, as well as to study and apply scientific approaches for practical planning and research methods. The principles of our projects for creating such a center are given in [10].

The research includes both inductive and deductive methods, based on the study and analysis of the current situation. It also uses a method for processing research results with mathematical statistics, as well as a logistics process modeling method.

The freight centers to be created must perform the following primary and secondary functions [11]:

Primary Activities:

- Intermodal and long-distance transport by all modes (especially using combined transport).
- Local freight collection and distribution.
- Storage of all types and physical conditions of cargo, including specialized warehouses (e.g., for dangerous goods and refrigerated storage).
- Freight handling services (e.g., packaging, kitting).

Secondary Functions:

- Preparation, maintenance, servicing, and repair of transport vehicles, containers, and equipment.
- Development of special infrastructure, such as railways, parking lots, transport management systems, electricity supply networks, and waste disposal.
- Facilities for related internal services, such as customs, postal services, public transport, banking, insurance, and security services.
- Parking areas for trucks and dangerous goods.
- Information systems, consulting, and training.

According to statistical data [8], the majority of freight on the main roads of the South Caucasus is transported by medium and heavy-duty trucks. This creates several problems:

- The main roads are congested daily with thousands of trucks.
- Energy consumption for freight transport has increased by approximately 30% due to this congestion.
- Air pollution has significantly increased due to diesel vehicles emitting harmful substances, which affects both human health and the environment.

This problem can be solved by collaboration between the two competing transport modes—road and rail—by combining their strengths into a single logistics transport system: rail for long-distance, planned, low-emission transport, and trucks for flexible "door-to-door" delivery, with direct freight flows to terminals (stations) for combined

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transport. This approach is already used effectively in many developed European countries.

According to our research, implementing a combined logistics transport system in the Caucasus will significantly improve road safety, reduce freight transport costs by up to 30%, and improve the environmental situation by sharply reducing vehicle emissions [12].

3 The Role of Freight Centers

- Studying the parameters of transport flows, analyzing their patterns, evaluating the operating modes of vehicles, modeling transport flows considering real road conditions, and developing methods for calculating pollutant emissions. Also, creating maps of pollutant levels and assessing the environmental situation on major highways.
- Creating an operational map of the transport system, identifying workplaces, determining parameters, and evaluating the technical and economic effects using modern automated and artificial intelligence (AI)-based systems.
- Coordinating the loading and unloading of terminals and railways, selecting the location of unloading platforms, researching and optimizing their structural parameters, and optimizing network routes.
- Defining the technical characteristics of modern terminal equipment and facilities, and planning infrastructure and digital communication systems in accordance with international standards and modern AI-based technologies.

Implementing digital technologies includes the following topics:

- The role of IT in logistics digitalization.
- Considerations and approaches in the digitalization process.
- Problems that transport and freight forwarding companies face during digital transformation, and common obstacles.
- The main advantages of digitalization in logistics.
- Will digitalization become the core business of logistics service providers?
- Can medium-sized logistics companies participate in this process, or is it only for large enterprises?
- How digitalization is changing intralogistics.

4 Integration and Harmonization

The implementation of this project also raises the issue of integrating and harmonizing Middle Corridor logistics centers with global intermodal transport networks. This requires the harmonization of relevant legislation in all participating countries, as well as the involvement of the World Bank. The reconstruction of railways is also on the agenda. Preparations are underway for the construction of the Anaklia deep-water port. Concurrently, active research is being conducted on the parameters of freight

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and transport flows, which makes it possible to assess road safety, environmental conditions, and challenges along this corridor.

Below are the results of our research analysis on the indicators for freight transportation from China to Georgia via the Middle Corridor:

5 Freight Cost Trends (2020–2024)

- While transport costs have decreased compared to air freight, both sea and combined (sea + rail) transport still have high FEU (Forty-foot Equivalent Unit) costs from China to Georgia.
- The trend shows that combined transport is becoming more competitive than sea transport in terms of efficiency and cost-effectiveness.
- In general, land transport remains the most expensive mode every year.
- In 2023: Combined transport was more cost-effective than sea freight.
- In 2024: Land transport prices increased again, which is a reflection of global political influences.

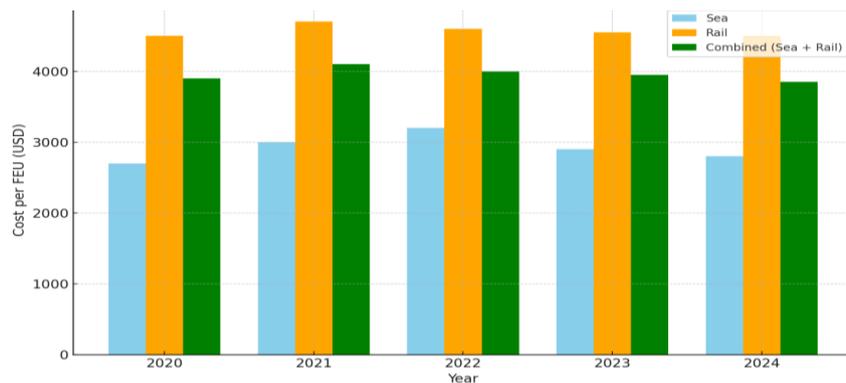


Fig. 2. Transport costs comparison (China-Georgia, 2020-2024)

6 Conclusions

- The most competitive transport corridor is the Middle Corridor (Trans-Caspian International Transport Route).
- The role of Central Asia is increasing significantly.
- This is an environmentally friendly, sustainable, and diversified route.
- Interweg Logistics plays a crucial role in organizing transport between Europe and Central Asia and in developing coordinated logistics solutions.
- Through a comprehensive logistical analysis of the Middle Corridor and the strategic positioning of logistics centers, Georgia can optimize transport efficiency, reduce costs, and improve service delivery across various industries. The establishment of these centers not only facilitates the transit of goods but

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also contributes to regional economic development by attracting investments
and creating employment opportunities.

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Strategic Management of SaaS Shipment-Tracking in Smart Logistics

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Abstract. Smart logistics leverages digital technologies to enhance supply chain visibility and performance. This paper investigates the strategic management of Software-as-a-Service (SaaS) shipment-tracking solutions in modern logistics operations. A comprehensive literature review reveals that real-time tracking and tracing systems can significantly improve operational efficiency, transparency, and supply chain visibility. However, organizations face challenges in aligning these technologies with strategic goals and overcoming adoption barriers. We integrate insights from two case studies – a postal service implementing a cyber-physical tracking system and an analysis of data analytics adoption in Ukrainian logistics – to illustrate both successful outcomes and prevailing challenges. The first case demonstrates how continuous shipment-tracking and predictive delivery algorithms enhanced service quality and efficiency, while the second highlights obstacles in data infrastructure and analytics capabilities that firms must address. We propose a framework for strategically managing SaaS tracking initiatives, emphasizing alignment of technology with organizational strategy, stakeholder buy-in, and capability development. The scientific novelty of this work lies in its holistic perspective combining empirical case evidence with current literature to identify best practices and gaps in the strategic deployment of SaaS tracking systems. The findings offer guidance for managers to implement SaaS-based shipment-tracking to achieve greater supply chain visibility, customer service improvements, and sustainable logistics performance, while also contributing new insights into the effective integration of cloud-based services in supply chain management.

Keywords: Smart logistics; Software-as-a-Service (SaaS); Shipment tracking; Supply chain visibility; Strategic management; Cloud logistics.

1 Introduction

In the era of “Logistics 4.0,” supply chains are increasingly adopting digitally connected tracking technologies to monitor shipments in real time. Smart logistics refers to the integration of advanced information systems and cloud services to enhance visibility, agility, and decision-making in logistics operations. Shipment-tracking solutions delivered as Software-as-a-Service (SaaS) have become particularly prominent, allowing firms to leverage cloud-based platforms for real-time data on cargo

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location and status without heavy upfront IT investments. Prior studies have shown that tracking and tracing devices provide real-time supply chain information and enable digital transformation in logistics. By improving transparency and data availability, such systems can streamline operations and support strategic objectives like higher on-time delivery and customer satisfaction. The goal of this study is to clarify how SaaS-based shipment-tracking systems affect both strategic alignment and operational performance in logistics firms. To achieve this goal, we carried out a multiple-case study of two European 3PLs. Twenty-three semi-structured interviews, on-site observations, and SaaS dashboard data were analysed through cross-case thematic coding. Accordingly, I address two research questions (RQs). What strategic and operational benefits emerge after SaaS tracking adoption? Which organisational and technological factors enable or hinder successful implementation?

However, effectively managing the adoption and integration of SaaS tracking solutions presents strategic challenges. Simply deploying new technology is not sufficient; organizations must align these tools with their business processes and strategies. Recent literature suggests a need for better understanding how digital logistics technologies influence business models and strategy execution. Many firms struggle to fully realize the benefits of supply chain digitalization due to organizational, technical, and environmental barriers. For example, issues such as data silos, user resistance, security concerns, and misalignment between technology providers and logistics goals can hinder the success of SaaS implementations.

2 Literature Review

2.1 Smart Logistics and SaaS Shipment-Tracking

The concept of smart logistics encompasses the use of digital technologies and data-driven services to enhance the efficiency and responsiveness of logistics networks. Central to smart logistics is the ability to monitor and control shipments in real time through connected devices and information systems. In practice, this often involves Internet-connected sensors and tracking devices on vehicles or cargo, transmitting location and status data to cloud platforms.

Research indicates that real-time tracking systems provide substantial value by enabling supply chain visibility – the capability to see and understand the flow of goods and information throughout the supply chain. Helo and Thai [1] analyze multiple industrial cases and find that deploying smart tracking devices yields improvements in operational efficiency, transparency, and security of logistics processes. Likewise, Swink *et al.* [2] emphasize that greater visibility (through timely, accurate data on shipments) is linked to better deviation management and predictive capabilities in supply chains.

Moreover, SaaS shipment-tracking often comes as part of broader cloud logistics platforms that integrate various functions (e.g., transportation management, warehouse management, and analytics). Yu and Chiou [3] describe cloud logistics plat-

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forms that facilitate information sharing and collaboration across supply chain partners. Their empirical study in an international logistics context found that cloud platform usage was positively associated with logistics operational performance and even with broader measures of organizational sustainability [3].

In summary, smart logistics leverages SaaS tracking technologies to achieve high levels of supply chain visibility and control. The literature establishes that these technologies provide clear operational benefits: improved tracking accuracy, faster response to disruptions, and enhanced coordination across the supply chain. Table 1 summarizes some of the key benefits reported in recent literature, mapping them to relevant performance dimensions. Overall, studies have documented enhancements in efficiency, service quality, and supply chain agility attributable to real-time tracking capabilities. Helo and Thai [1] note that companies deploying smart tracking devices experienced higher asset utilization and better transportation route management, contributing to cost savings. By knowing the exact location of assets (trucks, containers, etc.) and shipment conditions, logistics managers can optimize routes, reduce idle times, and improve load planning. Jagtap *et al.* [4] in the context of food logistics similarly highlight that real-time interconnectivity (enabled by IoT sensors feeding into tracking platforms) brings transparency and speed, enabling “the right product at the right place and right time” with minimal waste or delay. These efficiency gains can translate into lower logistics costs and faster throughput. Swink *et al.* [2] classify visibility into various types (e.g., inbound, outbound, internal) and argue that each type supports proactive management of deviations. In practical terms, greater visibility means fewer surprises – companies can anticipate problems like delays or misroutes and take corrective action early. Masudin *et al.* [6] provide evidence from humanitarian logistics that adopting tracking technologies (like RFID-based systems) significantly improves traceability, which then has a positive impact on overall logistics performance. Yu and Chiou [3] found that using a cloud logistics platform significantly improved customer service satisfaction, as managers were able to make more informed decisions and promptly communicate with clients. Nour [15] discusses that Logistics 4.0 firms using advanced IT enjoy increased agility and can better integrate sustainable practices, as technology provides the information backbone to implement green logistics strategies (like consolidating loads or avoiding empty runs). Table 1 below consolidates these benefits:

Table 1. Benefits of SaaS Shipment-Tracking for Logistics Performance

Performance Dimension	Improvements from SaaS Tracking	Sources
Operational Efficiency	Automated data capture; optimized routing and scheduling; reduced delays and idle time; lower transportation costs.	[1][11]
Visibility & Reliability	End-to-end shipment visibility; improved delivery reliability (on-time performance); early detection of disruptions and proactive intervention.	[1][2][6]
Customer Service	Real-time updates to customers; accurate delivery	[3]

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Performance Dimension	Improvements from SaaS Tracking	Sources
Agility & Flexibility	ETAs; enhanced communication and transparency leading to higher satisfaction.	[15]
	Ability to reroute or adjust plans quickly based on live data; faster response to demand or supply changes; resilience against disruptions.	
Sustainability	Route optimization reducing fuel use; better asset utilization lowering emissions; data to support sustainable logistics decisions.	[3][15]

Empirical evidence reinforces many of these points. For instance, Yu and Chiou [3] quantitatively demonstrated that cloud logistics platform adoption is highly correlated with improvements in logistics operations (correlation coefficient 0.837) and also positively linked to sustainable development performance. Their findings suggest that investing in such technology yields multidimensional benefits, from economic (efficiency gains) to social (better service) and environmental outcomes.

2.2 Challenges and Critical Success Factors in SaaS Tracking Adoption

Despite the compelling benefits, organizations often encounter substantial challenges when adopting SaaS-based tracking systems. Successful implementation is not guaranteed; it depends on both technical integration and strategic management. The literature identifies several common barriers and critical success factors (CSFs) for the diffusion of cloud and IoT-based logistics solutions. Technical and data integration barriers: Top management support and training are key to overcoming this. Time *et al.* [10] stress the importance of integrating business aspects – meaning that beyond IT departments, logistics and management teams should jointly own the project. Table 2 illustrates a set of common challenges and corresponding strategies or CSFs identified in the literature and practice:

Table 2. Challenges in SaaS Tracking Adoption and Strategic Management Responses

Challenge	Description and Impact	Strategic Response / CSF	Sources
System Integration	Difficulty integrating SaaS platform with legacy systems; data silos leading to incomplete visibility.	Invest in integration middleware and data standards; ensure compatibility; incremental rollout with testing.	[13]
User Adoption & Change	Employee resistance or low utilization of the new system; process inertia limiting usage of real-time data.	Strong change management and training; top management support; demonstrate quick wins to users.	[10]
Data Security & Privacy	Concerns over data breaches or unauthorized access; lack of trust in cloud service.	Choose reputable SaaS provider with high security standards; implement strict access controls; clear data policies.	[10]
Cost and ROI	Uncertainty about economic	Define KPIs (e.g., on-time delivery rate,	[3]

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Challenge	Description and Impact	Strategic Response / CSF	Sources
Justification	returns; initial costs visible but benefits diffuse or long-term.	inventory turns) and monitor improvements; conduct pilot to build business case.	
Strategic Misalignment	Technology viewed in isolation, not aligned with strategy; tracking data not used in decision-making.	Align project goals with strategic objectives (service level, market differentiation); re-engineer processes to use insights (e.g., proactive customer communication).	[4]
Partner Collaboration	Supply chain partners not adopting or sharing data, limiting end-to-end visibility.	Engage key partners early; possibly mandate platform use in contracts; provide integration support; leverage industry standards for data exchange.	[2]

From a strategic management viewpoint, one framework to consider is the Technology-Organization-Environment (TOE) model for technology adoption. Numerous studies apply TOE to SaaS/cloud adoption (e.g., ref. [13] and others). Under TOE, technological factors (like relative advantage, compatibility, complexity), organizational factors (such as top management support, readiness, and resources), and environmental factors (competitive pressure, partner requirements, regulatory environment) all influence the adoption decision and success. Environmentally, if competitors are adopting advanced logistics tech, that pressure can spur faster adoption (and conversely, lack of industry standards can slow it). Recent work by Yang et al. [9] suggests that supply chain cooperation and technological competence are critical drivers for successful digital technology adoption in manufacturing supply chains.

In summary, while SaaS shipment-tracking offers clear benefits, strategic management of its adoption involves addressing technical integration, guiding organizational change, ensuring security and trust, and aligning the technology closely with business processes and goals. The companies that overcome these challenges tend to do so by viewing the SaaS system not just as an IT tool, but as a strategic project involving people, processes, and partners. The following methodology and case study sections will illustrate these points in practical scenarios.

2.3 Research Gap and Contribution

Despite the rich body of work on the operational and strategic benefits of SaaS tracking, three important gaps remain unresolved. Contextual gap – most empirical studies focus on large multinationals in mature markets, while evidence from transitioning or emerging economies is scarce. Integration gap – existing research rarely explains how firms align real-time tracking data with high-level strategic objectives and decision-processes. Comparative gap – prior work tends to analyse single cases; cross-case syntheses that highlight contingent success factors are limited. To address these gaps, the present study (compares two contrasting 3PL contexts—one successful, one struggling—in Europe and Eastern Europe; links SaaS-tracking adoption steps to strategic - alignment theory, extending the Technology - Organisation - Envi-

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ronment (TOE) framework; and offers a staged roadmap that practitioners in resource-constrained settings can replicate.

3 Methodology

Research design and scope: The study adopts a multiple-case, explanatory design (Yin, 2018) because SaaS shipment-tracking is a contemporary phenomenon embedded in its organisational context. Two contrasting cases were selected to enable *analytical replication*: one successful (Bosnia-and-Herzegovina Post) and one challenged (Ukrainian 3PL sector). This design permits theory extension by comparing patterns across different environmental and organisational conditions. Case-selection criteria: Cases were chosen purposively using three criteria: documented use of a cloud (SaaS) shipment-tracking platform; (availability of publicly reported operational or strategic outcomes; (contrasting maturity contexts, allowing literal (success) and theoretical (challenge) replication.

Case selection: We selected two cases that provide complementary perspectives on SaaS shipment-tracking:

Case 1: Postal Shipment-Tracking System (Bosnia and Herzegovina Post) – This case (drawn from Stojčić et al. [8]) involves the development of a cyber-physical system for continuous tracking of postal items and predicting delivery times in a national postal service. We chose this case as a successful implementation example where a traditional logistics provider adopted advanced tracking and analytics. The case provides insights into system architecture (integration of GPS/GPRS devices, control center software) and the performance improvements achieved (e.g., prediction accuracy, service quality).

Case 2: Data Analytics Adoption in Ukrainian Logistics – This case (based on Mukha & Popova [7]) examines the challenges and readiness for data analytics (as a proxy for smart tracking) in the Ukrainian logistics sector. This scenario was selected to highlight a context where implementing such technologies faces obstacles like infrastructure gaps and skill shortages. It offers a contrasting perspective to Case 1, focusing on the problems and challenges in embracing logistics analytics and tracking in a developing/emerging market environment.

Data collection: Data for the cases were gathered from published case study reports and articles. For Case 1, we relied on the conference proceedings article by Stojčić et al. (2023) [8], which provides an abstract and methodological details of the postal tracking system implementation, as well as reported results (such as the number of shipments tracked and the performance of predictive models). For Case 2, we used the article by Mukha & Popova (2023) [7], which discusses the state of data analytics in Ukrainian logistics, including qualitative assessments of issues like data collection and interpretation.

4 Case Study Results

4.1 Case 1: SaaS Tracking Implementation in a Postal Logistics Service

The first case study examines the implementation of a continuous shipment-tracking system by the national postal service in Bosnia and Herzegovina (BiH Post). This initiative was motivated by increasingly stringent customer requirements for shipment visibility and on-time delivery in express mail services, as well as rising competition in the parcel delivery market. The organization recognized that traditional methods of tracking (often limited to scan events at hubs) were insufficient for real-time control and customer expectations. Thus, they embarked on developing a cyber-physical system (CPS) for real-time tracking of postal items and for predicting delivery times using data analytics [8]. Scientific and strategic insights: Case 1 demonstrates how a traditional logistics provider can strategically leverage SaaS and IoT technologies to modernize its operations. The key to success here was that the postal service treated the tracking system implementation as part of a broader service improvement strategy. They explicitly aimed to meet higher customer expectations and to compete with private couriers on speed and reliability. By coupling the tracking data with predictive analytics, they moved beyond reactive tracking to proactive logistics management. This reflects a strategic use of technology: rather than just generating data, they used the data to create value (in this case, value for customers via accurate ETAs, and value for the company via efficiency and reputation gains). The case aligns with literature that claims cloud-based logistics can improve both operations and sustainability – indeed, the postal service likely reduced missed deliveries (which cause re-deliveries) and optimized routes, contributing to sustainability.

Case 2: Readiness for SaaS-Based Tracking in Ukrainian Logistics

The second case synthesises the empirical findings of Mukha & Popova [7] concerning the diffusion of data-analytics capabilities—as an indispensable pre-requisite for SaaS shipment-tracking—among Ukrainian third-party logistics providers (3PLs). The source study combined a structured survey of $N = 68$ firms with three expert interviews and sectoral statistics. Results revealed limited sensor integration—only 27% of carriers collect real-time location data; (a substantial skills gap—63% of respondents lack in-house data-analytics staff; and infrastructural constraints such as patchy GSM/LTE coverage on transit corridors. These findings position Ukraine as a “nascent adopter” context and therefore provide a counter-point to the mature implementation observed in Case 1.

5 Discussion

The two case studies, juxtaposed with the literature, provide a comprehensive view of the strategic management imperatives in implementing SaaS shipment-tracking in smart logistics. In this section, we synthesize the findings, discuss how they confirm

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or extend current knowledge, and derive implications for practitioners and researchers.

5.1 Alignment with Literature and Theoretical Implications:

Case 1 (Postal Service) largely corroborates the benefits outlined in the literature review. The postal service experienced significant improvements in efficiency, visibility, and service reliability – exactly as numerous studies predicted [1][2][3][6]. This real-world example reinforces the notion that supply chain visibility through real-time tracking is a key driver of performance gains. It also demonstrates the concept of moving from passively collecting data to actively *using* data (via predictive analytics) to guide operations. This resonates with the calls in literature for better integration of analytics into decision processes. Ghouri and Mani [4], for instance, emphasized leveraging real-time information for downstream effects; the postal service did just that by informing customers and adjusting operations proactively.

5.2 Theoretical Contribution

This cross-context analysis advances three established theoretical lenses.(1) Technology–Organisation–Environment (TOE) framework.

While TOE emphasises technological readiness, organisational support and environmental pressure in adoption decisions: contentReference, our results suggest the need for a fourth, strategic-alignment readiness construct. Case 1 shows that a medium-sized postal operator can unlock SaaS-tracking value only when tracking KPIs are formally coupled with corporate service-level objectives; by contrast, Case 2 demonstrates how low alignment neutralises even moderate technological intent. This addition refines recent TOE-based SaaS studies that model adoption as a binary event and answers Hindawi’s call for “hybrid evaluation metrics” across Industry 4.0 technologies. Supply-Chain Visibility (SCV) theory.

Comprehensive SCV frameworks highlight information sharing and collaboration as visibility drivers. Our cases reveal a gap: only when raw tracking data are translated into predictive and prescriptive insights (as in Case 1) does visibility generate strategic advantage. This amplifies the SCV platform architecture proposed by Mattegunta (2025) [16] and complements the smart-city logistics evaluation that ranks IoT visibility solutions without tracing their analytical exploitation. Dynamic-Capabilities view. Digital dynamic capabilities—sensing, seizing, and reconfiguring through data—are now widely linked to supply-chain resilience. Our negative/positive case pairing demonstrates how SaaS-enabled sensing alone is insufficient; seizing (i.e., routinised use of ETA predictions) and organisational reconfiguring (route rescheduling, customer notifications) are prerequisites for value creation. Thus, we extend existing capability models by explicitly locating SaaS-tracking within the capability micro-foundations.

6 Scientific Novelty

The inclusion of two markedly different case studies (a technologically progressive postal service and a transitioning logistics sector in an emerging economy) provides a unique comparative angle. This approach yields *scientific novelty* in highlighting context-specific factors. For instance, much of the existing literature is based on cases in highly developed economies or large multinational firms. By examining the challenges in Ukraine's logistics sector, we shed light on how general theories (like those of technology adoption and supply chain visibility) manifest under resource constraints and less favorable conditions. The novelty lies in extending the applicability of current theories to new contexts and identifying any deviations. We propose that companies progress through stages: building data infrastructure, implementing real-time tracking, integrating predictive analytics, and strategic utilization of data.

7 Conclusion

This study examined the strategic management of SaaS shipment-tracking in smart logistics, contributing both theoretical insights and practical guidance. Through an extensive literature review and two illustrative case studies, we have shown that implementing SaaS-based tracking systems offers significant performance benefits – including improved operational efficiency, supply chain visibility, customer service, and agility – but realizing these gains requires careful alignment of technology with organizational strategy and capabilities. The **key findings** can be summarized as follows: SaaS shipment-tracking is a powerful enabler of smart logistics. It allows real-time data capture and sharing, which in turn drives better decision-making and performance improvements. Our research reaffirms that organizations leveraging these systems can achieve higher on-time delivery rates, more responsive logistics operations, and greater customer satisfaction. Case 1 demonstrated these outcomes in a postal service context, where on-time deliveries and predictive capabilities markedly improved after system implementation. Successful adoption of SaaS tracking is not merely a technical deployment; it is a strategic change process. Companies must invest in the necessary infrastructure (devices, connectivity, integration with existing systems) and in the human and process aspects (training, process re-engineering, change management). We identified critical success factors such as top management support, organizational readiness, and inter-firm collaboration. **Scientific novelty** was presented in our integrated perspective and cross-context analysis. We bridged the gap between technical supply chain analytics and management strategy, highlighting how each influences the other. The paper also sheds light on contexts (like emerging markets) that extend the current understanding of logistics digitalization beyond well-studied environments. We proposed a conceptual staged framework for adopting SaaS tracking, which can be tested and refined in future research.

In conclusion, the strategic management of SaaS shipment-tracking in smart logistics is a multi-dimensional challenge that, when navigated successfully, yields a

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smarter, more competitive, and more resilient supply chain. Organizations that deliberately align technology investments with strategic goals, cultivate the necessary skills and processes, and foster a culture of data-driven improvement are well positioned to harvest the full benefits of smart logistics.

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Integration of Telematics and Information Systems in Multimodal Logistics Terminals

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Abstract. Telematics systems are increasingly recognized as a fundamental element of modern logistics, particularly in multimodal transport terminals where real-time information exchange and process optimization are essential for operational efficiency. This paper examines how the integration of telematics and information systems improves the coordination between freight vehicles and terminal infrastructure. By employing technologies such as Global Positioning System tracking, vehicle sensors, Radio-Frequency Identification systems, and wireless data communication networks, telematics enables continuous monitoring of truck arrivals, cargo status, and estimated times of arrival. These insights support data-driven decisions regarding gate assignment, scheduling of loading operations, and allocation of terminal resources, which reduces congestion and minimizes vehicle dwell time. The research applies a case study methodology based on secondary data sources, operational reports, and field observations within a European logistics operator. This approach provides empirical evidence on how telematics contributes to improved scheduling accuracy, higher terminal throughput, and more sustainable operations. The findings reveal measurable benefits, including reduced emissions and fuel consumption, while also identifying challenges such as data accuracy, system interoperability, and infrastructure constraints. In the long term, the integration of telematics with terminal operating systems represents a critical step toward creating intelligent, adaptive, and environmentally responsive logistics hubs. The study provides valuable insights for logistics practitioners and highlights future research needs related to overcoming interoperability barriers and developing scalable intelligent system architectures.

Keywords: Telematics, Multimodal transport, Real-Time Data.

1 Introduction

The integration of telematics and information systems in multimodal logistics terminals is increasingly recognized as a crucial factor for improving operational efficiency, coordination, and sustainability within modern freight transport networks. Multimodal terminals serve as central nodes where different transport modes such as road, rail, and maritime intersect. These terminals require effective communication and

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synchronization between incoming vehicles, terminal infrastructure, and information systems to ensure smooth and timely freight handling [1]. Managing such complex and dynamic environments presents significant challenges, including congestion management, optimal resource allocation, and real-time decision-making. The motivation for this research lies in addressing these challenges by exploring how telematics can facilitate continuous tracking and monitoring of vehicles and cargo, enabling terminal operators to make timely and data-driven decisions. The main aim of this study is to analyze how the integration of telematics and information systems within multimodal terminals contributes to improved scheduling accuracy, enhanced coordination between transport modes, and increased operational efficiency. This research also seeks to evaluate the environmental impact of such integration, with a particular focus on reducing vehicle idling, fuel consumption, and emissions. Although several studies have addressed the role of digitalization and intelligent technologies in transport and logistics, research gaps remain in the specific context of multimodal terminals. In particular, there is limited empirical evidence on the application of telematics in real-world terminal operations and its measurable effects on both efficiency and sustainability. Furthermore, existing research often overlooks the challenges of system interoperability, data accuracy, and stakeholder collaboration, which are crucial factors in the successful deployment of telematics solutions [2],[3],[4],[5].

This paper aims to fill this gap by providing a case study analysis of one of the leading logistics operators in Europe. The novelty of this study lies in presenting empirical evidence from the practical application of telematics within the terminals of the Société Nationale des Chemins de Fer Luxembourgeois (CFL Group). Unlike previous research, which has largely remained conceptual or focused on technological potential, this study demonstrates how telematics integration within terminal operating systems can produce tangible benefits in real operational contexts. These benefits include reduced vehicle waiting times, optimized use of terminal equipment, and enhanced throughput. Additionally, the study highlights how telematics supports broader sustainability goals by minimizing fuel use and carbon dioxide emissions. In conclusion, integrating telematics and information systems within multimodal logistics terminals represents a significant advancement towards creating more efficient, responsive, and sustainable freight transport hubs. The case study presented in this paper provides valuable insights for logistics providers seeking to optimize multimodal operations in increasingly complex supply chains. At the same time, it points to the need for future research on overcoming interoperability barriers and developing intelligent system architectures capable of supporting scalable telematics applications in logistics terminals.

2 Methodology

This research is focused on the analysis of key processes involved in the integration of telematics and information systems within multimodal logistics terminals, with a particular emphasis on procedures relevant to the operations of the Société Nationale

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des Chemins de Fer Luxembourgeois Group. The primary objective is to examine how telematics supports the flow of information and coordination within terminal operations, while also identifying the limitations of data availability and transparency. The research process is based on a step-by-step examination of operational and technological procedures, including the arrival and dispatch of vehicles, cargo tracking, communication among participants in the supply chain, and the management of resources within the terminal. Data collection relied on three main sources: academic literature on logistics and terminal operations, publicly available reports of the Société Nationale des Chemins de Fer Luxembourgeois Group, and open-access data related to the application of telematics technologies in multimodal logistics.

Particular attention was paid to analyzing how telematic devices such as Global Positioning System trackers, vehicle sensors, and Radio-Frequency Identification systems installed in trucks, trains, and containers generate real-time data that is subsequently communicated with terminal information platforms. The study examines how this data is collected, processed, and integrated into the Terminal Operating System and related logistics applications, enabling more precise planning, timely dispatching, and transparent cargo tracking. This integration facilitates improved decision-making, reduces vehicle dwell times, optimizes resource allocation, and strengthens overall supply chain visibility. The process analysis was carried out by mapping the flow of information between vehicles, telematic devices, and information systems, focusing on bottlenecks and critical points where telematics contributes most to efficiency, delay reduction, and transparency.

At the same time, the study highlights the challenges of coordinating diverse transport modes and heterogeneous technological systems, which remain a barrier to seamless integration. The Société Nationale des Chemins de Fer Luxembourgeois Group terminal, which was selected as the subject of the case study, is equipped with six entry lanes for the reception of trucks. Under normal operational conditions, this design allows for a balanced traffic flow and minimal waiting times at the gates [6]. The terminal operates twenty-four hours a day, seven days a week, and for the purpose of this study, a three-day observation period was conducted.:

- As shown in Figure 1: Friday: 444 trucks in total, averaging 18.5 trucks/hour, with peak activity between 09:00–13:00 and a maximum of ~38 trucks/hour at 11:00.
- As shown in Figure 2: Saturday: 137 trucks in total, averaging 6.2 trucks/hour, with peak activity concentrated between 07:00–09:00, reaching up to 20 trucks/hour.
- As shown in Figure 3: Sunday: 88 trucks in total, averaging 3.7 trucks/hour, with generally low arrivals except for a late evening peak at 22:00 (~10 trucks/hour).

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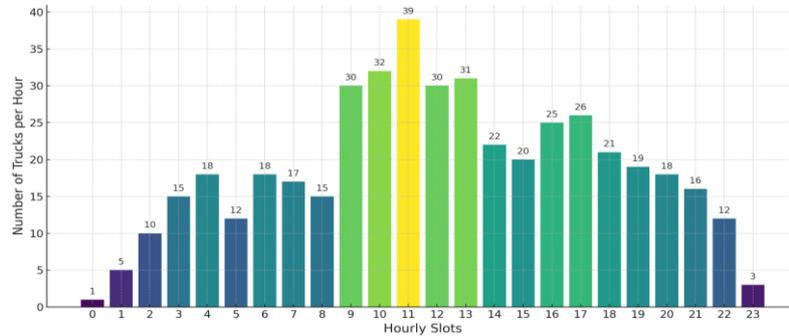


Fig. 1. Truck Arrivals at CFL Group Terminal-Friday

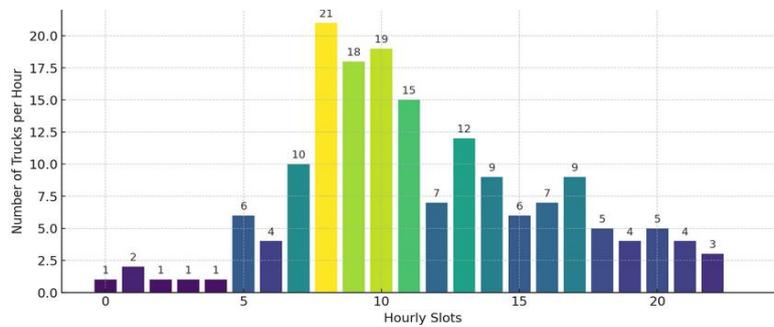


Fig. 2. Truck Arrivals at CFL Group Terminal-Saturday

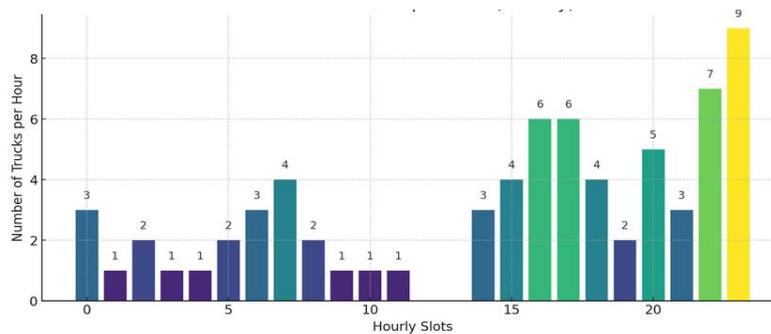


Fig. 3. Truck Arrivals at CFL Group Terminal-Sunday

During the experimental period, two of the entry lanes were temporarily closed due to technical maintenance and the testing of alternative operational scenarios. This situation provided an opportunity to analyze how the terminal’s operations responded under restricted access conditions. With only four lanes in service, and the daily inflow of trucks remaining unchanged, the functioning lanes were placed under increased

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pressure during peak periods. The most significant congestion occurred on Friday in the late morning hours (09:00–13:00), followed by Saturday early morning (07:00–09:00), while Sunday remained largely unaffected except for a moderate increase in the evening. During these peak hours, the reduced lane capacity caused visible congestion. The average waiting time at the entry point increased from the usual ten minutes to approximately sixteen minutes, with peak delays occasionally exceeding twenty minutes, particularly on Friday.

Nevertheless, thanks to the functionality of the telematics system, major disruptions were avoided. The use of tracking devices installed on vehicles made it possible to monitor incoming trucks in real time and distribute them according to the expected arrival time. Vehicles were automatically reallocated across the available lanes, while drivers received timely instructions through digital communication channels that informed them about the temporary closure and guided them towards alternative entry points. This timely flow of information reduced unexpected delays and helped to maintain operational continuity. In addition, the terminal’s digital platform updated vehicle priority queues based on cargo type, delivery deadlines, and pre-registered schedules. Staff resources were also reallocated at the functioning lanes to compensate for the reduced infrastructure, which helped to limit the impact on total throughput. As shown in Figure 4, these effects are clearly reflected in the hourly arrival patterns recorded for Friday, Saturday, and Sunday. The highlighted peak periods illustrate not only the absolute differences in traffic volumes, but also the shifting time windows of maximum activity, demonstrating how reduced capacity challenged operations but could still be managed effectively through telematics-supported coordination.

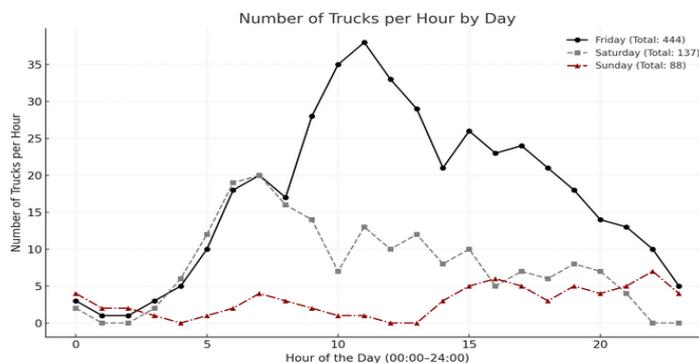


Fig. 4. Truck Arrivals at CFL Group Terminal-Daily Patterns and Peaks

3 Results and Discussion

The operational analysis conducted during the period of reduced entry capacity at the CFL Group terminal provided valuable insights into how a well-integrated telematics infrastructure can sustain high performance, even under constrained conditions. De-

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spite two of six entry lanes being temporarily closed, the terminal maintained an impressive level of efficiency, largely thanks to real-time data flow and well-coordinated operational procedures.

3.1 Maintaining Flow Under Pressure

Truck arrivals during the observed week, covering the full twenty-four-hour period, remained stable with a total of 444 vehicles recorded on Friday, 137 on Saturday, and 88 on Sunday. As illustrated in Figure 4, the terminal successfully managed the traffic flow by balancing the incoming volumes across the four active entry lanes. Peak hours differed by day: the highest concentration on Friday occurred between 09:00 and 13:00, with approximately thirty-eight trucks per hour; on Saturday, the peak occurred between 07:00 and 09:00, with about twenty trucks per hour; while on Sunday, the maximum was reached at 22:00, with around ten trucks per hour. As shown in Figure 4, a moderate increase in waiting times was recorded, rising from the usual average of ten minutes to approximately sixteen minutes during peak hours, with occasional spikes exceeding twenty minutes, particularly on Friday. Despite this increase, no significant bottlenecks or critical disruptions were observed. These results demonstrate that the system implemented at the Société Nationale des Chemins de Fer Luxembourgeois Group terminal proved not only robust but also adaptive under conditions of restricted capacity and operational pressure.

3.2 Telematics-Enabled Operational Resilience and Comparative Insights

A key factor behind the operational resilience observed during the testing period was the effective use of telematics technologies. Tracking devices installed in trucks, combined with dynamic routing and scheduling tools, enabled terminal staff to anticipate arrivals and make real-time adjustments to lane assignments. Drivers were promptly informed of gate closures through mobile communication channels, allowing for better distribution of incoming traffic and a significant reduction in congestion at the gates. The integration of these telematic functions with the terminal's digital management system ensured that processing delays were minimized. Incoming data from trucks, containers, and train units was seamlessly integrated into the central operating platform, which supported live queue management and dynamic reallocation of staff and equipment. This level of responsiveness proved critical in maintaining a smooth and reliable flow of operations throughout the testing period.

To broaden the relevance of this study, it is essential to compare the case of the Société Nationale des Chemins de Fer Luxembourgeois Group terminal with similar multimodal logistics hubs across Europe. Large intermodal terminals such as Rotterdam in the Netherlands, Duisburg in Germany, and Antwerp in Belgium have already adopted advanced telematics and information systems to coordinate the interaction between rail, road, and maritime transport [7],[8],[9]. While these terminals differ from Luxembourg in scale and infrastructural capacity, they face common challenges such as traffic congestion, data interoperability, and the need for efficient allocation

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of resources. Larger hubs demonstrate a higher degree of automation and digital integration [10], yet the Luxembourg case illustrates that even medium-sized terminals can achieve measurable improvements in efficiency, transparency, and sustainability through the adoption of telematics solutions. This comparative perspective highlights that the advantages of telematics are not limited to major ports and terminals but can also be applied in smaller operational contexts, thereby enhancing the generalizability of the findings presented in this paper.

3.3 Operational Excellence and Adaptability

The temporary closure of two entry lanes served as a natural stress test for the terminal, and the Société Nationale des Chemins de Fer Luxembourgeois Group demonstrated a high level of operational excellence in managing this challenge. Through a combination of advanced technologies, experienced personnel, and streamlined processes, the terminal continued to function effectively under pressure. Even with increased demand on the remaining entry points, the system ensured transparency, effective communication, and performance continuity. This case study demonstrates that when telematics is properly integrated into terminal operations, it can act as a stabilizing force that enables logistics networks to absorb shocks, adapt to unexpected constraints, and continue delivering reliable service. Beyond the context of Luxembourg, these findings underline that telematics solutions can be successfully applied in other multimodal logistics terminals across Europe. Larger hubs such as Rotterdam, Duisburg, and Antwerp operate on a much greater scale, but they face similar challenges related to congestion, interoperability, and sustainable performance.

The evidence from this study suggests that even medium-sized terminals can achieve significant efficiency gains, reduce emissions, and enhance resilience by adopting telematics-based coordination. This broader applicability enhances the scientific contribution of the study, demonstrating that the integration of telematics supports not only local improvements but also wider advancements in multimodal logistics management.

3.4 Broader Operational and Sustainability Benefits

During the three-day observation period, the integration of telematics and information systems generated measurable operational, energy, and environmental benefits that extended well beyond the regulation of traffic at the entry gates. As illustrated in Figure 5, the combined effects of optimized gate scheduling, reduced engine idling, and enhanced communication with drivers resulted in significant weekly savings and reductions across multiple dimensions of terminal performance. From the perspective of human resource management, the improved accuracy of arrival predictions, particularly during high-intensity traffic periods, enabled terminal managers to design work schedules with greater precision.

This approach is estimated to result in approximately 45 labor hours saved per week, thereby potentially reducing reliance on overtime, minimizing last-minute

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scheduling adjustments, and allowing highly skilled personnel to be reallocated to tasks with greater added value within the terminal. The projections further indicate substantial energy-related savings. The reduction of engine idling and smoother traffic circulation are expected to lead to a decrease in fuel consumption of approximately 85 liters per week. At the same time, the optimization of operational processes and reduced delays could lower the demand for auxiliary energy resources, yielding an additional saving of around 320 kilowatt-hours of electricity per week. These estimates provide indicative evidence that digital integration can directly enhance overall operational efficiency. Equally significant are the anticipated environmental benefits. By minimizing unnecessary engine idling and reducing internal vehicle movements within the terminal facility, telematics integration is projected to contribute to a weekly reduction of about 220 kilograms of carbon dioxide emissions. This decrease would be equivalent to removing several actively operating trucks from circulation, suggesting that digital solutions not only have the potential to improve operational efficiency but also to support broader sustainability objectives. These observations are consistent with global trends showing that advanced logistics hubs increasingly adopt integrated information and telematics systems to enhance both operational efficiency and sustainability outcomes. [10].

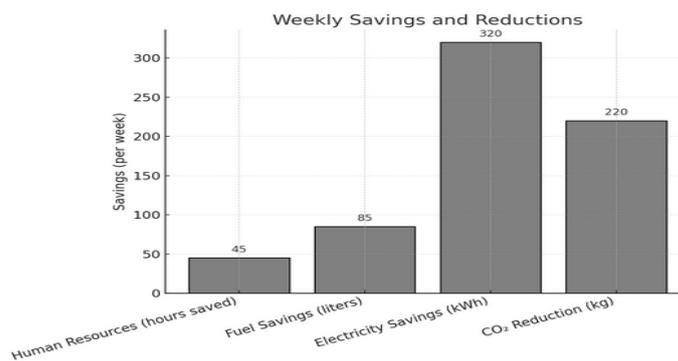


Fig. 5. Estimated Weekly Operational Savings

4 Conclusion

This research investigated the integration of telematics and information systems within the operational framework of the Société Nationale des Chemins de Fer Luxembourgeois Group multimodal terminal. The empirical analysis showed that telematics integration improves operational efficiency through optimized gate allocation, reduced vehicle dwell times, and better resource management, while also contributing to sustainability by lowering emissions and minimizing unnecessary idling.

The significance of this study extends beyond the immediate context of the Luxembourg terminal. The challenges identified, such as congestion, resource allocation, and system interoperability, are common to multimodal logistics facilities across Eu-

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rope. The findings therefore provide a transferable framework, indicating that telematics-based coordination can generate measurable efficiency gains not only in medium-sized terminals but also in larger hubs such as Rotterdam, Duisburg, and Antwerp. The evidence shows that even terminals with limited infrastructure can benefit from digital integration, which strengthens the generalizability of telematics applications within logistics theory and practice. From a scientific perspective, the study links operational data with broader discussions on adaptability and resilience in logistics networks. It also illustrates how telematics functions as a stabilizing mechanism, enabling terminals to absorb operational shocks, adapt dynamically to constraints, and maintain service reliability. Future research should expand on this work by comparing multiple terminals, assessing long-term impacts of digital integration, and developing standardized models to ensure interoperability between diverse transport modes and information systems.

In addition, policymakers and industry stakeholders should recognize the importance of investing in harmonized telematics standards to avoid fragmentation between different systems. Strengthening collaboration between terminal operators, technology providers, and regulatory bodies will be crucial for ensuring that the benefits of telematics are widely realized. Ultimately, the study underscores that digital transformation in logistics is not only a matter of efficiency, but also a strategic pathway toward building greener, smarter, and more resilient transport networks across Europe.

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Application of SWARA Method for Identifying Key Performance Indicators in a Transport Company

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Abstract. Transport companies in Bosnia and Herzegovina face numerous challenges that affect their business on a daily basis. Road transport is subject to significant legislative, infrastructural, and administrative obstacles, over which companies have limited influence. However, there are many internal monitoring and regulatory measures that can contribute to better performance, one of which is the monitoring of key performance indicators (KPIs) in transport. Large logistics systems monitor various performance indicators through software solutions in order to measure fleet performance, fuel consumption, capacity utilization and adherence to deadlines. For the serious development of the sector, the introduction and standardization of KPIs would be a crucial step toward greater efficiency, competitiveness and alignment with European Union practices. In this paper, based on the monitoring of 62 performance indicators by three decision-makers from the company IM-TRANSPORT, 16 most significant key performance indicators in transport were defined. The SWARA (Step-Wise Weight Assessment Ratio Analysis) method was applied to determine the relative weights of the criteria and sub-criteria. The results show that the most significant indicators are related to transport cost per kilometer, number of kilometers traveled per vehicle and the average number of kilometers per day.

Keywords: Key performance indicators, efficiency, transport, SWARA.

1 Introduction

The transport sector represents one of the key pillars of economic development in every country, as it directly impacts the efficiency of logistics flows, trade, employment, and investment. In Bosnia and Herzegovina, particularly in the field of road transport, transport companies play an important role in connecting the domestic economy with regional and international markets. However, despite this importance,

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transport companies in Bosnia and Herzegovina face a range of complex challenges that hinder their operations and reduce their competitiveness compared to companies from the EU and the wider region. One of the major issues is the inadequate and outdated transportation infrastructure. In addition to infrastructure-related challenges, companies are faced with a highly complicated and often inconsistent legislative and administrative framework. Also, a significant challenge is the lack of a qualified workforce, particularly professional drivers. This issue has been further intensified after the COVID-19 pandemic, when a large number of workers either left the sector or emigrated, leaving domestic companies without key operational personnel. High operating costs are yet another factor that negatively affects the profitability of transport companies. In addition to the price of fuel, which varies and often reaches high values compared to neighboring countries, transport companies in Bosnia and Herzegovina face high costs for fleet maintenance, technical inspections, insurance, customs duties, and other administrative fees. Long wait times at border crossings, especially with Croatia and Serbia, result in time losses, increased costs, and reduced competitiveness of BiH companies. In addition, the limited number of permits for entry and transit through EU countries, as well as the lack of reciprocity in certain bilateral agreements, pose additional challenges. The COVID-19 pandemic has further worsened existing problems. Although the sector is gradually recovering, many companies still feel the consequences in the form of reduced liquidity, long-term debt, and limited access to financing. Most transport companies in Bosnia and Herzegovina, especially micro and small enterprises, do not use formal performance management systems but operate based on personal experience without systematic monitoring of results. In this context, monitoring KPIs can play a crucial role in optimizing operations, increasing efficiency, and rationalizing costs. By using KPIs, it is possible to objectively measure driver performance, route efficiency, fuel consumption, fleet utilization, and on-time delivery compliance. At the global level, large logistics companies have been using software solutions for real-time performance monitoring for years. The introduction of such systems into the BiH transport sector would be crucial for its modernization and alignment with European standards. In this paper, the focus will be on identifying the most significant KPIs in road transport in Bosnia and Herzegovina, using the SWARA method. The aim of the paper is to contribute to the development of more efficient and systematic performance management in the road transport sector in Bosnia and Herzegovina. This paper consists of several sections, including: an Introduction, which clearly presents the idea of identifying key performance indicators (KPI), and the application of the SWARA method in a transport company; a Literature Review that includes some of the most relevant references in this field; a Research Methodology section presented in the form of a diagram, along with the main guidelines of the SWARA method and its application for KPI identification in transport. Finally, the Conclusion presents the main results, research limitations, and directions for future studies.

2 Literature Review

Even in ancient times, various forms of measuring and monitoring performance existed. Records were kept related to military victories, the number of constructed buildings, the number of animals purchased and sold, etc. Over time, with the development of the Industrial Revolution, specific methods of monitoring and performance indicators emerged for produced units, production time, and production costs. By the end of the 20th century, systematic KPI monitoring occurred in sectors like economics, logistics, healthcare and education. Meanwhile, digitalization brought the automatic collection and monitoring of key performance indicators. In the review paper [1], which included a large number of studies and research conducted from 2000 to 2017, the relationship between the supply chain and key performance indicators was analyzed. KPIs enable supply chains to successfully overcome crisis situations, such as natural disasters or pandemics. Through this extensive literature review, three main groups of KPIs were defined: operational indicators, financial indicators, and risk management indicators. A major challenge regarding key performance indicators is the lack of standardization in their selection and measurement. In study [2], a methodology for evaluating company performance using a logistics-based approach through KPIs was presented. It was proposed to link fundamental logistics principles – such as delivering the right product, at the right time, to the right place, in the required quantity and quality, at optimal costs – with measuring the efficiency of business processes. The proposed methodology is theoretical in nature and has not been applied to a real-world case, which could be the next step toward improving business processes. In order to improve the efficiency of the entire supply chain, study [3] analyzes the impact of KPIs of logistics processes on logistics costs. By analyzing real-world data from logistics practice, it was determined that KPIs such as delivery time and accuracy, capacity utilization, and storage and transportation costs have a great impact on improving business performance and enabling more efficient decision-making. Study [4] includes KPIs across all subsystems of logistics. A survey and research were conducted among logistics professionals to assess the impact of KPIs on business success. Thus, the study concluded that delivery optimization, order fulfillment accuracy, operating costs, customer satisfaction, inventory management, and flexibility and adaptability contribute to greater competitiveness and sustainability in the market. Additionally, study [5] describes the analysis and improvement of KPIs in modern organizations. KPIs, methods for selecting them, performance measurement, and technological support were defined. One of the main challenges is setting realistic and measurable KPIs, as well as training employees to record them. Study [6] presents a developed Su-KPI model that implies sustainable key performance indicators, covering environmental, social, and economic aspects. The focus is placed on sustainable development to help organizations measure and improve their processes. Multi-criteria decision-making methods play an important role and have a significant impact on KPI measurement. Thus, in study [7], the authors use the Fuzzy AHP method to determine the importance of criteria, while Fuzzy TOPSIS is applied for the ranking and selection of KPIs. The study highlights the importance of proper selection and

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identification of KPIs in the logistics sector. Moreover, the proposed model can be applied in other sectors as well. Additionally, the combination of multiple multi-criteria decision-making methods yielded excellent results in the study [8], where the integration of DEMATEL-ANP-VIKOR enabled the identification of interdependencies between KPIs and BSC (Balanced Scorecard perspectives), leading to more effective and rational decision-making in performance management. The analysis of KPIs using multi-criteria decision-making methods has also found its significance in the shipbuilding industry [9]. Through the integration of DEMATEL-ANP, the following KPIs were identified: delivered ship quality, production cycle time, production costs, labor efficiency, and user satisfaction. A practical example of applying the ELECTRE method in selecting KPIs is presented in the study [10]. The methodology was tested on a real-world industrial case, in which relevant KPIs were successfully identified and classified according to their importance. This allowed management to focus on the indicators that truly impact the operational and strategic goals of maintenance. Radović and Stević, in study [11], focus on the problem of selecting the most important KPIs in the transport sector using the SWARA method. Through consultations with experts in the field of transportation, an initial list of KPIs was identified, and they were then ranked by the experts according to their importance. This assessment served as the basis for applying the SWARA method, with the goal of calculating the weighting coefficients for each indicator. In addition, the SWARA method was applied in the field of procurement and distribution, in combination with the QFD method, to identify KPIs. The robustness of this model can be tested in other logistics subsystems, and it is possible to include multiple experts from various industries [12]. The SWARA method, in combination with the ARAS method, has been applied in selecting the optimal warehouse location, with the aim of reducing costs and ensuring faster deliveries in the context of e-commerce [13]. SWARA was first applied for ranking the sustainability indicators of energy systems in the study [14]. The identified KPIs included economic, environmental, and social indicators. SWARA proved particularly valuable in this context, as it is highly useful in situations where decisions are based on experts' qualitative assessments. The integration of KPIs is essential for comprehensive performance management in road transport, as clearly demonstrated in the study [15], where the focus is on linking multiple KPIs to improve overall operational efficiency and competitiveness. Furthermore, this study included a case study of a transport company in Spain to test the practical application of the model. KPIs play a significant role in the planning and design of new software systems for logistics services. Due to the large number of logistics services, the number of KPIs is constantly increasing. For this reason, study [16] focuses on a standardized and adaptable framework for KPIs measurement. In public transportation [17], it is also possible to establish an optimal set of KPIs that can support its organization and thereby improve operational efficiency, customer satisfaction, and performance-based decision-making. More than 20 KPIs were initially identified, but optimization narrowed them down to the most relevant indicators, including: arrival and departure punctuality, capacity utilization, waiting time, operating cost per kilometer, and user satisfaction. Key performance indicators are also important for intelligent transport systems,

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so in study [18], the impacts of intelligent transport systems were quantified, and the efficiency of traffic management was assessed, with the aim of easier decision-making and better planning of transport infrastructure. KPIs are intended both for the evaluation of existing ITS solutions and for guiding the planning of future interventions. Additionally, study [19] presents KPIs that can be used to measure the impact of intelligent transport systems on various aspects of transportation. The implementation of ITS solutions has a real effect only if their impacts can be quantitatively monitored through carefully selected performance indicators.

3 Research Methodology

The research methodology refers to a systematic approach to data collection, based on which key performance indicators in a transport company were defined. After designing a questionnaire that includes 62 key performance indicators, decision-makers evaluated them. Subsequently, the SWARA method was applied to evaluate the most significant indicators. The results obtained in this way can be used by all transport companies in Bosnia and Herzegovina to improve their business. The research methodology is presented in Figure 1.

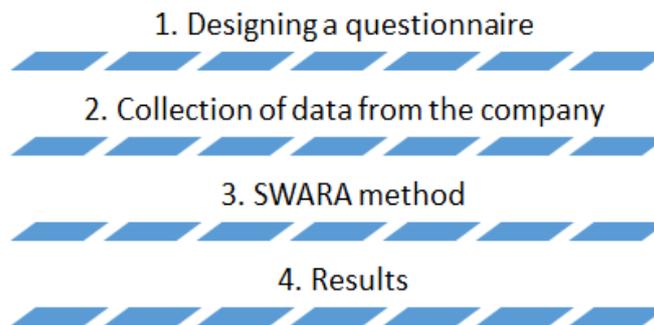


Fig. 1. Research methodology

The SWARA (Step-wise Weight Assessment Ratio Analysis) method is one of the methods for determining weight values that play an important role in a decision-making process. The method was developed by Kersulienė et al. [20] and, according to them, its key feature is the ability to incorporate expert opinions on the significance of criteria in the process of determining their weights. After defining and forming the list of criteria involved in a decision-making process, the SWARA method consists of the following steps, Figure 2.

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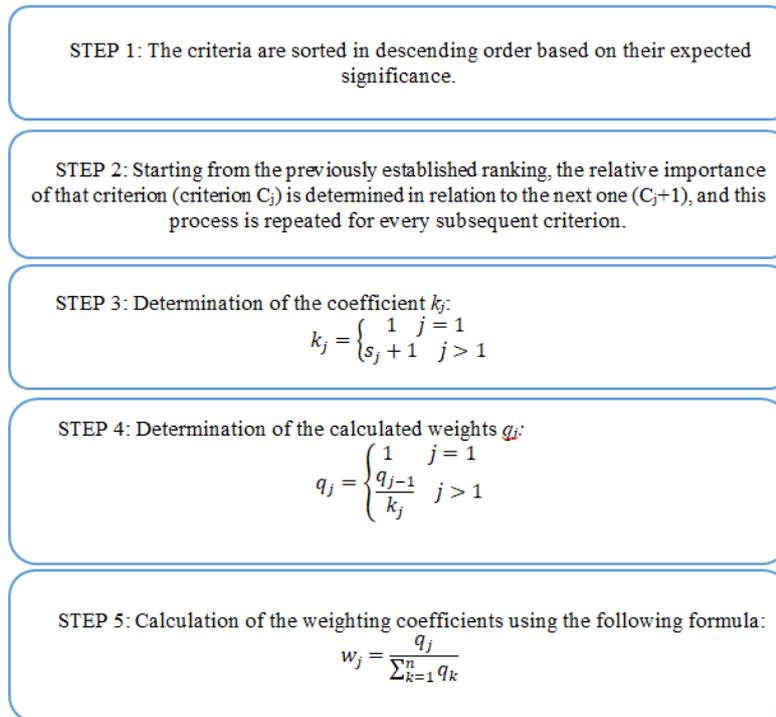


Fig. 2. Steps of the SWARA method

The application of the SWARA method in the identification and classification of key performance indicators (KPIs) in the company IM-TRANSPORT provides an objective and transparent framework for ranking KPIs, reducing the subjectivity of decision-makers, and enabling a clear hierarchy of priorities. The method is particularly suitable for the transport sector, where indicators are interrelated, such as costs, distance traveled, vehicle utilization, and route efficiency, thus allowing for the quantification and comparison of multiple criteria simultaneously. The result is a practical and easily applicable tool for optimizing business processes, strategic resource planning, and enhancing operational efficiency, while simultaneously laying the foundation for performance monitoring standardization and business modernization in line with European Union practices.

4 Application of the SWARA Method for Identifying Key Performance Indicators in Transport

The company IM-TRANSPORT has been operating in both international and domestic road transport for over twenty years. The company has over 60 employees, includ-

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ing three dispatchers in international transport who manage the organization and logistics of 50 freight vehicles. In addition, the company owns vans and tankers used to supply fuel for its own gas station. The dispatchers are long-time employees of the company and are well acquainted with the business operations, challenges, and obstacles encountered in this service industry. In this paper, they made a great contribution by identifying the most significant KPIs relevant to the transport sector.

By applying the SWARA method, the main performance indicators in transport were ranked in the first part of the calculation, as shown in Table 1.

Table 1. Main indicators

	S _j	K _j =S _{j+1}	q _j	w _j
C9 – Transport costs	1.000	1.000	1.000	0.217
C2 – Kilometers traveled	0.300	1.300	0.769	0.167
C1 – Vehicle utilization	0.250	1.250	0.615	0.133
C3 – Completed routes	0.333	1.333	0.462	0.100
C4 – Completed tours	0.000	1.000	0.462	0.100
C7 – Time spent in transport	0.000	1.000	0.462	0.100
C5 – Number of loadings	1.000	2.000	0.231	0.050
C6 – Number of unloadings	0.000	1.000	0.231	0.050
C8 – Shipment value and value of damaged goods	0.200	1.200	0.192	0.042
C10 - Complaints	0.000	1.000	0.192	0.042

Based on Table 1, it can be concluded that the most important indicator relates to transport costs, followed in significance by the indicator covering kilometers traveled. The vehicle utilization indicator ranks third, while the indicators related to completed routes, completed tours, and time spent in transport are equally significant. The number of loadings and the number of unloadings are 0.050 less significant than the previous three indicators. Shipment value and the value of damaged goods, along with complaints, occupy the lowest positions with equal values.

As previously stated, the most significant indicator is the one related to transport costs. In this regard, Table 2 shows the weighting coefficients of the sub-criteria from the Transport costs group.

Table 2. Weights of sub-criteria from the Transport costs group

	S _j	K _j =S _{j+1}	q _j	w _j	w _j ² =w _j *w ₁
C6 – Transport cost per kilometer traveled	1.000	1.000	1.000	0.183	0.03972
C1 – Average daily transport cost	0.375	1.375	0.727	0.133	0.02889
C7 – Transport cost per driver	0.000	1.000	0.727	0.133	0.02889
C2 – Transport cost per completed route	0.143	1.143	0.636	0.117	0.02528
C3 – Transport cost per completed tour	0.000	1.000	0.636	0.117	0.02528
C9 – Fuel cost per total kilometers traveled	0.000	1.000	0.636	0.117	0.02528
C8 – Average daily maintenance cost	0.167	1.167	0.545	0.100	0.02167
C4 – Transport cost per completed loading	1.000	2.000	0.273	0.050	0.01083
C5 – Transport cost per completed unloading	0.000	1.000	0.273	0.050	0.01083

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From Table 2, it can be concluded that the most significant sub-criteria in the Transport costs group are: transport cost per kilometer traveled, average daily transport cost, and transport cost per driver. After applying the SWARA method to all sub-criteria, a ranking was obtained consisting of all 62 indicators. Table 3 shows the 16 most significant key performance indicators in transport.

Table 3. Selected KPI in transport

	Criteria	Weight	Rank
1.	Transport cost per kilometer traveled	0.03972	1
2.	Number of kilometers traveled per vehicle	0.03611	2
3.	Average number of kilometers traveled per day	0.03333	3
4.	Coefficient of vehicle time utilization	0.02889	4
5.	Coefficient of vehicle utilization in operation	0.02889	4
6.	Average daily transport cost	0.02888	6
7.	Transport cost per driver	0.02888	6
8.	Number of completed routes per vehicle	0.02833	8
9.	Number of completed routes per driver	0.02833	8
10.	Transport cost per completed route	0.02528	10
11.	Transport cost per completed tour	0.02528	10
12.	Fuel cost per total kilometers traveled	0.02528	10
13.	Average number of completed tours per day	0.02500	13
14.	Number of completed tours per route	0.02500	13
15.	Number of completed tours per vehicle	0.02500	13
16.	Number of completed tours per driver	0.02500	13

Based on the ranked key performance indicators in transport, as shown in Table 3, it can be concluded that the most important is the transport cost per kilometer traveled, followed by the number of kilometers traveled per vehicle, and the average number of kilometers traveled per day. The coefficient of vehicle time utilization, and the coefficient of vehicle utilization in operation are equally significant. Next in importance are the average daily transport cost and the transport cost per driver. Following these indicators, the number of completed routes per vehicle and the number of completed routes per driver are equally significant. Also, equally important are the transport cost per completed route, transport cost per completed tour, and fuel cost per total kilometers traveled. Finally, in the last four positions in terms of significance are: the average number of completed tours per day, the number of completed tours per route, the number of completed tours per vehicle, and the number of completed tours per driver.

KPIs with lower ranks (e.g., 10–16) carry less weight, meaning their impact on overall transport efficiency or the company's strategic goals is not as significant compared to higher-ranked KPIs (1–5). Example: Transportation cost per completed route or per completed stop has lower ranks because the company's total transport costs

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depend more on the total number of kilometers traveled and fleet utilization than on individual routes or stops. Some KPIs are difficult to measure or partially beyond the direct control of management, such as the number of stops completed per driver or per route. Management should prioritize higher-ranked KPIs, as optimizing these parameters yields the greatest impact on efficiency and costs. Lower-ranked KPIs can be improved only after significant progress has been achieved on the priority indicators.

Since this study undertakes the identification and classification of KPIs for a single company in Bosnia and Herzegovina for the first time, it can be concluded that this research differs from previous studies due to its local context. Transport companies in BiH face daily challenges such as infrastructure limitations, administrative hurdles, and driver shortages. In addition, a case study was conducted, providing a concrete analysis that will directly assist this specific company in monitoring its KPIs. The results directly contribute to the optimization of costs.

5 Conclusion

Faced with infrastructural constraints, a complex regulatory environment, and rising operational costs, transport companies in Bosnia and Herzegovina are under pressure to optimize their internal processes. The results of this study indicate that significant improvements can be achieved through structured and strategic management of key performance indicators (KPIs). By applying the SWARA method to a sample of 62 indicators, the most relevant metrics directly affecting operational efficiency, productivity, and cost control were identified, with the most significant being transport cost per kilometer, number of kilometers traveled per vehicle, and average daily performance. It is also evident that indicators related to fleet utilization and route dynamics form the basis for intelligent resource planning.

By establishing a standardized KPI system, the transport sector in Bosnia and Herzegovina can significantly enhance business transparency, improve operational efficiency, and achieve greater compliance with the practices and requirements of the European Union market. Based on the ranked KPIs, transport companies should focus on optimizing transport costs per kilometer and enhancing vehicle efficiency through improved route planning and maximum utilization of vehicle time. It is essential to monitor driver-specific costs and daily transport expenses to identify high-cost routes and drivers and implement control measures, including training and incentives for economical driving. Furthermore, route planning and task allocation should aim to increase the number of completed routes and tours, accompanied by an analysis of costs per route and tour to improve profitability and productivity. Real-time monitoring of all key performance indicators enables informed decision-making and timely corrective actions. The main limitation of this study is that only three decision-makers were included in the analysis. However, all of them are long-term employees of the company with a deep understanding of transport organization, which ensures the reliability of the assessments. Additionally, the diversity of dispatchers' tasks, managing contracted transports versus working with market-based load and unload operations,

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along with their high workload, may limit the timely recording of certain data. These limitations suggest caution when generalizing the results; however, they do not diminish their relevance to the company's operational processes, strategic decision-making, and the continuous optimization of costs and resources.

Future research could focus on transport companies of various sizes in Bosnia and Herzegovina to conduct a more detailed analysis of key performance indicators, incorporating a broader range of experts to enhance the reliability of assessments. Additionally, combining the SWARA method with other MCDM techniques, such as WASPAS or MARCOS, could enable a more precise evaluation of KPIs and improve resource planning, cost optimization, and fleet management strategies.

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Evaluation of the Balkan Countries in Terms of the Logistics Performance Index efficiency

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Abstract. This study examines how effectively the Balkan countries attain logistics process efficiency as measured by the Logistics Performance Index (LPI). Six indicators from this index were used to rank nine Balkan countries. The ranking was conducted using the Entropy and CORASO (COMpromise Ranking from Alternative SOLUTIONS) methods. The results from the Entropy method showed that the most significant LPI indicator was the infrastructure. The ranking derived from the CORASO method suggested that Greece exhibited the highest performance result. These findings were validated through comparative analysis and sensitivity analysis. The results of this study exposed that the Balkan countries which are part of the European Union (EU) demonstrated superior performance in comparison to candidate countries. Therefore, in order to enhance their logistics performance, non-candidate countries ought to aim for full EU membership.

Keywords: Logistics performance, Balkan countries, Entropy method, CORASO method.

1 Introduction

In an environment characterized by perpetual change, it is necessary to maintain an efficient logistics chain that serves as a driver for a country's development and a booster of its competitiveness. Countries with more advanced logistics chains enjoy benefits that allow them to draw in foreign investors, promote exports, and improve productivity. [1]. Acknowledging the importance of logistics in national development, the World Bank has been developing and publishing the Logistics Performance Index (LPI) since 2007, serving as a crucial tool for evaluating logistics performance in various countries [2]. This index offers a comprehensive overview of logistics performance across numerous nations, including those in the Balkans. Additionally, it facilitates cross-country comparisons and assists in identifying which indicators are performing well and which require enhancement [3]. Consequently, the index acts as a reference framework for assessing the efficiency, effectiveness, and reliability of a country's logistics system.

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The robustness of this index is rooted in its indicators, which are derived from holistic assessments. Structured in this manner, the index facilitates the evaluation of logistics performance and offers essential insights into possible areas for enhancement for a specific country. [4]. This is of great significance for researchers and analysts, particularly for national governments, as it assists them in determining what must be enhanced to elevate the LPI, thus promoting national growth and development backed by a sophisticated logistics chain. This chain facilitates the rapid circulation of goods within the country, which is crucial for the diverse operations of business entities, as it guarantees the prompt acquisition of materials and raw inputs in the required quantities [5].

As a well-established indicator of logistics performance, the LPI plays a crucial role in shaping strategies for a country's logistics system [6]. The indicators associated with this index can offer significant insights into the logistics landscape, thus affecting the country's competitive edge. When a country attains elevated LPI scores, it suggests that the country has an advanced logistics system, encouraging international entities to leverage its logistics capabilities [7]. This index does not merely measure logistics performance; it also provides valuable information to various economic stakeholders. This index goes beyond simply assessing logistics performance; it also delivers essential information to a range of economic stakeholders. A high value of this indicator reflects effective resource distribution, robust trade practices, and enhanced national competitiveness.

The LPI has demonstrated its value as a significant tool and has been utilized in various studies. The distinctiveness of this research lies in its concentration on the Balkan countries. Historically, these regions have served as a bridge between East and West since the era of the ancient Roman Empire. These nations are positioned at a pivotal junction, connecting Europe, Asia, and the Middle East, and possess strategic relevance for global transportation. They play a crucial role in international logistics. Nevertheless, these nations show diverse outcomes in logistics performance, alongside differing levels of economic advancement and progress concerning European integration. Some Balkan countries are part of the European Union (EU), whereas others are aspiring members working on reform initiatives to achieve EU membership. This research aims to apply the LPI to the context of the Balkan countries, with the goal of pinpointing the shortcomings of each country and offering recommendations for enhancing their logistics performance. Consequently, the impetus for this research is to leverage the capabilities of Multi-Criteria Decision-Making (MCDM) techniques to evaluate and rank the logistics performance of the Balkan countries.

In light of this, the objective of this research is to assess and rank the Balkan countries regarding their logistics performance, with the intention of offering recommendations for enhancing logistics in these countries. The assessment will utilize MCDM methods. The Entropy method will be employed to ascertain the importance weights of the LPI indicators, whereas the countries will be ranked using the CORASO (COMpromise Ranking from Alternative SOLUTIONS) method. To fulfill this objective, the following research questions are formulated:

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1. What significance do individual LPI indicators hold for ranking Balkan countries?
2. Which Balkan countries are ranked the highest regarding logistics performance?
3. How do the strengths and weaknesses of individual Balkan countries compare to one another?

This research yields a threefold contribution. Firstly, it offers a theoretical contribution by strengthening the theoretical framework of logistics performance studies and introducing new hybrid approaches that integrate various MCDM methods. Secondly, it provides a practical contribution through a methodological approach grounded in real data, enabling the application of the research findings to enhance the logistics performance of the Balkan countries. Lastly, it contributes to the improvement of the regional standing of the Balkan countries by offering guidelines based on the results obtained, which focus on enhancing logistics performance and underscore the significance of these countries' transition and the enhancement of their competitiveness.

2 Methodology and methods

This research will be conducted in the following phases:

- Phase 1. Collection of data on logistics performance
- Phase 2. Preparation of data for analysis
- Phase 3. Implementation of the steps involved in the Entropy method
- Phase 4. Ranking of countries using the CORASO method
- Phase 5. Comparative analysis
- Phase 6. Sensitivity analysis

In the course of this research, it is essential to first gather data regarding logistics performance. The most recognized indicator associated with logistics performance is the LPI. This indicator is compiled by the World Bank and has been officially published in reports since 2007. Up to now, a total of seven reports have been released, encompassing data on logistics performance. The most recent report was published in 2023, and the indicators from this report will be utilized in this research. The LPI indicators are based on six criteria, which will serve as the benchmarks for this research (Table 1).

Table 1. Logistics performance indicators

Id	Indicator	Definition
C1	Customs	Efficiency of customs and border management
C2	Infrastructure	Quality of trade and transport infrastructure
C3	Services	Quality of logistics services
C4	Timeliness	Adherence to delivery schedules
C5	Tracking and tracing	Ability to track and trace shipments
C6	International shipments	Ease of arranging competitively priced international shipments

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Following the identification of the indicators to be utilized for the analysis, it is essential to ascertain which Balkan nations are to be included. Geographically, the analysis encompasses eight countries: Albania, Bosnia and Herzegovina, Bulgaria, Montenegro, Greece, North Macedonia, Serbia, and Romania. Nevertheless, this study will also incorporate Croatia, given that a portion of its territory lies within the Balkans. Consequently, the research will encompass these nine countries.

Following the selection of the report and its indicators, along with the choice of Balkan countries, the subsequent phase commences: preparation of data for analysis. This phase is executed as follows: first, access is gained to the official World Bank website, where the LPI index is found; next, data pertaining to individual indicators for these countries is collected; ultimately, based on this information, the initial decision-making matrix is constructed, which will be showcased in the results of this research.

The subsequent phase of this research involves assessing the significance of individual indicators through the Entropy method. This method is classified as an objective approach for evaluating weight importance, and its purpose is to ascertain the weight of an indicator based on the variability of values among the indicators. A higher dispersion within a particular indicator will result in a greater importance, and conversely, a lower dispersion will indicate lesser importance. This method was selected due to its extensive application in numerous studies, demonstrating favorable outcomes. Its benefits are evident in the following points:

- The weight of the criteria is established based on actual data rather than relying on expert opinions. This approach helps to eliminate bias in the decision-making process.
- This method is founded on the principles of Shannon's information theory, which quantifies the level of uncertainty or indeterminacy present in the data. Consequently, the weights are founded on mathematical principles.
- The computation involved in this method is straightforward, allowing for the determination of the criteria's weight when dealing with extensive data sets. Consequently, this method is applicable to both small and large data sets.

The steps carried out when applying this method are:

Step 1. Formation of the decision matrix

Step 2. Normalization

$$n_{ij} = \frac{x_{ij}}{x_{j \max}}, \quad (1)$$

Where: $x_{j \max}$ is the maximum value of the individual criterion

Step 3. Determining the Entropy Value (E_i)

$$E_i = \frac{\sum_{j=1}^n p_{ij} \ln p_{ij}}{\ln n} \quad (2)$$

Step 4. Calculating criterion weights

$$w_j = \frac{1-E_i}{\sum_{i=1}^m (1-E_i)} \quad (3)$$

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Following the assessment of weight significance through the Entropy method, the fourth phase involves ranking the Balkan countries utilizing the CORASO method. This method represents a more recent approach to ranking alternatives. Its implementation has demonstrated considerable stability in establishing the ranking sequence of alternatives [8]. The reasons for utilizing this method in the current research are as follows:

- The CORASO method employs standard normalization similar to other MCDM techniques, which mitigates the influence of normalization during the ranking of alternatives.
- This method ranks alternatives based on the alternative solutions, specifically the maximum and minimum values of those alternatives.
- The outcomes of the CORASO method reveal whether a specific alternative is nearer to the maximum alternative, resulting in a positive alternative value; conversely, if the alternative is closer to the minimum alternative solution, the value assigned by this method for that alternative is negative.

The steps carried out in this method are as follows:

Step 1. Creation of the decision-making matrix. In this step, this matrix is formed based on the values of alternatives corresponding to specific criteria.

Step 2. Data normalization. In this step, individual alternative values are divided by the maximum value of the alternative for the specific criterion.

$$n_{ij} = \frac{x_{ij}}{\max x_j} \quad (4)$$

Step 3. Determining alternative solutions. The maximal solution represents the highest value of alternatives for a specific criterion, whereas the minimal solution denotes the lowest value of alternatives for that criterion.

Step 4. Weighting the normalized data. In this step, normalized values are multiplied by the weight assigned to the respective criteria.

$$v_j = w_j \cdot n_{ij} \quad (5)$$

Step 5. Aggregate values.

$$S_j = \sum_{i=1}^n \tilde{v}_j \quad (6)$$

Step 6. Deviations from alternative solutions.

$$R_j = \frac{S_j}{S_{j \max AS}} \quad (7)$$

$$R'_j = \frac{S_{j \min AS}}{S_j} \quad (8)$$

Step 7. Determining the value from the CORASO method.

$$Q_i = \frac{R_j - R'_j}{R_j + R'_j} \quad (9)$$

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Once the ranking of the Balkan nations has been established, a comparative analysis will be conducted. The objective of this analysis is to utilize the identical initial decision-making matrix along with the same criteria weights and to ascertain the ranking through various MCDM methods. Consequently, four MCDM methods will be employed in this research to compare the outcomes of these methods with the CORASO method.

The last phase of this research involves performing a sensitivity analysis. The aim of the sensitivity analysis is to adjust the criteria weights and to assess the extent to which changes in these weights influence the ultimate ranking of the alternatives. In this research, the initial weights derived from the Entropy method will be utilized, and the individual values of the criteria will be decreased by 30, 60, and 90%. This approach will minimize the impact of the individual criteria, allowing for an evaluation of how this affects the final ranking of the Balkan countries.

To facilitate the understanding of these phases of the research, they will be illustrated graphically in Figure 1.

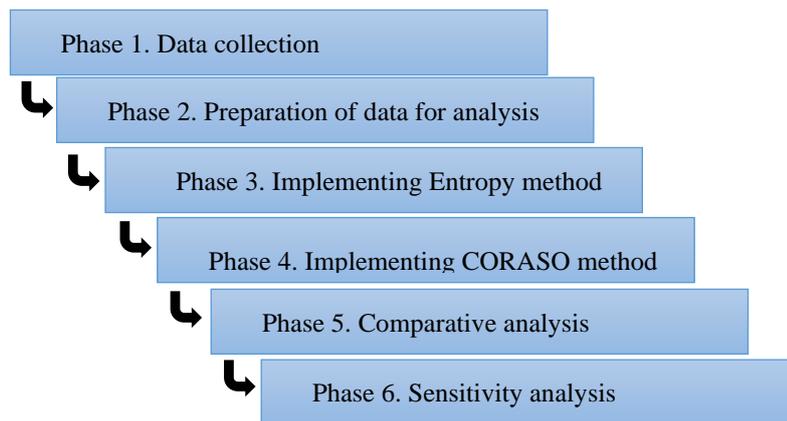


Fig. 1. Phases of the research methodology

3 Results

To ascertain which Balkan country exhibits the most effective logistics performance, it is essential to implement the procedures outlined in the Entropy and CORASO methods. As observed from the procedures of these methods, the initial two steps are identical for both approaches: constructing the initial decision-making matrix and normalizing the data. Consequently, the initial decision-making matrix will be established first. As indicated in the research methodology, this decision-making matrix is created by utilizing the values for the Balkan countries derived from the 2023 LPI report (Table 2).

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Table 2. LPI values for the Balkan countries

	C1	C2	C3	C4	C5	C6
Albania	2.4	2.7	2.8	2.3	2.5	2.3
Bosnia and Herzegovina	2.7	2.6	3.1	2.9	3.2	3.2
Bulgaria	3.1	3.1	3.0	3.3	3.5	3.3
Croatia	3.0	3.0	3.6	3.4	3.2	3.4
Greece	3.2	3.7	3.8	3.8	3.9	3.9
Montenegro	2.6	2.5	2.8	2.8	3.2	3.2
North Macedonia	3.1	3.0	2.8	3.2	3.5	3.2
Romania	2.7	2.9	3.4	3.3	3.6	3.5
Serbia	2.2	2.4	2.9	2.7	3.4	2.9

The next step of these methodologies involves the normalization of the initial decision-making matrix. In this step, the maximum values for the indicators across these countries are first identified, after which the individual country values for the indicators are divided by these maximum values (Table 3). This process results in the formation of the normalized decision-making matrix.

Table 3. Normalized LPI values for the Balkan countries

	C1	C2	C3	C4	C5	C6
Albania	0.750	0.730	0.737	0.605	0.641	0.590
Bosnia and Herzegovina	0.844	0.703	0.816	0.763	0.821	0.821
Bulgaria	0.969	0.838	0.789	0.868	0.897	0.846
Croatia	0.938	0.811	0.947	0.895	0.821	0.872
Greece	1.000	1.000	1.000	1.000	1.000	1.000
Montenegro	0.813	0.676	0.737	0.737	0.821	0.821
North Macedonia	0.969	0.811	0.737	0.842	0.897	0.821
Romania	0.844	0.784	0.895	0.868	0.923	0.897
Serbia	0.688	0.649	0.763	0.711	0.872	0.744

According to the values derived from the normalized decision-making matrix, it is clear that Greece exhibits the highest indicators across all LPI criteria and will consequently be ranked first. Nevertheless, in order to establish the rank for the other countries, the subsequent steps of these methods will be executed.

To determine the weight of the LPI indicators, the steps of the Entropy method will be executed. Given that this method has been applied in various studies, the remaining steps of the method will not be elaborated in detail but will be described in terms of how they were computed. After establishing the normalized decision-making matrix, it is essential to compute the entropy value, which serves as the foundation for determining the criterion weights. This value is derived by initially calculating the natural logarithm of the normalized values, then multiplying these normalized values by their corresponding natural logarithm values, and subsequently summing these products across all criteria. The resulting total is then divided by the natural logarithm of the number of observed countries, which is nine, to yield the entropy value. Ultimately,

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one is subtracted from the entropy value and divided by the total difference between one and the entropy value, thereby producing the final weight value of the LPI indicators (Table 4). According to the steps undertaken in the Entropy method, the findings indicate that the Infrastructure indicator (C2) holds the highest significance ($w_2 = 0.183$), followed closely by the Timeliness indicator (C4) ($w_4 = 0.172$). Consequently, the Balkan countries must enhance infrastructure indicators pertaining to transport infrastructure and the improvement of goods delivery.

Table 4. Weight values of LPI indicators obtained by applying the Entropy method

	C1	C2	C3	C4	C5	C6
E_i	-0.478	-0.775	-0.630	-0.668	-0.528	-0.627
	C1	C2	C3	C4	C5	C6
w_j	0.152	0.183	0.168	0.172	0.157	0.168

After establishing the criterion weights, the Balkan countries are ranked based on the LPI values. Once normalization is completed, weighting occurs, wherein the normalized values are multiplied by their respective weights. This step is standard in all MCDM methods. Subsequently, the alternative solutions are identified, which consist of the highest and lowest values of the weighted data for each criterion. Next, the maximum and minimum alternative solutions are recognized, indicating the highest and lowest values of the alternatives for every criterion. Thereafter, all these alternatives, including the alternative solutions, are aggregated (Table 5). Ultimately, the deviation from the alternative solutions is computed, and the rank is established utilizing the CORASO method. The findings indicated that Greece ranked as the top Balkan country in terms of LPI, followed by Croatia and then Romania. From these results, it can be inferred that EU countries exhibit the most favorable characteristics concerning LPI indicators, succeeded by North Macedonia and then Bosnia and Herzegovina. The Balkan country with the lowest ranking is Albania.

Table 5. Ranking of Balkan countries using the CORASO method

	S_j	R_j	R'_j	Q_i	Rank
Albania	0.675	0.675	0.964	-0.176	9
Bosnia and Herzegovina	0.792	0.792	0.822	-0.019	6
Bulgaria	0.866	0.866	0.752	0.070	4
Croatia	0.879	0.879	0.740	0.086	2
Greece	1.000	1.000	0.651	0.211	1
Montenegro	0.764	0.764	0.851	-0.054	7
North Macedonia	0.843	0.843	0.772	0.044	5
Romania	0.867	0.867	0.751	0.072	3
Serbia	0.735	0.735	0.885	-0.092	8
MAX AS	1.000				
MIN AS	0.651				

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The reasons for these outcomes are as follows: Greece achieved the highest indicators across all LPI criteria, which is the reason for its first-place ranking. Croatia needs to enhance all indicators to surpass Greece. Nevertheless, Croatia lacks the indicators necessary for second place; consequently, it must focus on improving criteria C2, C5, and C6, as Bulgaria and Romania have demonstrated superior indicators in these areas. Therefore, Croatia should prioritize the enhancement of these three indicators before addressing the others. The lowest performance was recorded by Albania, which possesses the weakest indicators for five criteria. As a result, this country must engage in various initiatives to enhance its logistics performance.

To assess the outcomes derived from the CORASO method, a comparative analysis will be conducted. For this comparative analysis, alongside the CORASO method, four additional methods have been chosen: FUCA (Faire Un Choix Adéquat in French), SAW (Simple Additive Weighting), MABAC (Multi-Attributive Border Approximation Area Comparison), and ARAS (Additive Ratio Assessment). It is noteworthy that the FUCA method does not employ data normalization [9]. This method evaluates alternatives according to their values and multiplies these values by the corresponding weight. Owing to its defined steps, this method was utilized for comparative analysis. The SAW method is recognized as the most straightforward MCDM method, which establishes the rank order through two phases (normalization and weighting). Because of its ease of use, this method is advised for comparative analysis [10]. The MABAC method is distinctive because it employs intricate linear normalization, and the weighting differs from that of other MCDM methods [11]. The alternative in this method is ranked in relation to the average value of the weighted data [12]. The ARAS method, like MABAC, uses a different normalization, i.e., percentage normalization. The ranking of this method is based on the optimal function [13]. By using these methods, the influence of normalization on determining the final ranking is eliminated.

The results obtained from this comparative analysis (Figure 2) demonstrate that the rank order is only altered with the FUCA method. This is due to the fact that it does not rely on the initial values of the indicators, but rather uses them for the purpose of ranking, ultimately determining the final order based on the established ranking. Consequently, Croatia's position deteriorated with this method, whereas Bulgaria's position improved by two ranks. The other methods applied demonstrated no differences in rankings when compared to the CORASO method. From these results, it can be inferred that the CORASO method's outcomes are validated, with Greece exhibiting the most favorable results.

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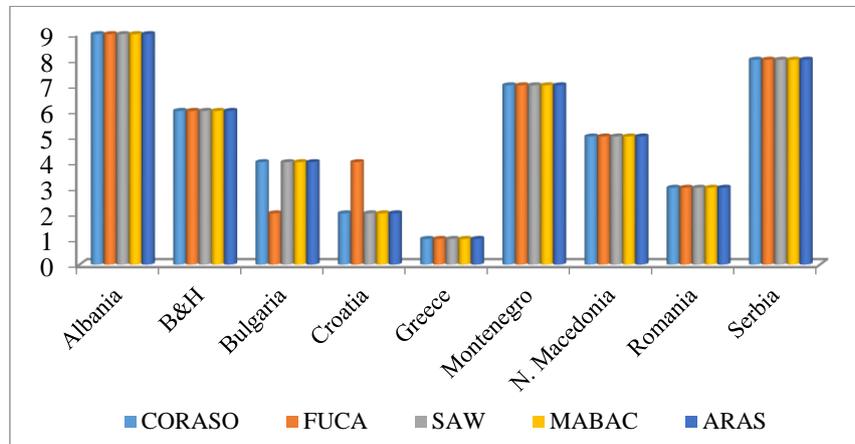


Fig. 2. Results of the comparative analysis

As mentioned during the sensitivity analysis, each individual criterion will be adjusted by 30%, 60%, and 90%. Given that there are six indicators in the LPI measurement, a total of 18 scenarios will be executed. The indicators that remain unchanged will be proportionally increased to ensure that their total weight is roughly equal to one.

The findings of this analysis indicated a shift in the ranks of the Balkan countries (Figure 3) corresponding to changes in the weights of specific criteria. The most significant changes were observed in Romania. This country was typically positioned third; however, following a 90% reduction in the Customs indicator, it ascended to second place. This shift can be attributed to Romania's inferior performance on this indicator compared to Croatia, which allowed it to rank higher when the impact of this indicator diminished. Conversely, when the Services indicator experienced a 90% change, Romania's ranking suffered the most, resulting in it being surpassed by North Macedonia and Bulgaria. This outcome is explained by Romania's previously superior indicators in comparison to these countries for this criterion, leading to a decline in its ranking as the influence of this indicator waned. Thus, other ranking changes can be analyzed in relation to the baseline scenario, which reflects the initial rankings based on weights derived from the Entropy method.

Through the implementation of sensitivity analysis, all Balkan nations have the opportunity to enhance their logistics performance by formulating specific strategies. Romania needs to address the Customs indicator, while Bulgaria must enhance one of the three indicators related to Services, Tracking and Tracing, and International Shipments to surpass Romania. Additionally, North Macedonia is required to improve the Services indicator to exceed Romania's performance. Other countries must work on improving multiple indicators to attain superior logistics performance, as the analysis indicates that altering a single indicator is insufficient to affect the ranking of these countries.

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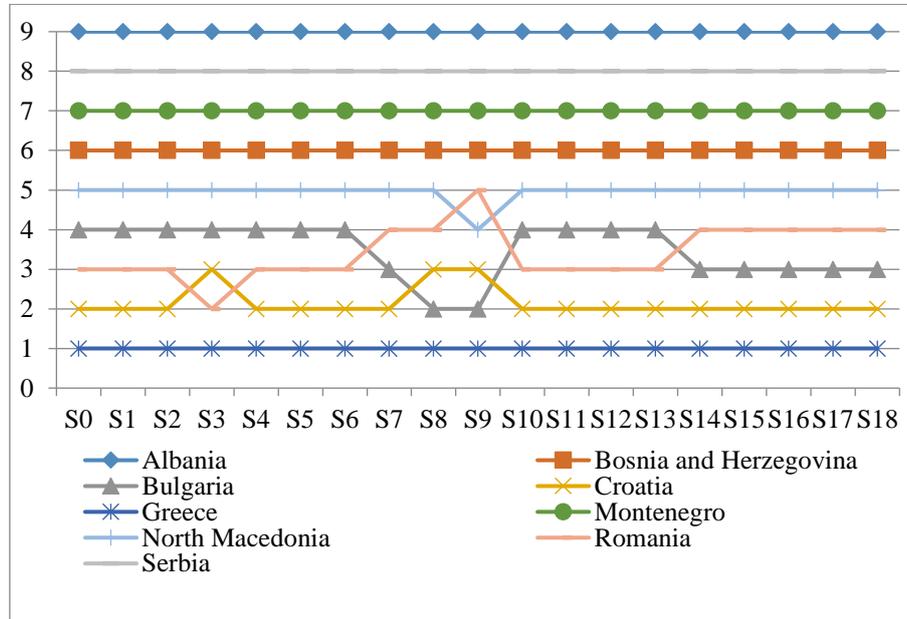


Figure 3. Results of the sensitivity analysis

4 Discussion

This study was conducted to evaluate the logistics performance of the Balkan countries for the year 2023. For this purpose, the Logistics Performance Index (LPI) released by the World Bank was utilized. It is important to highlight that the World Bank does not issue this index annually; thus, prior to 2023, the last publication of this index occurred in 2018. Consequently, there was a five-year gap in the release of this report. The LPI index acts as a mechanism to pinpoint solutions and opportunities for nations within the trade and logistics domain [14]. Therefore, it is essential for countries to identify the six indicators monitored by this index where they fall short compared to others and to focus on enhancing these indicators. Naturally, it is also crucial to acknowledge the indicators where they excel relative to other nations. On these indicators, they should leverage their strengths in logistics and trade performance to capitalize on these advantages.

Nevertheless, this research primarily concentrated on examining the status of the LPI index within the Balkan countries. The study encompassed nine Balkan countries, either entirely situated on the Balkan peninsula or partially located there. To facilitate a comparison among these nations, a methodology grounded in MCDM techniques was employed. Specifically, the Entropy and CORASO methods were utilized for this purpose. The findings derived from the Entropy method indicated that Infrastructure emerged as the most significant indicator. This particular indicator exhibited the highest level of dispersion among the indicators of the countries under observation, thus

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warranting the greatest emphasis. Consequently, it is imperative for the Balkan countries to prioritize the enhancement of their infrastructure to improve their transportation links. In addition to Infrastructure, Timeliness also represents a crucial criterion. This criterion underscores the necessity for logistics operations in these countries to be executed punctually and in accordance with the delivery schedule. Only through such adherence can trust be established, leading to an increase in activities transiting through these countries.

The CORASO results indicated that Greece had the highest indicators among the Balkan nations, with Croatia following closely behind. What distinguishes Greece from its counterparts is its superior performance across all six LPI indicators. Consequently, any methodology employed, along with any alternative techniques utilized to ascertain the criteria weights and the rankings, would yield the conclusion that Greece is the top-ranked nation among the other Balkan countries. This was evidenced through the execution of comparative and sensitivity analyses, in which Greece consistently secured the first position in each ranking. Conversely, nations such as Albania, Serbia, Montenegro, and Bosnia and Herzegovina exhibited unsatisfactory results concerning the LPI indicator. Therefore, these countries must adopt strategic measures to enhance their logistics performance, thereby improving their LPI indicators and increasing their competitiveness in the market.

The findings indicated that the Balkan countries that are part of the EU exhibit superior indicators in comparison to other Balkan countries that are aspiring to join the EU. One contributing factor to this is that EU member states have more effective regulations and standards governing logistics operations in these countries. Additionally, there is a greater investment in enhancing infrastructure and customs regulations that are applicable in these countries. EU member states benefit from agreements that allow for reduced tariffs within EU countries, and in some cases, no tariffs at all. This arrangement enables these countries to operate cohesively, providing them with a significant advantage over other European nations.

5 Conclusion

This research has revealed the status of logistics performance in the Balkan countries. These performances were assessed according to the 2023 LPI report. By employing a hybrid methodology that integrates the Entropy and CORASO methods, it was shown that Greece exhibited the highest indicators across all LPI criteria when compared to other Balkan nations. Conversely, Albania displayed nearly all the lowest LPI indicators and was identified as the lowest-performing country regarding logistics performance in this research. Additionally, this research indicated that the logistics performance of Balkan countries that are EU members surpasses that of those that are EU candidate countries. Consequently, non-EU countries must prioritize improvements in customs policy and border crossings, followed by enhancements in other indicators, as they currently trail EU member states in all indicators. Only in the area of shipment tracking do a few countries match the values of Croatia. These

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findings substantiate the notion that EU membership plays a significant role in enhancing the logistics performance of countries. Therefore, candidate countries should aim to achieve EU membership, at least to elevate their logistics performance.

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Maritime Transport

Barriers to Blockchain Technology in Ports: The Case of Samsun Port

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Abstract. Nowadays, the applications of blockchain technology are increasing day by day, directly impacting transparency, efficiency, and service quality in businesses. Consequently, blockchain technology has become an essential component that requires close attention. Applications such as bringing all stakeholders together on a common platform and establishing a unified data language have emerged as critical and indispensable issues in port operations, especially as the digitalization process accelerates and data security becomes a priority. However, various obstacles exist that hinder the implementation of blockchain technology and need to be addressed. Accordingly, identifying the barriers to blockchain technology applications in port operations has become not just an option but a necessity. Existing literature, however, addresses these barriers only to a limited extent and does not explore them sufficiently. To fill this gap, this study proposes the Interval-valued p,q,r-Spherical Fuzzy SWARA model. The study identifies “Technological Infrastructure Deficiencies” as the most significant barrier.

Keywords: Blockchain, Barriers to Blockchain Technology Applications, Port Operations, Interval-valued p,q,r-Spherical Fuzzy SWARA.

1 Introduction

Nowadays, the virtual world has merged with the real world, and data has become a highly valuable commodity. With the Fourth Industrial Revolution, data sharing between objects and people is offered through smarter systems, creating opportunities for new applications by integrating with the online world [1]. In this context, in recent years, developed countries have continued to invest in blockchain technology to gain a competitive advantage. Especially in an environment where product variety has increased globally while the market has contracted, competition has intensified significantly, leading firms to search for alternative areas of competition. This situation has directed companies more towards supply, logistics, and technological activities rather than product diversity and quality [2].

Blockchain is defined as a decentralized database technology that protects against alterations and enables verified transactions among users. Research has shown that

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blockchain reduces issues of distrust and doubt by presenting verified transactions in a completely transparent manner to all participants. In addition, through a data access system and consensus mechanism, it allows users to manage and monitor their transactions on the network. By offering innovations in various fields (such as industry, finance, and healthcare), blockchain has increased its popularity with its immutable structure [3]. Blockchain has been defined as a transparent, distributed, tamper-proof, and robust data structure in which the reliability of transactions carried out on the network is verified by the stakeholders of the network [4].

Blockchain is a revolutionary core technology that was initially applied in digital currencies and later expanded to a wide range of other fields. It provides advantages such as decentralization, transparency, resistance to tampering, and accessibility of information [5]. The significance of blockchain undoubtedly lies in the features it encompasses. This technology has three fundamental characteristics: first, the ability to conduct transactions without reliance on any central authority, individual, or group; second, the fact that every piece of information recorded in the system is absolutely irreversible and undeletable, with a permanent historical copy always available; and third, the requirement of identity verification before initiating transactions, where each user possesses a personal private key [6].

One of the applications of blockchain technology in supply chains is in logistics operations. Logistics is a broad field that includes processes such as materials management, supply chain planning, warehousing, transportation, and distribution. Its main objective is to ensure that goods and services are delivered at the right cost, to the right place, at the right time, and in the right manner. The use of blockchain technology in the logistics sector makes supply chain management more effective and reliable. Blockchain technology helps optimize logistics processes, reduce costs, and enhance trust among parties [7]. Moreover, this technology is transparent, secure, efficient, traceable, and cost-saving. It is formed by the sequencing of multiple data blocks, encrypted with a unique cryptographic structure, and recorded in a secure and transparent manner through its distinctive verification mechanism. Developing this technology and equipping it with performance-enhancing features provides innovation-oriented qualities that improve operational efficiency and accelerate processes [8].

Although blockchain technologies offer many benefits to businesses, various obstacles have been encountered in practice. Overcoming these obstacles would not only enhance performance in port operations but also contribute to addressing the requirements of efficiency, transparency, and security. Furthermore, the relevant literature reveals significant and critical gaps on this subject. Therefore, this study demonstrates that no decision support system or decision-making framework has been employed in the context under consideration, and that decision-making processes continue to rely primarily on traditional evaluation methods.

The primary objective of this study is to comprehensively examine the barriers to the adoption of blockchain technology in the port industry and to identify the significance levels of these barriers. Using the case of Samsun Port, the analysis aims to reveal the specific challenges encountered in the sector and to evaluate their impacts on operational efficiency, transparency, and digital transformation processes. In doing so, the

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study seeks to fill the gap in the literature on the integration of blockchain technology into port management and to provide concrete insights that can guide policymakers and practitioners.

Consequently, the study serves as a guide for addressing these shortcomings. Finally, the decision-making framework proposed in this study to address the relevant decision problem contributes to filling the existing theoretical and methodological gaps in the literature, thereby offering valuable insights for researchers in the field. In this regard, the proposed approach for evaluating the barriers to blockchain technologies in port operations provides a robust and reliable theoretical framework for academic studies, research, and practical solutions. Thus, the study may serve as a critical reference point, particularly for researchers focusing on solving decision-making problems in this domain. In this context, the study aims to identify the barriers to blockchain technology applications in port enterprises operating in the province of Samsun and to propose solutions using the Interval-valued p,q,r -Spherical Fuzzy SWARA model. The study consists of four sections. The second section presents a literature review on blockchain technologies in enterprises. The third section covers the introduction of the methods employed in the study. In the final section, the research is concluded by presenting policy recommendations, outlining future research plans, and discussing the limitations of the current study.

2 Literature Review

This section presents studies on blockchain and the barriers to blockchain technologies.

- The study provides an empirical overview of the current state of blockchain and distributed ledger technology usage in both the private and public sectors [9].
- Proposed and discussed the concept of a blockchain-based voting system in their study [10].
- Emphasized that storing patient data on blockchain could help overcome the shortcomings of existing models [11].
- Investigated the analysis of blockchain technology implementation in corporate environments [12].
- Proposed a framework system using a blockchain-based smart contract algorithm to manage the painting works of a construction project by considering cost, duration, and quality factors [13].
- Examined blockchain technology, its current applications, and potential other uses of the protocol, offering various recommendations [14].
- Explained the relationship between blockchain technology and the Internet of Things, noting that processes can be automated via smart contracts, thereby ensuring secure verification, cost savings, and time efficiency [15].
- Investigated how blockchain systems operate and the security services they provide, including data integrity, usability, privacy, and fault tolerance [16].

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- Analyzed the definition, advantages, and disadvantages of blockchain technology [17].
- Evaluated the applications of blockchain technology in smart logistics, focusing on information, transportation, finance, and management [18].
- Conducted a bibliometric analysis of blockchain technologies based on data from 613 articles obtained from supply chain research [19].
- Discussed the development and infrastructure of blockchain, explaining its advantages for the supply chain and its applied use cases [20].
- Evaluated the role of blockchain technology in the recycling of waste products within the context of sustainable logistics [21].
- Examined a manufacturer's logistics outsourcing strategies in relation to green logistics, greenwashing, and blockchain [22].
- Investigated the feasibility and performance impact of blockchain technology using established models [23].
- Provided an evaluation and recommendations regarding the use and future of blockchain technology in the logistics sector [2].
- Examined how blockchain can ensure document security in libraries, address issues related to the exchange and storage of electronic documents, and support processes such as archiving and document tracking [24].
- Conducted a systematic literature review on blockchain in logistics, analyzing 113 articles according to a two-dimensional framework [25].

The detailed literature review presented above highlights a significant gap: research on the extent and levels of barriers to blockchain technology adoption remains quite limited. This indicates the necessity of examining the issue more thoroughly from both theoretical and practical perspectives. In particular, identifying the degree of importance of different barriers is critical for developing feasible strategies within the industry. In this context, the present study is expected to make original and meaningful contributions to the literature, not only in terms of its methodological approach but also through its chosen area of application.

3 Methodology

In determining the significance levels of the barriers to blockchain technology applications in port enterprises operating in Samsun, the Interval-valued p,q,r-Spherical Fuzzy SWARA method was utilized. In this section, the explanations regarding Interval-valued p,q,r-Spherical Fuzzy Sets, and the Interval-valued p,q,r-Spherical Fuzzy SWARA method are provided.

3.1 Interval-valued p,q,r- Spherical Fuzzy Sets

A component of uncertainty, membership degrees, can be expressed as a range rather than a single fuzzy value thanks to interval-valued fuzzy sets. Degrees of member-

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ship, non-membership, and neutrality may require different expressive powers and have different importance and constraints. The importance of membership, non-membership, and neutral intervals of degrees vary accordingly. For such situations, the interval-valued-p,q,r-spherical fuzzy set (IV-p,q,r-SFS) is a useful tool. IV-p,q,r-SFSs are broader than many fuzzy sets, including FS, IFS, PyFS, PFS, SFS, T-SFS, IVFS, IVIFS, IVPyFS, IVPFS, IVSFS, and IVT-SFS [26]. Because of its characteristics, IV-p,q,r-SFSs are a valuable tool for resolving multi-criteria decision-making problems.

Assume that Z be a discourse universe. Then, an IV-p,q,r-SF set \tilde{A} on Z is defined as $\tilde{A} = \{(\alpha, \tilde{\mu}_{\tilde{A}}(\alpha), \alpha, \tilde{\eta}_{\tilde{A}}(\alpha), \alpha, \tilde{\nu}_{\tilde{A}}(\alpha)) | \alpha \in Z\}$, where $\tilde{\mu}_{\tilde{A}}$, $\tilde{\eta}_{\tilde{A}}$, and $\tilde{\nu}_{\tilde{A}}$ are mappings from Z to the set of closed subintervals of range $[0,1]$. Here, the membership function is represented as $\tilde{\mu}_{\tilde{A}} = [\mu_{\tilde{A}}^L, \mu_{\tilde{A}}^U]$, the non-membership function is denoted as $\tilde{\eta}_{\tilde{A}} = [\eta_{\tilde{A}}^L, \eta_{\tilde{A}}^U]$, and the neutral membership function is depicted as $\tilde{\nu}_{\tilde{A}} = [\nu_{\tilde{A}}^L, \nu_{\tilde{A}}^U]$. For all $\alpha \in Z$, the condition $0 \leq (\mu_{\tilde{A}}^U)^p(\alpha) + (\eta_{\tilde{A}}^U)^q(\alpha) + (\nu_{\tilde{A}}^U)^r(\alpha) \leq 1$. Moreover, the refusal degree is defined as $\tilde{\pi}_{\tilde{A}} = [\pi_{\tilde{A}}^L, \pi_{\tilde{A}}^U]$, where $\pi_{\tilde{A}}^L = \left(1 - \left((\mu_{\tilde{A}}^U)^p(\alpha) - (\eta_{\tilde{A}}^U)^q(\alpha) - (\nu_{\tilde{A}}^U)^r(\alpha)\right)^{\min\{p,q,r\}}\right)^{\min\{p,q,r\}}$, and $\pi_{\tilde{A}}^U = \left(1 - \left((\mu_{\tilde{A}}^L)^p(\alpha) - (\eta_{\tilde{A}}^L)^q(\alpha) - (\nu_{\tilde{A}}^L)^r(\alpha)\right)^{\min\{p,q,r\}}\right)^{\min\{p,q,r\}}$ [26].

For convenience, the triplet $\langle [\mu_a^U, \mu_a^U], [\eta_a^U, \eta_a^U], [\nu_a^U, \nu_a^U] \rangle$ is called IV-p,q,r-SF number (IV-p,q,r-SFN) a . Let a_1 and a_2 be two IV-p,q,r-SFNs. Then, the basic operations, the score function, and the accuracy function are defined as below [26]:

$$\delta_1 \oplus \delta_2 = \left\langle \left[\sqrt[p]{(a_1)^p + (a_2)^p - (a_1)^p(a_2)^p}, \sqrt[p]{(b_1)^p + (b_2)^p - (b_1)^p(b_2)^p} \right], \right. \quad (1)$$

$$\left. \begin{aligned} & [c_1 c_2, d_1 d_2], \\ & \left[\sqrt[r]{(1 - (a_2)^p)(e_1)^r + (1 - (a_1)^p)(e_2)^r - (e_1)^r(e_2)^r}, \right. \\ & \left. \sqrt[r]{(1 - (b_2)^p)(f_1)^r + (1 - (b_1)^p)(f_2)^r - (f_1)^r(f_2)^r} \right] \end{aligned} \right\rangle$$

$$\delta_1 \otimes \delta_2 = \langle [a_1 a_2, b_1 b_2], \quad (2)$$

$$\left[\sqrt[q]{(c_1)^q + (c_2)^q - (c_1)^q(c_2)^q}, \sqrt[q]{(d_1)^q + (d_2)^q - (d_1)^q(d_2)^q}, \right. \\ \left. \left[\sqrt[r]{(1 - (c_2)^p)(e_1)^r + (1 - (c_1)^p)(e_2)^r - (e_1)^r(e_2)^r}, \right. \right. \\ \left. \left. \sqrt[r]{(1 - (d_2)^p)(f_1)^r + (1 - (d_1)^p)(f_2)^r - (f_1)^r(f_2)^r} \right] \right]$$

$$\lambda \delta = \left\langle \left[\sqrt[p]{1 - (1 - (a)^p)^\lambda}, \sqrt[p]{1 - (1 - (b)^p)^\lambda} \right], [(c)^\lambda, (d)^\lambda], \quad (3)$$

$$\left[\sqrt[r]{(1 - (a)^p)^\lambda - (1 - (a)^p - (e)^r)^\lambda}, \sqrt[r]{(1 - (b)^p)^\lambda - (1 - (b)^p - (f)^r)^\lambda} \right] \rangle$$

$$\delta^\lambda = \left\langle [(a)^\lambda, (b)^\lambda], \left[\sqrt[q]{1 - (1 - (c)^p)^\lambda}, \sqrt[q]{1 - (1 - (d)^p)^\lambda} \right], \quad (4)$$

$$\left[\sqrt[r]{(1 - (c)^q)^\lambda - (1 - (c)^q - (e)^r)^\lambda}, \sqrt[r]{(1 - (d)^q)^\lambda - (1 - (d)^q - (f)^r)^\lambda} \right] \rangle$$

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$$S(\delta) = \frac{[(a)^p(1 - (c)^q - (e)^r)] + [(b)^p(1 - (d)^q - (f)^r)]}{3} \quad (5)$$

$$A(\delta) = \frac{[(a)^p(1 + (c)^q + (e)^r)] + [(b)^p(1 + (d)^q + (f)^r)]}{3} \quad (6)$$

Assume that δ_j be a collection of IV-p,q,r-SFNs, where $j = 1, \dots, n$. Accordingly, the IV-pqr-SF weighted arithmetic aggregation operator (IV-p,q,r-SFAWO) and the IV-p,q,r-SF weighted geometric aggregation operator (IV-p,q,r-SFGWO) for IVpqr-SFNs are given below, where $\omega = (\omega_1, \dots, \omega_n)$ is the weight vector, $0 \leq \omega_j \leq 1$, and $\sum_{j=1}^n \omega_j = 1$ [26]:

$$\begin{aligned} & \text{IV-p, q, r-SFAWO}(\delta_1, \dots, \delta_m) = \\ & \left(\sqrt[p]{1 - \prod_{j=1}^n (1 - (a_j)^p)^{\omega_j}}, \sqrt[p]{1 - \prod_{j=1}^n (1 - (b_j)^p)^{\omega_j}}, [\prod_{j=1}^n (c_j)^{\omega_j}, \prod_{j=1}^n (d_j)^{\omega_j}], \right. \\ & \left. \sqrt[r]{\prod_{j=1}^n (1 - (a_j)^p)^{\omega_j} - \prod_{j=1}^n (1 - (a_j)^p - (e_j)^r)^{\omega_j}}, \right. \end{aligned} \quad (7)$$

$$\left. \sqrt[r]{\prod_{j=1}^n (1 - (b_j)^p)^{\omega_j} - \prod_{j=1}^n (1 - (b_j)^p - (f_j)^r)^{\omega_j}} \right) \quad (8)$$

$$\begin{aligned} & \text{IV-p, q, r-SFGWO}(\delta_1, \dots, \delta_m) \\ & = \left(\left[\prod_{j=1}^n (a_j)^{\omega_j}, \prod_{j=1}^n (b_j)^{\omega_j} \right], \left[\sqrt[q]{1 - \prod_{j=1}^n (1 - (c_j)^p)^{\omega_j}}, \sqrt[q]{1 - \prod_{j=1}^n (1 - (d_j)^p)^{\omega_j}} \right] \right. \end{aligned}$$

$$\left. \sqrt[r]{\prod_{j=1}^n (1 - (c_j)^q)^{\omega_j} - \prod_{j=1}^n (1 - (c_j)^q - (e_j)^r)^{\omega_j}}, \right. \quad (9)$$

$$\left. \sqrt[r]{\prod_{j=1}^n (1 - (d_j)^q)^{\omega_j} - \prod_{j=1}^n (1 - (d_j)^q - (f_j)^r)^{\omega_j}} \right) \quad (10)$$

The normalized Hamming distance (H_{δ_1, δ_2}) and the normalized Euclidean distance measures (E_{δ_1, δ_2}) between IVpqr-SFSNs δ_1 and δ_2 are provided below [26]:

$$\begin{aligned} H_{\delta_1, \delta_2} = \frac{1}{6} (& |(a_1)^p - (a_2)^p| + |(b_1)^p - (b_2)^p| + |(c_1)^q - (c_2)^q| + |(d_1)^q - (d_2)^q| \\ & + |(e_1)^r - (e_2)^r| + |(f_1)^r - (f_2)^r|) \end{aligned} \quad (12)$$

$$E_{\delta_1, \delta_2} = \sqrt{\frac{1}{6} (|(a_1)^p - (a_2)^p|^2 + |(b_1)^p - (b_2)^p|^2 + |(c_1)^q - (c_2)^q|^2 + |(d_1)^q - (d_2)^q|^2 + |(e_1)^r - (e_2)^r|^2 + |(f_1)^r - (f_2)^r|^2)} \quad (13)$$

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The normalized Hamming distance (H_{δ_1, δ_2}) and the normalized Euclidean distance measures (E_{δ_1, δ_2}) between IVpqr-SFSNs δ_1 and δ_2 are provided below [26]:

$$H_{\delta_1, \delta_2} = \frac{1}{6} (|(a_1)^p - (a_2)^p| + |(b_1)^p - (b_2)^p| + |(c_1)^q - (c_2)^q| + |(d_1)^q - (d_2)^q| + |(e_1)^r - (e_2)^r| + |(f_1)^r - (f_2)^r|) \quad (14)$$

$$E_{\delta_1, \delta_2} = \sqrt{\frac{1}{6} (|(a_1)^p - (a_2)^p|^2 + |(b_1)^p - (b_2)^p|^2 + |(c_1)^q - (c_2)^q|^2 + |(d_1)^q - (d_2)^q|^2 + |(e_1)^r - (e_2)^r|^2 + |(f_1)^r - (f_2)^r|^2)} \quad (15)$$

3.2 Interval-valued p,q,r- Spherical Fuzzy SWARA

The implementation steps listed below will be followed.

Step 1. The process of determining the criteria is carried out. In addition, the experts whose opinions will be consulted are also determined. In this context, the criteria are characterized by $C = \{C_1, \dots, C_n\}$, the experts by $U = \{U_1, \dots, U_z\}$, where $j = 1, \dots, n; k = 1, \dots, z$.

Step 2. Experts determine the importance levels of the criteria and the performance of the options on these criteria by using the linguistic terms in Table 1. $t_{jk} = \langle [\mu_{jk}^U, \mu_{jk}^U], [\eta_{jk}^U, \eta_{jk}^U], [v_{jk}^U, v_{jk}^U] \rangle$ represents the IV-p,q,r-SF importance of j-th criterion determined by k-th expert.

Table 1. The linguistic terms and their IV-p,q,r-SF counterparts.

Code	Linguistic Terms	IV-p,q,r-SF Numbers					
		μ_{a^U}	b	c	d	e	f
EH	Extremely High	0.85	0.9	0.1	0.15	0.1	0.15
VH	Very High	0.75	0.85	0.15	0.2	0.15	0.2
H	High	0.65	0.75	0.2	0.25	0.2	0.25
A	Average	0.5	0.65	0.25	0.35	0.25	0.35
L	Low	0.2	0.55	0.3	0.4	0.45	0.55
VL	Very Low	0.15	0.4	0.25	0.35	0.55	0.65
EL	Extremely Low	0.01	0.3	0.2	0.25	0.65	0.75
Code	Linguistic Terms	IV-p,q,r-SF Numbers	0.2	0.15	0.2	0.75	0.85
		μ_{a^U}	0.15	0.1	0.15	0.85	0.95

In the study of Ali and Naem (2023), we observe a certain approach for determining the value of the p,q,r triplet [27]. Similarly, it is acceptable to select the smallest value triple that will meet the condition $0 \leq (\mu_A^U)^p(\alpha) + (\eta_A^U)^q(\alpha) + (v_A^U)^r(\alpha) \leq 1$ for a scale due to the logic presented in Karaaslan and Karamaz (2024) [26]. Accordingly, p=2, q=2, r=3 will be employed in this case for the IV-p,q,r-SFNs which correspond to the scale in Table 1.

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Step 3. The weights of experts are determined. In this study, we will give equal weights to experts.

Step 4. The IV-p,q,r- SF integrated importance values of criteria $t_j = \langle [\mu_j^U, \mu_j^L], [\eta_j^U, \eta_j^L], [v_j^U, v_j^L] \rangle$ are computed via the IV-p,q,r-SFAWO specified in Eq. (7).

Step 5. The crisp importance values of criteria $\mathcal{S}(t_j)$ are calculated by applying Eq. (5).

Step 6. The ranking order of criteria is determined according to their $\mathcal{S}(t_j)$ values.

Step 7. The comparative importance of each criterion c_j is determined by subtracting the $\mathcal{S}(t_j)$ value of the second important criterion from the $\mathcal{S}(t_j)$ value of the first important criterion in the pairwise comparison based on the criteria rankings. The same process is performed for all ordered pairs of criteria. On the other hand, $c_j = 1$ is determined for the first placed criterion.

Step 8. The revised comparative importance of each criterion λ_j is computed using Eq. (16)

$$\lambda_j = \begin{cases} 1, & \text{if } j = 1, \\ c_j + 1, & \text{if } j \neq 1. \end{cases} \quad (16)$$

Step 9. The non-normalized weight of each criterion ζ_j is calculated by applying Eq. (17).

$$\zeta_j = \begin{cases} 1, & \text{if } j = 1, \\ \frac{\zeta_{j-1}}{\lambda_j}, & \text{if } j \neq 1. \end{cases} \quad (17)$$

Step 10. The weight of each criterion is determined using Eq. (18).

$$w_j = \frac{\zeta_j}{\sum_{j=1}^n \zeta_j}. \quad (18)$$

4 Application

In this study, a multi-criteria decision model was developed to identify the barriers to blockchain technology applications in port enterprises operating in Samsun. First, based on the decision model, a literature review and expert opinions were used to determine the criteria related to the barriers to blockchain technology applications in port operations. Since the identified criteria do not have the same level of importance, it is necessary to rank them. Within this scope, the Interval-valued p,q,r-Spherical Fuzzy SWARA method was employed to rank the barriers to blockchain technology applications in port enterprises.

During the criteria determination process, opinions were obtained from a total of five experts, including four port managers and one academician. In line with previous studies and theoretical frameworks, the criteria representing the key factors affecting the adoption of blockchain technology in ports were selected, constituting a managea-

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ble number that aligns with the objectives of the study. During the expert selection process, managers experienced in port management and operations, as well as individuals possessing knowledge and expertise relevant to the focus of the study, were preferred.

Additionally, relevant literature, including the studies of [28], [29], [30], [31] [32], [33], [34],[35] and [36] was reviewed to construct Table 2.

Table 2. List of Criteria

Criteria	
C1	High Costs
C2	Lack of Laws and Regulations
C3	Bringing All Stakeholders Together on a Common Platform
C4	Establishing a Common Data Language
C5	Adaptation of Customs Authorities to Blockchain Technologies
C6	Individuals or Companies Not Fully Familiar with Blockchain Technology
C7	Technological Infrastructure Deficiencies
C8	Lack of Trust in Blockchain Technologies
C9	Other Barriers (e.g., Number of Qualified Users, Training Requirements, Lack of Visionary Investors)

Experts evaluated the importance of criteria using the linguistic terms provided in Table 1. These evaluations are presented Table 3.

Table 3. The linguistic evaluations of criteria provided by experts.

Table 3. The linguistic evaluations of criteria provided by experts.

Expert	C1	C2	C3	C4	C5	C6	C7	C8	C9
U1	H	A	VH	H	A	L	VH	A	A
U2	VH	L	L	A	L	A	H	H	A
U3	H	A	A	A	H	VH	VH	VH	A
U4	H	L	L	H	A	VH	H	A	VL
U5	H	A	VH	VH	H	A	VH	H	L

The IV-p,q,r-SF integrated importance values of criteria are presented in Table 4.

Table 4. The IV-p,q,r-SF integrated importance values of criteria

		C1				C2					
μ_a^U	μ_a^U	η_a^U	η_a^U	ν_a^U	ν_a^U	μ_a^U	μ_a^U	η_a^U	η_a^U	ν_a^U	ν_a^U
0.674	0.775	0.189	0.239	0.190	0.239	0.415	0.474	0.255	0.331	0.541	0.640
		C3				C4					
μ_a^U	μ_a^U	η_a^U	η_a^U	ν_a^U	ν_a^U	μ_a^U	μ_a^U	η_a^U	η_a^U	ν_a^U	ν_a^U
0.577	0.681	0.193	0.251	0.465	0.526	0.627	0.720	0.222	0.289	0.326	0.388
		C5				C6					
μ_a^U	μ_a^U	η_a^U	η_a^U	ν_a^U	ν_a^U	μ_a^U	μ_a^U	η_a^U	η_a^U	ν_a^U	ν_a^U
0.539	0.624	0.235	0.302	0.437	0.512	0.604	0.701	0.210	0.276	0.418	0.480

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C7						C8					
μ_a^U	μ_a^U	η_a^U	η_a^U	ν_a^U	ν_a^U	μ_a^U	μ_a^U	η_a^U	η_a^U	ν_a^U	ν_a^U
0.715	0.817	0.168	0.219	0.171	0.219	0.627	0.720	0.222	0.289	0.326	0.388
C9											
μ_a^U	μ_a^U	η_a^U	η_a^U	ν_a^U	ν_a^U						
0.411	0.465	0.241	0.317	0.574	0.673						

The results of IV-p,q,r-SWARA are given in Table 5.

Table 5. The results of IV-p,q,r-SWARA.

Criterion	$\mathcal{S}(t_j)$	c_j	λ_j	ζ_j	w_j	Rank
C7	0.7238	0.0000	1.0000	1.0000	0.1419	1
C1	0.6422	0.0816	1.0816	0.9245	0.1312	2
C8	0.5341	0.1081	1.1081	0.8344	0.1184	3
C4	0.5341	0.0000	1.0000	0.8344	0.1184	3
C6	0.4770	0.0571	1.0571	0.7893	0.1120	5
C3	0.4264	0.0506	1.0506	0.7512	0.1066	6
C5	0.3712	0.0552	1.0552	0.7120	0.1010	7
C2	0.1944	0.1768	1.1768	0.6050	0.0858	8
C9	0.1826	0.0119	1.0119	0.5979	0.0848	9

The most important criterion is “C7 Technological Infrastructure Deficiencies. The identification of “C7 Technological Infrastructure Deficiencies” as the most important criterion does not imply that the study’s findings are superficial. On the contrary, this result is the outcome of a systematic and quantitative analysis aimed at identifying the primary barriers to the adoption of blockchain technology in ports. Its contribution to the literature includes highlighting the most critical barrier, providing guidance for policy and strategy development, and offering insights that help fill existing research gaps. High costs affecting the adoption of blockchain technology in ports are frequently cited as a key barrier in the literature. This study demonstrates that high costs are not limited to initial investments but also encompass long-term financial burdens such as maintenance, training, and sustainable implementation. Thus, it contributes to the literature by emphasizing the need to assess high costs in a multidimensional and systematic manner. Additionally, this finding highlights the importance of prioritizing cost factors in the context of the port industry and provides a foundation for the development of more comprehensive blockchain adoption models.

5 Conclusion

Nowadays, digital transformation in businesses and achieving efficiency in business processes are considered important components. However, perspectives toward newly emerging technologies lead to various obstacles and difficulties. In particular, due to the lack of knowledge about the innovations and conveniences that blockchain

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technology can bring, prejudices arise in businesses, and various barriers hinder institutions from adopting this technology.

In this context, the study analyzes the factors related to the barriers to the implementation of blockchain technology in port operations. The study proposes a decision-making procedure composed of Interval-valued p,q,r-Spherical Fuzzy Sets methods. Evaluating the study within the relevant methodological framework aims to analyze the barriers to blockchain technology adoption in port operations and to fill critical research gaps in the related literature.

The results of the study indicate that the most significant barrier is “Technological Infrastructure Deficiencies.” This finding demonstrates that giving greater importance to technological infrastructure can increase efficiency and performance in port operations. Relevant port operators can achieve improvements in business processes and establish stronger future-oriented strategies by investing more in technological infrastructure.

The results obtained from this study can be directly applied to facilitate the adoption of blockchain technology in ports and support digital transformation processes: Policy and strategy development: Prioritizing the identified barriers enables port authorities to focus their investment and improvement plans on the most critical areas. Technological infrastructure improvement: Identifying technological infrastructure deficiencies as the most critical barrier helps ports prioritize digital infrastructure investments. Training and awareness programs: When barriers related to human resources and management processes are identified, training and awareness programs can be implemented to enhance staff knowledge and skills. Process optimization and integration: A systematic analysis of barriers facilitates planning steps that increase the feasibility of implementing blockchain technology in port operations.

It is important to address the study’s limitations more critically in the conclusion or discussion section. For instance, the sample size and the selected expert group may limit the generalizability of the findings. Additionally, focusing solely on Samsun Port restricts the direct applicability of the results to other ports or different geographic contexts. Future research should provide clearer and more actionable recommendations, such as conducting similar analyses in different ports and logistics contexts, examining the impact of emerging technological developments, modeling cost and infrastructure barriers in greater detail, and performing comparative studies based on quantitative data. This approach enhances the critical depth of the research while increasing the reliability and applicability of both academic and practical outcomes.

In summary, the study’s findings provide concrete guidance for both strategic decision-making and practical implementation in port management. Future studies and research can apply the proposed model or an improved version of it in different countries and cities, validate its applicability, and further develop the model in this context. Therefore, future research may also investigate the impact of changes related to blockchain technology adoption in port operations on the applications of other businesses

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Enhancing Ship Traffic Capacity with Microscopic Modelling: The Świnoujście–Szczecin Waterway Case Study

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Abstract. This study addresses the problem of increasing congestion and limited passing opportunities on the Świnoujście–Szczecin fairway, a critical maritime transport route in Poland. To evaluate possible improvements, a microscopic traffic model within a Monte Carlo simulation framework was developed and applied to three scenarios: current traffic conditions in 2022, projected traffic growth beyond 2025 without infrastructure changes, and projected traffic with the construction of an additional passing lane in the Policki Canal. The results show that without intervention, annual vessel delays may rise to over 200 ship-days, while the passing lane reduces delays by approximately 17% and lowers congestion-related costs by about USD 0.5 million annually. The main contribution of this research lies in demonstrating how stochastic traffic modeling can support infrastructure planning, confirming that the passing lane is a strategic investment for the long-term efficiency and competitiveness of the Szczecin–Świnoujście port complex.

Keywords: Waterway capacity, vessel traffic simulation, Monte Carlo method, passing lane, port infrastructure planning, congestion reduction.

1 Introduction

Managing ship traffic on narrow inland waterways demands advanced modeling techniques that can support both strategic infrastructure development and day-to-day operational planning. The Świnoujście–Szczecin fairway, one of Poland’s key maritime transport routes, faces mounting pressure from growing port activity and the arrival of larger vessels enabled by the “12.5 m Project.”

To alleviate these constraints, the construction of a passing lane in the Policki Canal has been suggested as a way to reduce traffic conflicts and improve overall navigational performance. The present study examines the expected effects of such an intervention with the aid of a purpose-built microscopic simulation tool (Fig. 1).

Traditional capacity assessment methods, derived from ship domain concepts, remain static and cannot capture the inherently random nature of vessel traffic. For this rea-

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son, modern research increasingly applies stochastic simulations [1, 2, 3]. Various techniques have been explored, including alternating-passage modeling [4; 5], discrete optimization [6], queuing theory [7], and cellular automata [8]. In most cases, vessel domains are used as safety envelopes defining interaction rules between ships [9]. The effectiveness of a traffic system is usually described by two core measures:

- the amount and distribution of vessel delay,
- the average queue length and its variability.

Recent studies confirm the growing role of simulation-based approaches in optimizing vessel traffic capacity in ports and waterways. Monte Carlo and microscopic models have been applied to assess the effects of deepening and channel restrictions [10, 11]. Microscopic simulation frameworks have also been developed to optimize port access and berth allocation, highlighting the importance of vessel interaction rules [12, 13]. Furthermore, the integration of agent-based and behavioral modeling has been demonstrated to enhance traffic management efficiency under VTS coordination [14]. A more recent contribution is the application of mixed simulation methods for port traffic modeling, which combines stochastic and deterministic techniques to achieve higher accuracy [15]. These studies collectively confirm that simulation models are indispensable for both strategic infrastructure planning and operational traffic management in modern ports.

The present results provide a rare empirical case study from the Baltic region, showing that a targeted passing lane can significantly reduce delays under projected traffic growth. This aligns with international findings that local infrastructure upgrades yield system-wide benefits. Unlike general port-level models, the study links stochastic traffic behavior directly to investment evaluation, strengthening the practical relevance of microscopic simulations for long-term waterway planning.

While previous simulation studies have examined port capacity, berth allocation, or general vessel traffic flows, few have focused on a specific constrained fairway under realistic operational conditions. The novelty of this study lies in applying a validated microscopic Monte Carlo-based traffic model to the Świnoujście–Szczecin waterway, explicitly incorporating the design and operational role of a new passing lane in the Policki Canal. This approach not only quantifies the impact of future traffic growth on vessel delays but also translates these delays into measurable economic costs. By linking stochastic traffic behavior with infrastructure investment outcomes, the study provides practical decision support for maritime authorities and port planners, offering insights directly applicable to long-term waterway development in a major European transport corridor.

Earlier studies validated a stochastic traffic model for the Świnoujście–Szczecin route using real delay observations [16, 17], confirming its suitability for practical applications. Building on that foundation, the present work focuses on the potential benefits of adding a passing lane within the Policki Canal (Fig. 1).

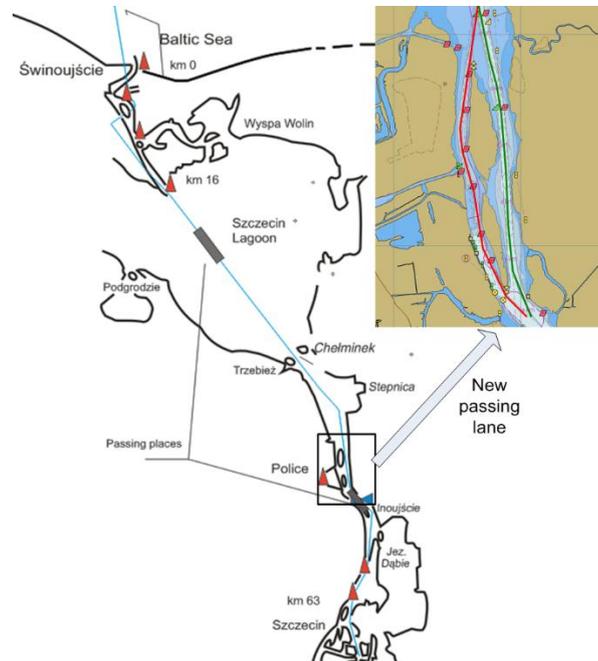


Fig. 1. Location of the proposed deep-water passing lane in the Policki Canal (marked in red) and the existing 12.5 m deep-water fairway (marked in green).

2 Aim of the study and methodology

The study aims to evaluate the impact of constructing a passing lane in the Policki Canal on vessel traffic efficiency along the upgraded Świnoujście–Szczecin fairway. The passing facility is intended to enable full two-way movement of seagoing ships and to mitigate delays under increasing traffic demand. The analysis focuses exclusively on seagoing vessels operating within the main channel; inland craft and leisure boats were excluded.

The methodological framework is based on microscopic traffic modeling within a Monte Carlo simulation approach. To represent passing and overtaking situations, vessels were divided into four principal size categories with an additional subdivision by ballast condition, resulting in six traffic classes (Table 1). These classes determined which vessel combinations could safely meet or overtake each other in specific sections of the fairway (Table 2). Regulatory zones and operational constraints are illustrated in Fig. 2. Within the simulation, matrices of admissible passing widths and draught restrictions were implemented to ensure a realistic representation of vessel encounters.

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Table 1. Adopted division of ships in terms of traffic streams.

Group of ships	Dimensions	Group name (designation)
1 & 2	L < 100m	Small
3 & 4	L ≥ 100m and L < 150m	Medium
5	L ≥ 150m L < 200m	Large
6	L ≥ 200m	Maks

Table 2. Basic principles of traffic regulation on the Świnoujście-Szczecin waterway.

No.	Episode	Kilometer of track "from" [km]	Kilometer of track "to" [km]	Type	Ability to pass in accepted size classes
1a	Port of Świnoujście	0	5.3	Bend/straight	1/1, 1/2, 1/4, 2/2, 2/4
1b	Paprotno/Mielin	5.3	11.4	Bend	1/1, 1/2, 1/4, 2/2, 2/4
1c	Piastowski Canal	11.4	17.0	Straight	1/1, 1/2, 1/4, 2/2, 2/4
2	Szczecin Lagoon N	17.0	23.8	Straight	1/1, 1/2, 1/4, 2/2, 2/3, 2/4, 2/5, 4/4
3	Pass Lagoon BT II-III	23.8	28.8	Passing area	1/2/3/4/5/6
4	Szczecin Lagoon S	28.8	41.0	Straight	1/1, 1/2, 1/4, 2/2, 2/3, 2/4, 2/5, 4/4
5	Mixed N	41.0	49.5	Bend/straight	1/1, 1/2, 1/4, 2/2, 2/4
6	Pass Police (Scenario A and B)	49.5	51.5	Passing area	1/2/3/4/5
6	Police Pass and Police Canal (Scenario C)	43.6	51.5	Passing area	1/2/3/4/5/6
7	Mixed S	51.5	64.0	Bend/straight	1/2, 2/2

Legend: example designations: 1/2 - group 1 can pass with group 2. 1/2/3/4/5/6 - can pass in all groups, 1/2/3/4/5 - can pass in all groups except 6 (Max).

Vessel speeds were assumed according to the speed table taken from Port Regulations (Table 3).

Table 3. Permissible ship speeds [knots] in groups on individual sections of the Świnoujście-Szczecin waterway.

No	Fairway section [km]	Container ship (C _B < 0.65)		Bulk carrier (C _B ≥ 0.75)	
		T > 10 m	T ≤ 10 m	T > 10 m	T ≤ 10 m
1	5.7 ÷ 17.0	8	8	6	6
2	17.0 ÷ 48.5	10	12	8	10
3	48.5 ÷ 54.4	8	10	7	9
4	54.4 ÷ 63.5	7	7	6	6

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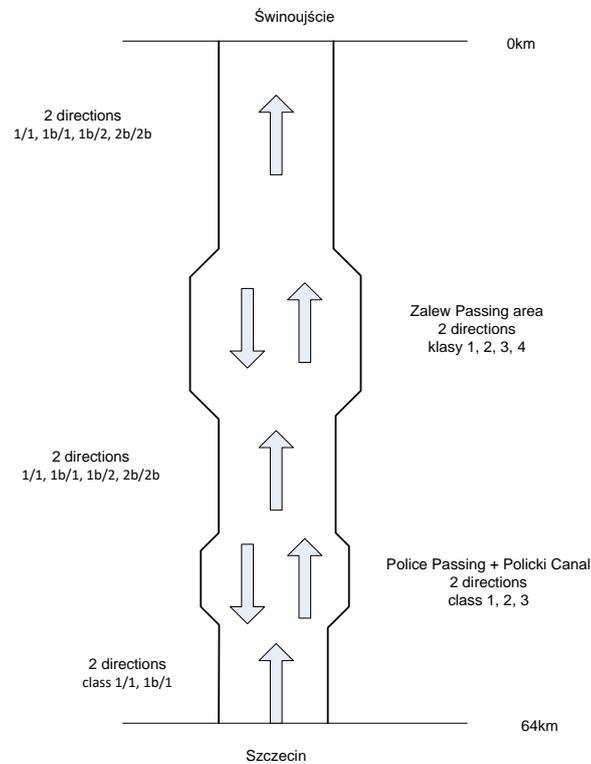


Fig. 2. Basic principles of traffic regulation on the approach of the Świnoujście-Szczecin waterway.

The adoption of arbitrary groups of ships was preceded by an analysis of ship size and a table of width and length ratios of passing ships for the planned Świnoujście-Szczecin waterway, dredged to 12.5 meters.

2.1 Analysis and forecast of traffic volumes

Ship traffic levels at the ports of Szczecin and Police have remained relatively stable, averaging around 3,000 and 300 annual entries, respectively. In contrast, Świnoujście recorded a noticeable upward trend between 2014 and 2021, with traffic volumes growing by roughly 3–5% each year. The rise is largely attributed to intensified ferry operations. Figure 3 illustrates the yearly dynamics of vessel arrivals to the Szczecin–Świnoujście port complex over the period 2009–2021.

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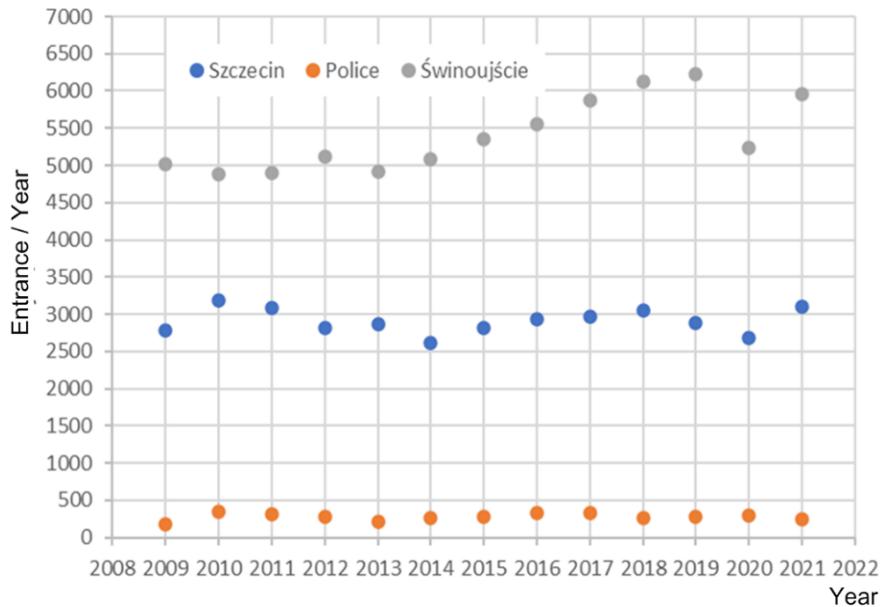


Fig. 3. Dynamics of vessel traffic entering Szczecin, Police and Świnoujście in 2009-2021.

The main criterion for estimating future ship traffic is the assumption that the average intensity of entering ships to Szczecin and Police is 3000 and 300 entries/year, respectively, which corresponds roughly to a ten-year average. Attached to these intensities was the number of estimated maximum ships according to the projects' assumptions, that is, the value of 325 ships per year. The approach track to Świnoujście and Świnoujście itself were not taken into account.

Three traffic scenarios, labeled A, B, and C, were analyzed:

- Scenario A: Baseline conditions for 2022, assuming the upgrading of the main waterway to a 12.5 m depth, but without corresponding modernization of individual wharves and without the construction of a passing facility in the Policki Canal.
- Scenario B: Projected conditions after 2025, assuming a target increase in large vessel traffic to 325 calls per year on the 12.5 m fairway, but without the construction of a passing facility in the Policki Canal.
- Scenario C: Projected conditions after 2025, assuming both the increase in large vessel traffic to 325 calls per year on the 12.5 m fairway and the construction of a new passing facility in the Policki Canal.

The initial parameters for traffic estimation are shown in Table 4.

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Table 4. The assumed growth dynamics of the number of entries of each size group of ships in Szczecin and Police (combined) and the traffic forecast for scenarios A, B, and C.

Group	Dimensions	Baseline frequency for 2022 [%].	Scenario A. 2022 without quays for 12.5m	Scenario B. 2025 completion of all quays for 12.5m	Scenario C. 2025 Traffic as in Scenario B and the passing of the Police Canal
1	L < 100m	59.4	1960	1960	1960
2	L ≥ 100m L < 150m	32.5	1073	1073	1073
3	L ≥ 150m L < 200m	7.2	238	238	238
4	L ≥ 200m	0.9	30	355	355
	Total	100	3300	3625	3625

For the target projected number of ship entrances to Szczecin and Police for each scenario, group traffic intensities were determined for both one-way and two-way traffic. These intensities served as input data for the simulation model.

3 Simulation model for PortSym ship traffic flow study

A dedicated simulator was developed to model vessel movements along the waterway. The simulation approach is microscopic, meaning that each vessel is treated individually as a discrete object. The model operates based on stochastic principles, utilizing a Monte Carlo simulation framework (see Fig. 4).

The simulation logic is organized into three core modules:

- Ship generation and input: Randomized creation of vessels based on defined traffic parameters.
- Movement and queue handling: Vessel progression along the waterway, including queuing when passage is restricted.
- Decision logic for entry and exit: Rules governing when vessels are permitted to enter or leave the simulated waterway sections.

The basic features of PortSym are:

A. Ship Characteristics

- Vessel arrival times are generated according to a Poisson distribution.
- Ship lengths and dimensions are sampled from uniform distributions, constrained within group-specific bounds.
- Vessel speeds are drawn from a truncated normal distribution, with regulatory limits applied as upper bounds.
- It is assumed that 50% of vessels are outbound (seaward) and 50% are inbound (toward port).
- Night-time traffic operations are excluded from the simulation.

B. Waterway Representation

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- The fairway is divided into discrete sections, each characterized by specific passing capabilities and speed restrictions.
- Passing rules between vessel groups are implemented through pre-defined matrices that govern allowable encounters.

C. Movement Logic

- The model verifies whether a vessel can enter the waterway based on the real-time positions of other ships and the applicable passing rules.
- If passage is not possible, the vessel queues until conditions permit safe entry.
- Vessel movement is modeled at constant, section-specific speeds without dynamic speed adjustments.

D. Output and Data Handling

- The simulation logs detailed data for each vessel, including delays, passing events, and queuing statistics.
- Simulation dynamics are driven by three synchronized loops operating at a 1-minute time resolution:
 1. Ship generation and system status logging.
 2. Vessel position updates and verification of passing conditions.
 3. Decision-making for vessel entry permissions.

The model was verified for algorithmic errors using simple, properly selected test input data at the outset.

The data provided by the model makes it possible to analyze the basic parameters of the waterway system's traffic stream.

Model verification was carried out on simple examples for which analytical solutions existed. At a further stage, the model was verified with real track delays [17]. A high convergence of the resulting values was obtained (differences of 10%). For the first time, the model was used during the design of a passing pass at the Szczecin Lagoon for the so-called "12.5m" project (deepening of the Świnoujście-Szczecin track to 12.5m).

The program was written in Python using the PyCharm interpreter and relevant modules. The model was verified for algorithm errors using simple, appropriately selected test input data at the beginning. The hourly intensities for the model are shown in Table 5.

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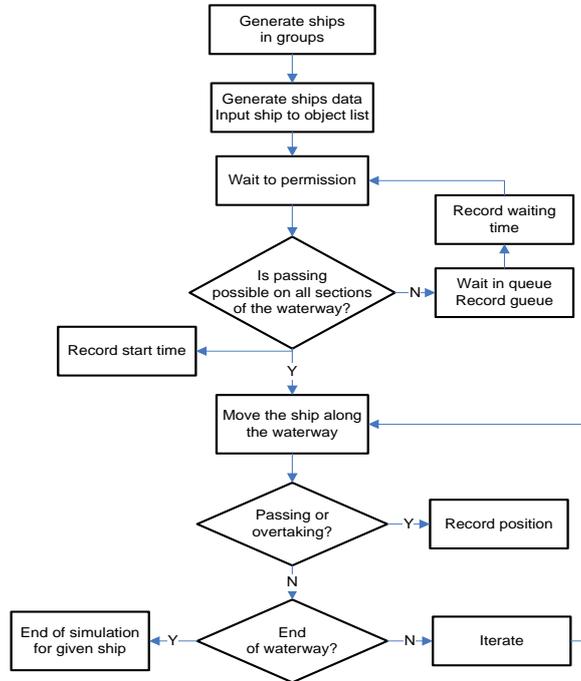


Fig. 4. PortSym model operation diagram for a single vessel

Table 5. Hourly ship intensities [st./h] in one direction (to sea / to port) for each year adopted into the model for the traffic scenarios studied.

Group/year	2022	2025	2035
1	0.1119	0.1119	0.1119
2	0.1119	0.1119	0.1119
3	0.0612	0.0612	0.0612
4	0.0612	0.0612	0.0612
5	0.0136	0.0136	0.0136
6	0.0017	0.0202	0.0202
Total 1 direction of traffic	0.3615	0.3800	0.3800

4 Results of simulation studies of traffic performance on the upgraded track for selected

4.1 Cost of ship downtime

Based on the publication [18], the daily total cost of ships was determined for three different groups: bulk carriers, container ships, and tankers. It was assumed that in

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2020 the cost increased compared to 2006 (about 3% per year - average inflation). Based on these, the daily average cost of operating units in size groups was determined (Table 6). It does not take into account the cost of LNG or LPG units, which, due to the specific cargo, is much higher than analyzed.

Table 6. Averaged daily demurrage costs of ships in groups.

Group	Cost [USD/day]
1 and 2	15000
3 and 4	20000
5	25000
6	30000

4.2 Conduct surveys and analyze their results

The study was conducted for the assumed size groups, their intensities and the adopted traffic stream layout. A simulation time of 365 days (1 year), a simulation step time of 1min and a simulation parameter recording time of 3h were assumed. Simulations of a single scenario take about 1 minute.

The data was analyzed in terms of the basic parameters of the waterway system's traffic stream, including:

1. Distribution and probability of entry/entry queue in classrooms,
2. Classroom lag time,
3. Sums of ships generated in classes,
4. Downtime costs.

Table 7 shows the results of the annual simulation for the projected traffic data in the 3 scenarios considered.

Table 7. Annual downtime in entry and exit groups [days/year]

Group/year	A	B	C
1	29	35	32
2	14	19	14
3	75	74	61
4	31	32	23
5	17	18	16
6	2	27	25
Total	169	205	171

The simulation results (without active traffic control) indicate that annual vessel downtime under current traffic conditions is approximately 170 ship-days per year. However, following the introduction of Group 6 (maximum-sized) vessels, which

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exert the greatest load on the waterway, this figure is projected to increase to around 205 ship-days per year. With the implementation of a passing lane in the Policki Canal, the annual downtime is expected to return to approximately 170 ship-days. The probability of a group queue increases significantly with the traffic load of large vessels is particularly high for the group of maximum and medium (L=150m) loaded vessels (Table 8).

Table 8. Probability of queuing in groups

Group/year	A	B	C
1	3.3%	2.5%	5.5%
2	1.9%	2.7%	3.6%
3	12.3%	14.2%	15.1%
4	3.6%	3.6%	4.4%
5	2.2%	1.6%	3.6%
6	0.3%	3.6%	1.1%

The annual cost of vessel downtime, without the introduction of maximum-sized vessels, is estimated at approximately USD 2.5 million (Table 9). Following the introduction of Group 6 vessels, this cost is projected to increase to around USD 3.1 million per year. However, the implementation of a passing lane in the Policki Canal would reduce the annual downtime cost to approximately USD 2.6 million, representing a 16% reduction.

The net annual savings resulting from the construction of the passing lane are estimated at USD 0.5 million (i.e., USD 3.1 million minus USD 2.6 million). Assuming a service life of 25 years for the facility, the cumulative financial benefit would amount to approximately USD 12.5 million, equivalent to over 50 million PLN.

Table 9. Annual cost of downtime [million USD]

Group/year	A	B	C
1 and 2	0.6	0.8	0.7
3 and 4	1.6	1.6	1.3
5	0.3	0.3	0.2
6	0.0	0.4	0.4
Total	2.5	3.1	2.6

5 Results

The simulation results provide a comprehensive picture of how traffic growth and infrastructure upgrades are likely to influence navigation efficiency on the Świnoujście–Szczecin fairway. The main quantitative findings are as follows:

1. The microscopic Monte Carlo-based traffic model showed close agreement with observed data, with deviations below 10%, confirming its reliability.

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2. Under current conditions (2022), vessel delays amount to about 169 ship-days annually.
3. Without a new passing lane, traffic projections after 2025 indicate an increase in delays to roughly 205 ship-days per year.
4. Introducing a passing lane in the Policki Canal reduces downtime to about 171 ship-days annually, a 17% improvement compared to the no-investment case.
5. The economic effect of the passing lane is estimated at approximately USD 0.5 million in annual savings. Over a 25-year horizon, this equates to more than USD 12.5 million (over 50 million PLN).
6. The greatest delays and queuing risks are associated with medium-size (Group 3) and maximum-size (Group 6) vessels.

6 Conclusions

The results confirm that the existing fairway infrastructure cannot meet future traffic demand once larger ships begin regular operations. The construction of a passing lane in the Policki Canal emerges as a critical measure to maintain navigational efficiency, reduce congestion, and secure the competitiveness of the port complex. The study also shows that infrastructure planning should prioritize vessel classes most affected by delays (Groups 3 and 6).

The main limitation of the present research is that the model excludes active traffic management methods such as VTS-based dynamic scheduling or pilot coordination, as well as external factors like wind, current, and restricted visibility. These aspects may further influence traffic efficiency and should be considered in future extensions of the model.

Future research should focus on integrating dynamic vessel behavior, environmental conditions, and advanced traffic management into the simulation framework. Applying the approach to other constrained waterways would also allow validation of its generalizability and support broader applications in maritime infrastructure planning.

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Bridge Safety: Application for Real-Time HR Streaming

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Abstract. Maritime navigation, particularly during critical operations such as port approaches or nighttime navigation, is demanding. Human error remains a dominant contributing factor in maritime accidents, including groundings and collisions. This paper presents an experimental system for real-time streaming of heart rate (HR) data from a wearable smartwatch to the ship's bridge network, with the aim of assessing the OOW's physiological state. Using Bluetooth Low Energy (BLE), the HR signal is captured and encoded into a NMEA sentence format. The data is then part of standard navigation equipment, such as the bridge navigational watch alarm system (BNWAS), and transmitted through the automatic identification system (AIS), enabling monitoring by shore authorities.

Keywords: Bridge safety, Physiological Monitoring, AIS.

1 Introduction

The purpose of the research is to integrate physiological monitoring with maritime communication networks to enhance situational awareness on ships. Maritime navigation remains one of the complex operational domains, where the safety of the vessel, crew, cargo, and environment depends heavily on the decisions made by OOWs'. Despite ongoing technological advancements in electronic navigation, integrated advanced bridge systems, human error continues to be the leading contributing factor in maritime accidents, groundings, and collisions [1].

Several incidents, including grounding due to misinterpretation of navigational displays, or collisions caused by delayed reaction to alarms, underscore the persistent vulnerability of bridge operations to workload and fatigue in situational awareness [2,3]. Watchkeeping officers operate in high-stress, monotonous, or demanding conditions, particularly during port approaches, narrow channels, traffic separation schemes, or heavy weather. Under the conditions mentioned, physiological states such as fatigue may impair decision-making or lead to delayed responses, often with serious consequences [4,5]. To avoid such a situation, the Bridge Navigational Watch Alarm System (BNWAS) became compulsory in 2002 within the IMO resolution MSC.128(75), which introduced performance standards for BNWAS and established

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the technical foundation for its design. For older vessels the regulations were adopted in 2013. Since BNWAS is implemented on the bridge, the EMSA (2024) report [1] indicates that the contribution of the human element to accidents has decreased from 85% in 2005 to about 80% in 2024. The average number of reported incidents has been 2,660 per year. It appears that investing in better sensors and navigational equipment on the bridge has not managed to reduce the incidence of human-factor causes, so it seems worth trying to equip the officer on watch with physiological sensors.

Thus, the interest in integrating physiological monitoring into maritime operations is growing. The non-invasive measurement of biometric signals - such as heart rate (HR), skin conductance (EDA), or pupil dilation - has the potential to offer real-time insight into the workload and alertness of the OOWs' [6]. Exposure to long monotonous shifts, irregular sleep cycles, and limited physical activity, contributes to fatigue and physiological decline during duty [7]. Continuous physiological monitoring using wearable devices has gained increasing attention as a means to enhance safety in high-risk operational environments, including maritime navigation. By detecting early signs of cognitive overload, fatigue, or drowsiness, such systems can trigger warnings or decision-support mechanisms that improve situational awareness and bridge safety. During monotonous conditions, such as prolonged transits or night watches, officers of the watch are prone to reduced alertness characterized by alpha wave dominance, slower reaction times, and impaired decision-making, which significantly increase the likelihood of navigational errors, collisions, or groundings [8]. Also, in cases where medical emergencies, such as cardiac arrest, occur on the bridge, the inability to respond promptly can have serious consequences. Early detection of such cases through continuous monitoring of physiological signals provides a safety net [9]. By alerting other crew members or shore-based authorities via systems integrated with bridge watch alarms and AIS protocols [10], it may be possible to prevent incidents and improve maritime bridge safety [11].

In the following sections, we present a practical implementation of such an approach: a mobile application capable of streaming OOWs' physiological data in real time from a consumer smartwatch via Bluetooth Low Energy (BLE).

To introduce physiological measurements on the bridge, we begin with comprehensive research, trials, and impact assessments to demonstrate safety benefits and operational feasibility.

The next steps in implementing the idea would be for a sponsoring Member State to submit a formal proposal to the subcommittee, where the results will be discussed, refined, and, if they prove workable, developed into draft performance standards. Pilot projects and correspondence groups would be tasked with assessing human factors, data protection, and cyber risks before a recommendation is forwarded to the Maritime Safety Committee. We assume that the IMO will then, as usual, initially issue a non-binding guideline, while the final inclusion in SOLAS will take more time. Based on the experience with the implementation of the Bridge Navigational Watch Alarm System, it will take an IMO and SOLAS for the next 10 years.

2 Methodology

The ability to detect early signs of physiological changes in officers on watch (OOW) can significantly improve the situational awareness on ships. Monitoring physiological states allows the identification of overload or drowsiness, offering a preventive mechanism to maintain optimal performance. The methods to monitor physiological states, ranging from invasive techniques, such as EEG (electroencephalography) and blood sampling, to non-invasive solutions, such as skin conductance (EDA) and heart rate monitoring. Given the dynamic environment of a ship's bridge, we selected a non-invasive, wrist-worn device for both practical and ethical reasons. A detailed explanation follows in the subsequent subsections, where we describe the instruments and devices used, the participant, and the experimental protocol applied in this study. The structured approach ensures methodological transparency and allows replication or further development of the system in future studies.

2.1 Instrumentation

We employed a commercial-grade smartwatch (*SilverCrest HR Band*), capable of continuously measuring heart rate. The signal is acquired using Bluetooth Low Energy (BLE) communication, processed through a custom-built mobile application (*HRStreamApp*), and converted into a synthetic NMEA sentence format (Fig.1).

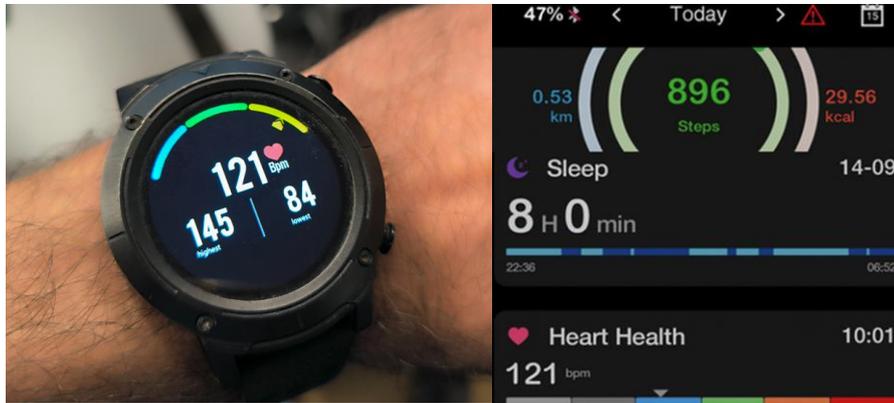


Fig. 1. Left: Commercial smartwatch used for real-time HR monitoring during bridge operations. Right: Commercial application displayed HR data and rest time (Sleep).

The HR data was encoded into a custom NMEA sentence format:

$$\$PHRRT,hmmss,HR,RestCS,$$

where HR indicates the heart rate in beats per minute, and then send via Ethernet to the ship's bridge console and NMEA multiplexer. From there, the data is logged by

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the Voyage Data Recorder (VDR), displayed and monitored on the Information System, and included in the Automatic Identification System (AIS) broadcasts. The configuration supports enhanced situational awareness and improves navigational safety.

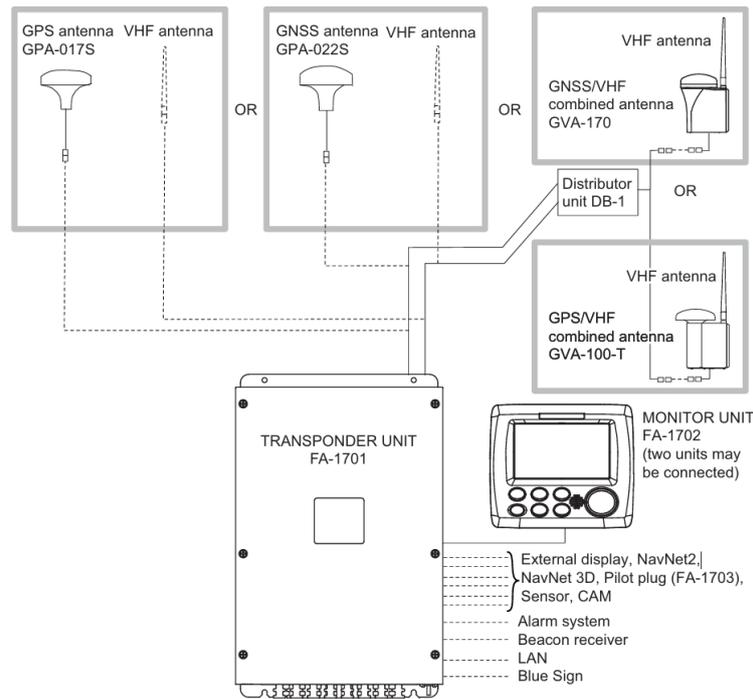


Fig. 2. The essential components of the AIS broadcasting setup. In the center is the Furuno transponder unit responsible for encoding and transmitting AIS data. In the right is the AIS monitor used to configure and observe outgoing messages. On the left the GPS antenna ensures positional accuracy, while the VHF antenna enables data transmission to nearby vessels and coastal stations.

AIS operates on VHF data link using the protocol, where each minute is divided into 2250 slots per channel and all transceivers are synchronized via GPS to avoid overlapping. Within this structure, messages are divided into static and voyage related data, refreshed about every six minutes, and dynamic data such as position, speed, course and heading, refreshed according to vessel speed and maneuvering status, from every few minutes at anchor down to every two seconds at high speed. The system constantly senses the channel and reserves slots, while also identifying free slots that can be used for binary application messages defined under ITU-R M.1371.

To incorporate physiological data into the broadcast for example, a string such as *\$PHRRT,hmmss,HR,RestCS* - it could be inserted into a free slot, which isn't a special reserved space, but simply a time slot not in use. However, it would require that receiving systems are updated to correctly decode and interpret the proprietary pay-

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load to maintain navigational safety, either by inclusion within the functions identifiers (FI) within message 8 (Binary Broadcast Message) or 25 (Single Slot Binary Message). The first is preferable since a lot of similar functionality was included within this frame (e.g., meteorological data (FI=31), route information (FI=27), and number of persons on board (FI=16)). This ASM (Application Specific Message) would be internationally harmonized (i.e., using DAC (Designated Area Code) 1 for international) and an available FI field (e.g., 37 is still available according to the International Organization for Marine Aids to Navigation - [12]) from the reserved range in order to avoid conflicts with the existing architecture. An example of a possible message structure is given in Table 1. The ASM would be transmitted via AIS Message 8, with the following overall structure (per ITU-R M.1371-5 [13]):

Table 1: Structure of the AIS Binary Message for Staff Status Monitoring The table defines the bit allocation, field size, and description of each component. The Staff Entry provides detailed status information for an individual crew member.

Main Fields	Bits	Description
Message ID	6	8 (Binary Broadcast Message)
Repeat Indicator	2	Standard AIS repeat field
Source MMSI	30	Maritime Mobile Service Identity of source
Spare	2	Reserved
DAC	10	1 (International)
FI (Function Identifier)	6	37 – Staff Status Monitoring
Number of Staff Reported	4	Up to 5 recommended
Spare	4	Reserved for future use
Staff Entry (SE)	32	One entry per staff member (repeated for each staff)

Subfields (Staff Entry)	Bits	Description
Staff ID	8	Unique identifier per staff member
Heart Beat Status	8	Heart rate in bpm (0 = undefined)
Fatigue Level	4	0 = undefined, 1 = rested, 14 = extreme fatigue, 15 = reserved
Alert Status	3	0 = undefined, 1 = normal, 2 = warning, 3 = alert, 4 = distress, 5–7 reserved
Location Code	2	0 = undefined, 1 = bridge, 2 = engine room, 3 = undefined
Spare	7	Reserved for future use

For research purposes, the signal was transmitted via the Furuno bridge console FA-1701 (Fig. 2). Onshore, the ships' AIS message, besides standard information, includes the converted NMEA messages, which can be interpreted as virtual "HR/Rest" physiological states, giving remote observers insight into the condition of navigators aboard. The setup mimics the integration of physiological awareness into the ship's navigational information system, representing a proof-of-concept for real-time biometric situational awareness.

2.2 Participants

At this stage, the system was tested in a pilot trial involving one experienced participant, during training in the nautical simulator. The aim of the test was to evaluate the functionality of real-time data integration into maritime communication systems.

2.3 Research Protocol

The research was designed as a single-case observational study. The participant wore the smartwatch throughout a 10-minute watchkeeping session during routine navigation. The heart rate signal was captured and streamed using the *HRStreamApp*, converted into NMEA format, to simulate physiological telemetry. No behavioral intervention was applied. The goal was to observe whether changes in heart rate—naturally occurring during a routine watch—could be captured and interpreted using ship's information system.

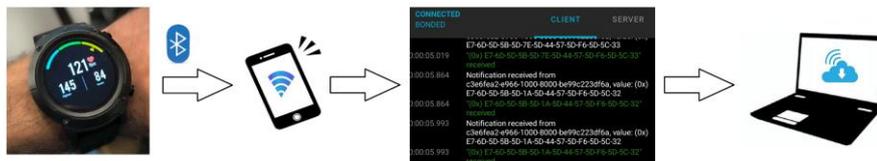


Fig. 3. The experimental design: data collection consists from a smartwatch, transmission via Bluetooth to a mobile application and upload to the ship's information center.

2.4 Data Analysis

Data was recorded in both raw BLE HR values and converted NMEA sentences. Post-test analysis focused on verifying signal continuity and alignment between raw HR and NMEA representation, and usability and stability of the mobile app and BLE connection under operational conditions. The objective was functional verification, thus confirming the technical feasibility of the HR-to-NMEA integration concept in a realistic maritime environment.

3 Results

A mobile phone app first scans for nearby Bluetooth Low Energy devices and establishes a connection with the sensor. Whenever new data is available the device pushes a packet to the phone. Each packet is a sequence of bytes. The following bytes contain the raw heart rate value. On the phone, these bytes are displayed in hexadecimal format (Figure 4), before being decoded and converted into an NMEA sentence.

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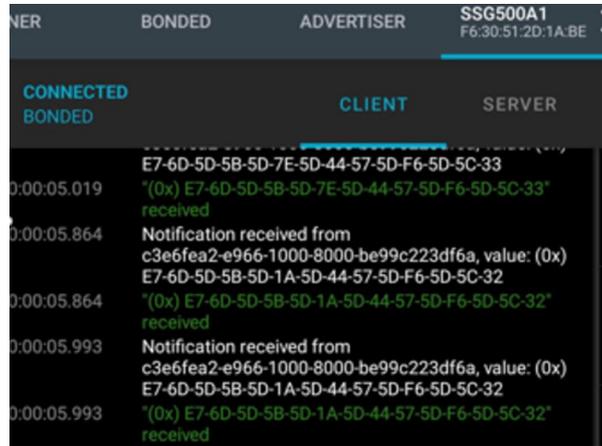


Fig. 4. Extracted BLE signal displayed in hexadecimal format, representing raw HR data prior to conversion into NMEA sentences.

Table 2: Extracted HEX to decimal value

timestamp	hex	HR[bpm]
08:02:15.511	9B-11-21-30-21-2F-21-61-61-26-0A-23-1C-3A-84-C2	97
08:02:15.512	9B-11-21-30-21-2F-21-61-61-26-0A-23-1C-3A-84-C2	97
08:02:16.548	9B-11-21-30-21-1B-21-63-61-2A-45-7B-1C-3E-9F-56	99
08:02:16.548	9B-11-21-30-21-1B-21-63-61-2A-45-7B-1C-3E-9F-56	99
08:02:17.524	9B-11-21-30-21-AC-21-67-61-32-F6-2B-1C-0D-29-10	103
08:02:17.524	9B-11-21-30-21-AC-21-67-61-32-F6-2B-1C-0D-29-10	103
08:02:18.499	9B-11-21-30-21-AD-21-69-61-39-31-43-1C-11-01-E4	105
08:02:18.500	9B-11-21-30-21-AD-21-69-61-39-31-43-1C-11-01-E4	105

The heart rate value is stored in the byte directly before the marker 0x61. This byte is written in hexadecimal and must be converted into decimal to obtain beats per minute. For example, in the sequence ... -63-61- ... the value 63 in hex equals 99 in decimal, so the heart rate is 99 bpm. (Table 2).

Table 3: NMEA log

HR[bpm]	REST TIME[hours]	NMEA
97	8	\$PHRRT,080200,97,8*5C
97	8	\$PHRRT,080201,97,8*5D
99	8	\$PHRRT,080202,99,8*50
99	8	\$PHRRT,080203,99,8*51
103	8	\$PHRRT,080204,103,8*64
103	8	\$PHRRT,080205,103,8*65
105	8	\$PHRRT,080206,105,8*60
105	8	\$PHRRT,080207,105,8*61

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The heart rate signal is taken from the decoded hexadecimal stream and encoded into a proprietary NMEA sentence format for transmission and logging (Table 3). The chosen format is based on the NMEA 0183 standard and follows the structure $\$PHRRT, hhmss, HR, RestCS$, where $PHRRT$ is the sentence identifier, $hhmss$ is the UTC time, HR is the measured heart rate in decimal form, $Rest$ represents the rest time in hours, and CS is the checksum. The checksum is calculated by applying an exclusive OR operation to all characters between the $\$$ and the $*$ and writing the result as a two-digit hexadecimal value, ensuring the integrity of the transmitted data. For example, a measured heart rate of 99 bpm with an 8-hour rest time at 08:02:02 would be encoded as $\$PHRRT,080202,99,850$, which is suitable for integration with other maritime navigation and monitoring systems.

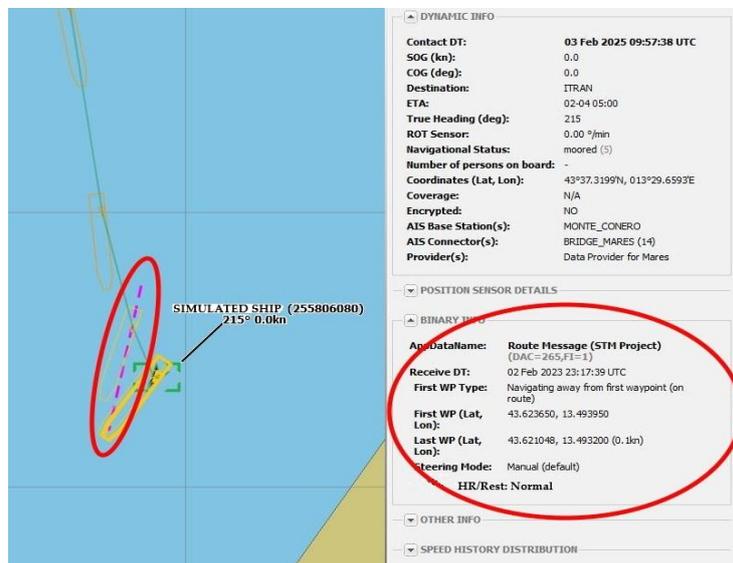


Fig. 5. Vessel deviates from the first waypoint, triggering an alarm at port authorities; confirmation of stable crew condition based on heart rate and rest data, ensuring safe situation management.

When the simulated vessel in Figure 5 was en route, the alarm appeared, due to navigating away from the first waypoint because of weather circumstances. The deviation triggered an alarm at the VTS headquarters, indicating that the planned track was not being followed. Despite the alert, the port authorities reviewed the physiological data transmitted from the vessel, including the crew's heart rate and rest time records. The information confirmed that both the workload and recovery status of the crew were within safe limits, and the authorities acknowledged that the crew was fit to handle the situation and allowed them to proceed with the necessary maneuvers to ensure safety.

4 Discussion

We focused on an accessible and practical solution: a standard commercial smartwatch worn by the OOW. The advantage of this approach lies in its simplicity and interoperability. Smartwatches transmit HR data via Bluetooth Low Energy (BLE), and with our approach, the signal is cloned on the device. The BLE packets are captured and decoded, converting hexadecimal HR data to decimal BPM values, which are then encoded into a custom NMEA sentence format, and transmitted via Ethernet to the ship's Ethernet multiplexer, allowing further distribution. The signals can then be logged by the Voyage Data Recorder (VDR) for post-incident analysis, displayed on the information system, and optionally broadcast via AIS, using a reserved/custom slot.

The design ensures that bridge crew and remote authorities (e.g., Vessel Traffic Services or port authorities) can have access to the physiological condition of the person in control of the vessel, especially during high-risk operations such as pilotage, restricted visibility navigation, or narrow passages. Typically, the alarm starts on the bridge, where the officer of the watch is first alerted. If no response is received within the set time, the alarm is transferred to call the master. Should there still be no acknowledgment, the alarm escalates to a ship-wide level so that other crew members are alerted. If the message remains unacknowledged, the system can be configured to send a binary AIS message to shore, notifying the coastal station or VTS, which can then take action to ensure the vessel's safety.

Future development should focus on enhancing signal stability in BLE cloning and validating the system in multi-user watchkeeping scenarios across different vessel types.

A discussion must be also raised on cybersecurity and ethical considerations, given the vulnerability of the Automatic Identification System (AIS) to spoofing and misuse. Our system transmits physiological data to AIS only when an individual error is reported, thereby aiming to protect privacy by restricting data access. However, we recognize that AIS, as a publicly accessible system, is susceptible to cybersecurity threats such as spoofing, data breaches, and misuse, which could result in unauthorized access to sensitive physiological data. Such breaches could have severe consequences, including the creation of blacklists or other unethical uses of personal information, as well as the potential for falsified reports to trigger unjust data exposure.

Before continuing to address cybersecurity, we will include the integration of robust encryption protocols and secure authentication mechanisms to safeguard data transmitted via AIS. Additionally, implementing anomaly detection systems could help identify and mitigate spoofing attempts or unauthorized access in real time. Regular security audits and system updates would further enhance resilience against evolving cyber threats. We also suggest exploring blockchain or other decentralized technologies to ensure data integrity and traceability, reducing the risk of falsification.

From an ethical perspective, the potential misuse of data raises significant concerns about privacy and fairness. Our system design prioritizes minimal data exposure, but erroneous or falsified reports of mistakes could unjustly compromise an individual's

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privacy. To mitigate this, we advocate clear policies on data access, ensuring that only verified and authorized entities can view the data, and only under strictly defined circumstances. Furthermore, individuals should have the right to appeal or challenge reports of errors to prevent wrongful data disclosure. Ethical guidelines must be established to govern the use of physiological data, emphasizing transparency, accountability, and consent. This includes informing individuals about how their data may be used and providing mechanisms to opt out or contest its release.

5 Conclusion

We explore the feasibility of using this solution during ship-bridge operations to detect variations in physiological responses that may indicate elevated stress levels or reduced alertness, thus offering a potential means of preventing human-factor-related incidents at sea. The monitoring of physiological signals offers a promising way for enhancing maritime safety, improving situational awareness, decision-making, and vigilance. By continuously tracking heart rate, early signs of drowsiness, high stress, or even critical events such as cardiac arrest could be detected and addressed, potentially preventing collisions or groundings caused by human error. In future iterations of this work, we intend to expand on these cybersecurity measures and ethical frameworks, potentially collaborating with regulatory bodies to align with international maritime safety and privacy standards. By addressing these concerns, we aim to balance the goal of reducing human-error-related accidents at sea with the imperative to protect individual rights and data security. This discussion will be incorporated into the manuscript to provide a comprehensive view of the challenges and safeguards associated with our proposed system. In conclusion, our study presents a system feasibility test showing that, in cases of anomalies in reported navigation, a heart rate tracking methodology may reduce accident risk. Future research should include multiple participants and real-world scenarios to increase the significance and applicability of the findings.

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SpillSim – A Simulation Tool for Oil Spills in Marine Environments

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Abstract. Oil spills pose a serious threat to marine ecosystems, requiring effective tools for risk assessment, forecasting, and response planning. This paper presents SpillSim, a lightweight and flexible simulation program designed for modeling the transport and fate of petroleum products in the marine environment. The model is based on a particle-tracking approach and the OpenDrift framework, with integration of physicochemical data from the ADIOS Oil Database. Key processes such as advection, wind drift, evaporation, dispersion, emulsification, sedimentation, and biodegradation are implemented, allowing realistic representation of oil slick evolution. SpillSim provides a modular architecture, offline capability, and diverse visualization options, including time-series plots, static and interactive maps, and automated PDF reports. Three illustrative scenarios—hydraulic oil leakage from an offshore wind turbine, a port collision with marine diesel spill, and a large-scale open-sea tanker accident—demonstrate the program’s flexibility and potential applications. The results confirm SpillSim’s suitability both as a scientific research tool and as practical support for maritime administration, offshore industry operators, and environmental risk management. Future development will focus on integration with real-time forecasting systems, expansion of physicochemical process modules, and the use of artificial intelligence for automated analysis.

Keywords: Oil spill, SpillSim, OpenDrift, ADIOS Oil Database, particle tracking, marine environment, simulation, environmental risk assessment, maritime safety, offshore industry.

1 Introduction

Oil spills are among the most serious threats to the marine environment [1]. Such events may result from tanker accidents, offshore installation failures, leaks in ports, as well as smaller incidents associated with shipping and vessel operations [2]. The growing offshore wind sector introduces additional sources of environmental risk, including hydraulic and lubricating oil leaks from turbines and substations [3]. According to data from the International Tanker Owners Pollution Federation [4], the number of large spills has decreased in recent decades due to improved safety standards and technologies; however, they still occur worldwide regularly and can cause enormous ecological and economic losses. Every spill—regardless of its scale—

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requires a rapid and effective response, which in practice means the necessity to forecast the behavior of the substance in water.

The importance of forecasting and computer modeling [5–7] in the context of oil spills is increasing in line with the requirements set by maritime administrations and international organizations. Numerical models make it possible to predict spill trajectories, assess the persistence of pollution, and evaluate risks to protected areas, critical infrastructure, and shipping lanes [8,9]. In the case of the Baltic Sea, due to its semi-enclosed nature, limited water exchange with the North Sea, and high anthropogenic pressure, this issue is of particular importance [10]. Even relatively small spills can have long-lasting impacts on the ecosystem and lead to local environmental disasters.

Numerous oil spill modeling tools are described in the literature, including GNOME developed by NOAA [11] and OpenDrift, an open numerical framework [12]. GNOME is widely used in the United States and serves as the standard tool for emergency response agencies. OpenDrift, on the other hand, offers considerable flexibility and the possibility of extension with additional modules, making it an attractive research tool. Despite the availability of such solutions, in many cases, there is a need to develop dedicated applications that account for specific local conditions and enable integration with proprietary databases and visualization tools.

Against this background, the SpillSim program was developed with the primary goal of providing a flexible and user-friendly tool for simulating oil spills in the Baltic Sea, as well as in other marine areas. The program is based on the OpenDrift framework, extended with custom modules for integration with the ADIOS Oil Database, automatic generation of PDF reports, and creation of interactive maps (Folium) with additional thematic layers (e.g., Natura 2000 protected areas, TSS, MPA). As a result, SpillSim combines a scientific approach with practical applicability and can be used both in academic research and in technical analyses for the maritime industry and governmental administrations.

The purpose of this article is to provide a detailed description of the SpillSim program, its theoretical and technical foundations, as well as to present selected simulation scenarios. This study contributes by delivering a transparent, reproducible, and offline-capable simulation framework that bridges scientific modeling and operational use. It combines established physical principles with practical implementation features such as ADIOS oil-data integration, automated reporting, and high-quality visual outputs. In addition to describing the tool itself, an attempt will be made to highlight its potential applications and directions for further development.

In light of the challenges discussed above, despite the availability of established oil-spill models, there remains a practical need for a lightweight, transparent, and offline-capable tool that can be adapted to local settings and integrated with authoritative oil property data. Operational users (administrations, port authorities, offshore operators) frequently face constraints such as limited connectivity, short decision windows, and the need to export publication-quality visualizations for incident briefings. From a research perspective, there is also value in open, modular, and reproducible workflows that expose model assumptions and allow controlled “what-if” experiments (e.g., sensitivity to wind drift coefficients, current forcing, or oil weathering).

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SpillSim was designed to meet these dual needs by combining OpenDrift's Lagrangian core with ADIOS-based physicochemical properties, transparent configuration, and automated maps/reports tailored to the Baltic Sea and similar semi-enclosed basins [8,10,12].

The remainder of this paper is organized as follows. Section 1.1 provides a review of key studies on oil-spill trajectory and weathering modeling, positioning SpillSim within the existing research landscape. Section 2 describes the modeling fundamentals and numerical approach, including physical and chemical processes implemented in the framework. Section 3 presents the architecture and operation of the SpillSim program, while Section 4 illustrates selected simulation scenarios representing different maritime spill conditions. Section 5 discusses practical applications, development perspectives, and limitations of the model. Finally, Section 6 concludes the paper by summarizing the main findings and outlining directions for future work.

Literature review

Foundational reviews have synthesized advances in oil-spill fate and transport modeling, including advection, windage, turbulent diffusion, and weathering [1,8,13,14]. Operationally, NOAA's GNOME has long served as a standard platform for incident response in the U.S., coupling trajectory forecasts with weathering modules and expert workflows [11]. OpenDrift drift [11,13,14] generalizes Lagrangian particle tracking with interchangeable readers and process modules; subsequent studies evaluated current forcing, vertical mixing, and satellite-informed constraints on surface drift [16–18]. Large-event reconstructions [19] and cost/impact syntheses [2] further underline the importance of credible inputs (currents, wind, waves) and realistic oil properties. In the Baltic context, the semi-enclosed geometry and vulnerable coastlines motivate conservative planning, monitoring, and response [4,10]. Within this landscape, SpillSim contributes a lightweight, offline-capable, and modular workflow that integrates ADIOS oil properties, emphasizes reproducibility, and automates vector-quality visual outputs for both research and operations.

2 Methods and Fundamentals of Modeling

Modeling oil spills is a complex task that requires consideration of the physical, chemical (ChemicalDrift 1.0), and biological processes occurring in the marine environment. In practice, this necessitates the use of numerical models that are, on the one hand, sufficiently accurate to realistically reproduce real-world conditions, and, on the other hand, computationally efficient enough to be used in operational applications. SpillSim is based on a particle-tracking approach (Lagrangian particle tracking), which is currently recognized as one of the most universal and flexible methods for simulating the transport of substances in the marine environment [8,20,21].

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2.1 Particle-Based Approach

In the particle-tracking method, the spill is not treated as a homogeneous slick but rather as a collection of representative particles, each corresponding to a defined portion of oil mass. These particles move according to equations of motion that account for:

- advection (transport driven by ocean currents),
- wind drift (typically 2–4% of the wind speed at the surface, depending on oil properties),
- turbulent diffusion (random spreading of particles in the water),
- weathering processes (e.g., particle breakup, sedimentation to the seabed).

Each particle is thus a dynamic object, whose trajectory depends both on hydrometeorological conditions and on the properties of the oil itself. This approach allows for great flexibility, as new processes can easily be added or existing modules modified.

2.2 Physical and Chemical Processes

The transport and fate of oil in the marine environment are governed by several inter-related physical and chemical processes that must be represented in the model. Evaporation removes light fractions of crude oil and petroleum products from the water surface, particularly during the first hours after a spill, with rates depending on air and water temperature, wind speed, and the oil's physicochemical properties [13]. Emulsification occurs when oil mixes with seawater, forming water-in-oil emulsions that increase the slick volume and modify its viscosity. Dispersion describes the mechanical breakup of oil into fine droplets due to wave action and turbulence, enhancing mixing within the water column. Over longer timescales, biodegradation and decomposition by microorganisms gradually reduce the mass of hydrocarbons. Finally, sedimentation may occur near the coast where heavier fractions settle to the seabed.

SpillSim implements these processes using the OpenDrift framework, complemented by data from the ADIOS Oil Database, which provides physicochemical parameters for hundreds of oil types [11,18]. This integration allows the model to reproduce a wide range of oil behaviors under varying environmental conditions.

2.3 Advection and Drift

The primary factor determining the trajectory of particles is advection, i.e., transport by ocean currents [17]. SpillSim allows for the use of both real data (e.g., hydrodynamic forecasts in NetCDF format) and constant parameters (e.g., a current of 0.1 m/s from the east).

In addition, the model accounts for wind drift. Studies indicate that an oil slick on the sea surface moves at a speed of approximately 3% of the wind velocity, with deviations depending on viscosity and surface tension [22]. In SpillSim, this coefficient can

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be configured depending on the scenario, providing high flexibility for experimental simulations.

2.4 Turbulent Diffusion

At the local scale, particle motion is determined by turbulence in the ocean surface layer. In the model, these are represented by random perturbations added to particle velocities. SpillSim implements standard solutions of this type, based on Brownian motion theory, which enables realistic dispersion of the slick over time.

2.5 ADIOS Oil Database

One of the key components of the program is its integration with the ADIOS Oil Database (NOAA). This is an international database containing physicochemical characteristics for several hundred types of oils and fuels, including density, viscosity, evaporative fractions, emulsification properties, and others. This makes it possible to reproduce the specific properties of a given substance rather than merely simulate an “average oil.” In SpillSim, this database is available in the form of JSON files, which allows the program to operate offline without the need to connect to NOAA servers.

2.6 Environmental Data

The model requires four main categories of environmental input data, which can be provided either as fixed parameters or from numerical forecasts:

- Wind – can be specified as a constant parameter (speed, direction) or as a time series.
- Ocean current – similar to wind, it may originate from numerical forecasts or be defined manually.
- Water and air temperature – influences the rate of evaporation and emulsification.
- Waves – represented in a simplified manner through dispersion and emulsification coefficients.

SpillSim is designed to support both quick test simulations and the use of full environmental datasets in NetCDF format, enabling integration with professional forecasts.

2.7 Advantages of the Approach

The particle-based approach, combined with a modular architecture, provides SpillSim with several important advantages. The framework offers high flexibility in configuring input parameters, allowing users to tailor simulations to diverse environmental conditions and oil types. It is fully operational in offline mode, which makes it suitable for field applications and training scenarios with limited connectivity. The

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modular design enables easy extension with new processes, such as additional biodegradation or shoreline-interaction schemes. Furthermore, the model ensures transparent visualization, as the oil slick is represented by thousands of individual particles whose movement and weathering can be tracked in detail. Altogether, these features make SpillSim a versatile tool for both research and operational applications.

3 Description of the SpillSim Model

3.1 Origins and Design Assumptions

The SpillSim program was developed in response to the need for a lightweight, flexible, and open tool for simulating oil spills. Existing solutions, such as GNOME or professional commercial packages, often require access to online data, substantial computational resources, or are restricted to specific marine areas. SpillSim, by contrast, was designed to operate efficiently on standard computers, even without Internet connectivity, while maintaining compatibility with current scientific models of oil-spill behavior.

The program is simple to configure, featuring a user-oriented structure that facilitates the setup and testing of various scenarios. Its modular design allows straightforward extension and integration of additional physical or chemical processes. The system is fully capable of offline operation, making it suitable for use in remote or field environments. Furthermore, SpillSim offers multiple forms of result visualization, including charts, static maps, and interactive maps, to support both analytical and operational needs. Finally, it is integrated with the ADIOS Oil Database, enabling a realistic representation of diverse oil types and enhancing model fidelity.

3.2 Program Architecture

SpillSim was developed in Python to ensure broad accessibility and seamless integration with scientific and visualization libraries. The architecture follows a modular structure comprising several interdependent components. The core simulation engine is contained in the file `SpillSim.py`, which initializes the OpenDrift (OpenOil) model, defines particle seeding, manages the computational loop, and coordinates output generation. The configuration module, `config.py`, allows the user to specify input parameters such as oil type, quantity, location, and environmental conditions, ensuring a clear separation between setup and execution. Reporting functions are handled by `report_generator.py`, which automatically produces simulation summaries and PDF reports. Visualization capabilities are provided by two dedicated modules: `map_slider.py`, responsible for generating an interactive time-slider map with optional EMODnet overlays (e.g., Natura 2000 areas, MPAs, TSS), and `map_static.py`, which creates static maps showing the final slick distribution for quick inspection.

This modular architecture facilitates the addition of new functionalities without affecting the core code, enabling flexible development and experimentation.

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3.3 Process of Operation

The operation of SpillSim follows a structured workflow that reflects the typical stages of oil-spill modeling. First, the user defines all input parameters for the simulation scenario, including the spill location, number of particles, oil type (retrieved from the ADIOS database), substance quantity, and environmental conditions such as wind, current, and water temperature. These parameters can be provided manually or imported from external files, for instance, in NetCDF format.

Based on the specified inputs, the model performs particle seeding, where each particle represents a defined portion of oil mass. Typical simulations involve between 1,000 and 10,000 particles, balancing computational efficiency with adequate spatial resolution.

The next stage involves integration of physicochemical data from the ADIOS Oil Database, allowing the simulation to represent processes such as evaporation, emulsification, and viscosity changes over time. During the numerical simulation, particle trajectories are computed over successive time steps under the combined influence of wind, current, and turbulent diffusion. The temporal resolution (e.g., one-hour intervals) and total duration of the simulation are user-defined.

Finally, the model provides comprehensive visualization and analysis outputs, including oil mass-balance charts (showing evaporated, emulsified, and surface fractions), geographic trajectory maps, interactive time-slider visualizations, and automatically generated PDF reports summarizing the scenario and results.

3.4 Visualization and Reporting

One of the key advantages of SpillSim is its advanced system for visualizing simulation results. The program produces several complementary forms of output that support both scientific analysis and operational reporting. Time-series plots illustrate the temporal evolution of oil mass, evaporation rate, and water content in the emulsion, while trajectory maps display the movement of oil particles on a geographic basemap. The system also includes interactive maps developed with Folium, featuring time-slider functionality, overlay options (e.g., Natura 2000 areas, TSS, wind farms), and customizable turbine or platform markers. In addition, automatically generated PDF reports compile all relevant figures, tables, and scenario descriptions into a coherent summary.

Through this integrated visualization and reporting system, SpillSim extends beyond producing raw numerical outputs and provides ready-to-use analytical materials for technical documentation, decision-making, and scientific publication.

3.5 Offline Mode and Operation under Limited Data Conditions

One of the design requirements was the ability for the program to operate in offline mode. In many situations—such as on vessels, during training exercises, or under conditions without Internet access—it is not possible to rely on online data. SpillSim

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enables full simulation using constant environmental parameters and a local copy of the ADIOS database. When hydrodynamic forecast files in NetCDF format are available, the program can be supplied with real data, further enhancing its functionality.

3.6 Development and Future Directions

The current version of SpillSim is stable and enables simulations across a wide range of marine spill scenarios. Nevertheless, several avenues for further development have been identified. Future work will focus on integrating the model with real-time meteorological and oceanographic forecasting systems, thereby enabling dynamic, data-driven simulations. Planned enhancements also include the implementation of additional process modules, such as biodegradation kinetics and the deposition of heavy oil fractions, as well as the development of advanced three-dimensional visualization tools to improve result interpretation. Another area of improvement involves the expansion of reporting capabilities, including the automatic generation of comparative analyses and structured summaries for multi-scenario studies. Finally, SpillSim is envisioned to be linked with decision-support platforms used by maritime authorities and offshore wind farm operators, strengthening its role as both a research and operational tool.

3.7 Example Scenarios

One of the main strengths of the SpillSim program is the ability to rapidly define different spill scenarios. Thanks to flexible configuration, the user can simulate both minor incidents in ports and major environmental disasters involving tankers or offshore platforms. This chapter presents example applications of the program, illustrating its functionality and potential.

Scenario 1 – Hydraulic Oil Spill from a Wind Turbine.

The first scenario reflects a situation that could potentially occur at an offshore wind farm. It was assumed that one of the turbines experienced a hydraulic system failure, resulting in a spill of 340 liters of LUBRICATING OIL (AIR COMPRESSOR) NEW_500.

The environmental parameters used for the calculations were as follows:

- Wind speed: 3 m/s from 45° (NE).
- Ocean current: 0.1 m/s from 90° (E).
- Water temperature: 18 °C.
- Simulation time: 72 hours.

The simulation results included:

- A map of the oil particle trajectory spread (Fig. 1).
- Changes in the oil mass balance over time (evaporated, emulsified, remaining on the surface) (Fig. 2,3).

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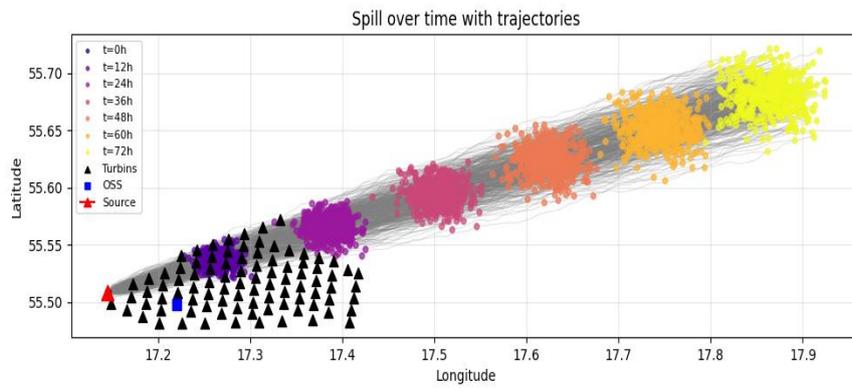


Fig. 1. Location of the oil slick over time during simulation no 1

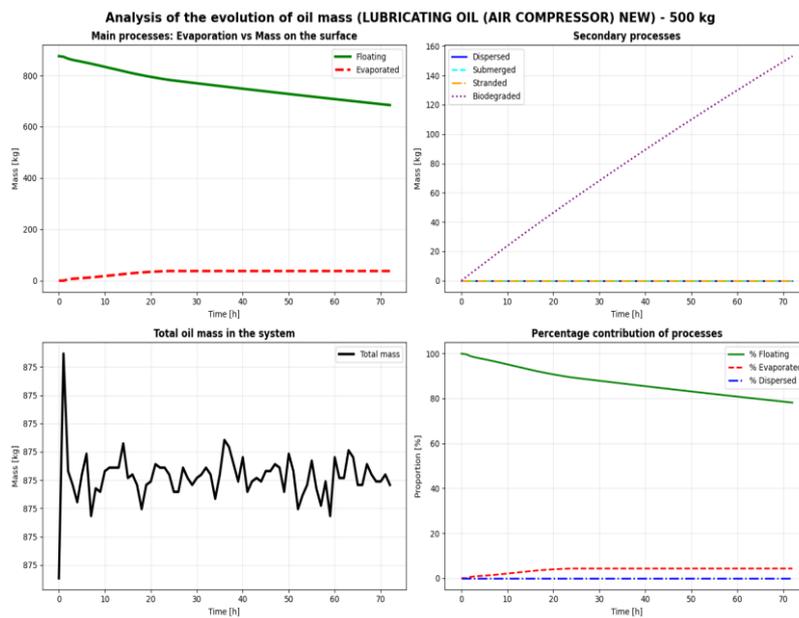


Fig. 2. Evolution of the oil slick over time during simulation no 1

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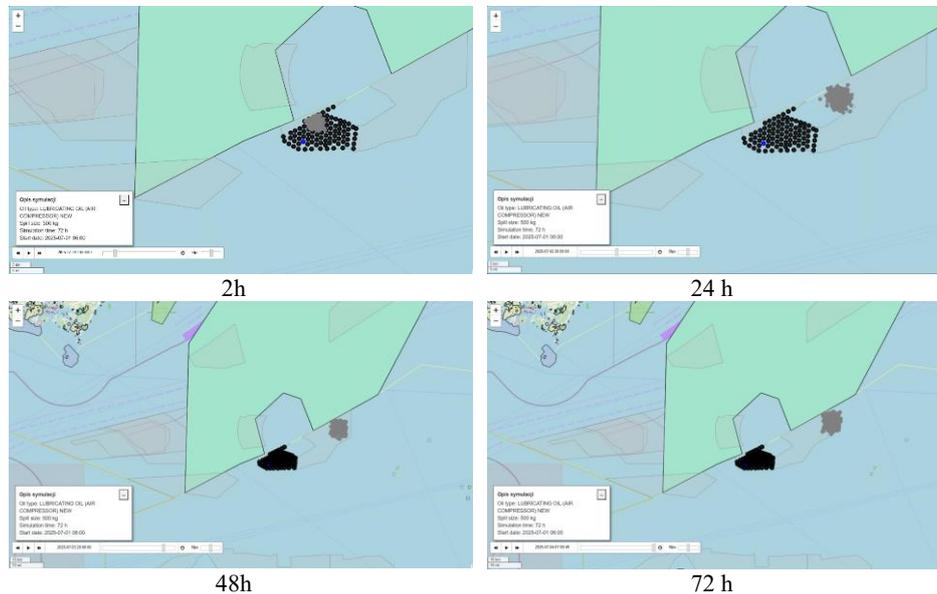


Fig. 3. Oil spill simulation no 1.

The analysis of results showed that under the given environmental conditions, the main factor driving the spread of oil was the ocean current, while wind played a lesser role. The dominant transport mechanism of the spill was clearly the ocean current (0.1 m/s, direction 90°), whereas the influence of wind (3 m/s, direction 45°) was significantly weaker. After 72 hours, as much as 684 kg (78.2%) of the total oil mass remained on the surface, while only 38 kg (4.3%) had evaporated, indicating that evaporation of light fractions was a process of limited significance.

Processes such as dispersion and emulsification were virtually absent—both remained at 0 kg (0.0%). Biodegradation progressed steadily throughout the simulation, reaching 153 kg (17.5%) at the end.

The results indicate that under moderate wind (3 m/s NE) and weak current (0.1 m/s E), the slick drifted predominantly eastward, maintaining a compact shape with limited spreading. Evaporation accounted for a minor fraction of mass loss due to the relatively low volatility of the hydraulic oil. These findings confirm that small spills of high-viscosity oils in calm conditions tend to remain localized, emphasizing the importance of prompt local containment rather than large-scale response mobilization.

Scenario 2 – Collision of a Small Tanker in the Port Area.

In the second scenario, a spill of 50 tons of MARINE DIESEL FUEL OIL was considered as a result of a vessel collision in the port area of Świnoujście (53°55'N, 14°16'E). This type of spill poses a significant environmental risk due to the proximity of coastal areas and critical infrastructure.

The environmental parameters adopted were as follows:

- Wind speed: 7 m/s from 270° (W).

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- Ocean current: 0.3 m/s from 0° (N).
- Water temperature: 12 °C.
- Simulation time: 120 hours.

Under the given environmental parameters (wind 7 m/s from the west, ocean current 0.3 m/s from the north, water temperature 12 °C) and a simulation time of 120 hours, the oil was subject to intense physical and chemical processes. The spill quickly moved northeast, following the current and prevailing wind force, covering a distance of more than 96 km (Fig. 4).

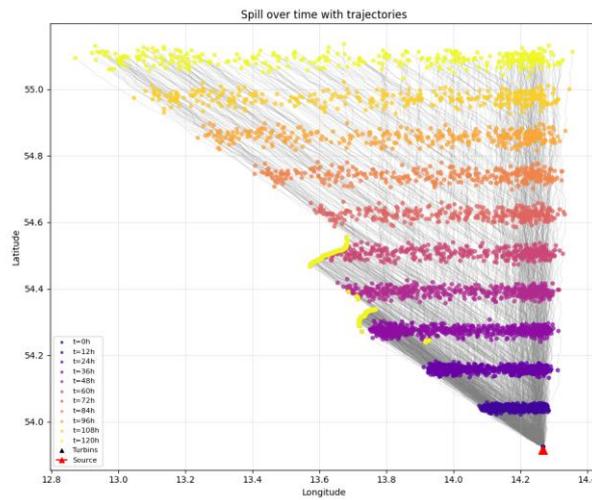


Fig. 4. Spill over time during simulation no 2

Evaporation was the dominant process during the first hours of the simulation: 374 kg (44.4%) of the total mass evaporated within 120 hours, reflecting the high volatility of the lighter diesel fuel fractions.

Dispersion accounted for as much as 440 kg (52.2%) of the product, meaning that a significant portion of the substance was dispersed in the water as microdroplets.

Sedimentation and biodegradation played only a minor role: 16 kg (2.0%) of the oil was deposited, while 11 kg (1.3%) underwent biodegradation during the entire simulation. After 120 hours, only a marginal amount of oil remained on the surface—just 0.1% (Fig. 5).

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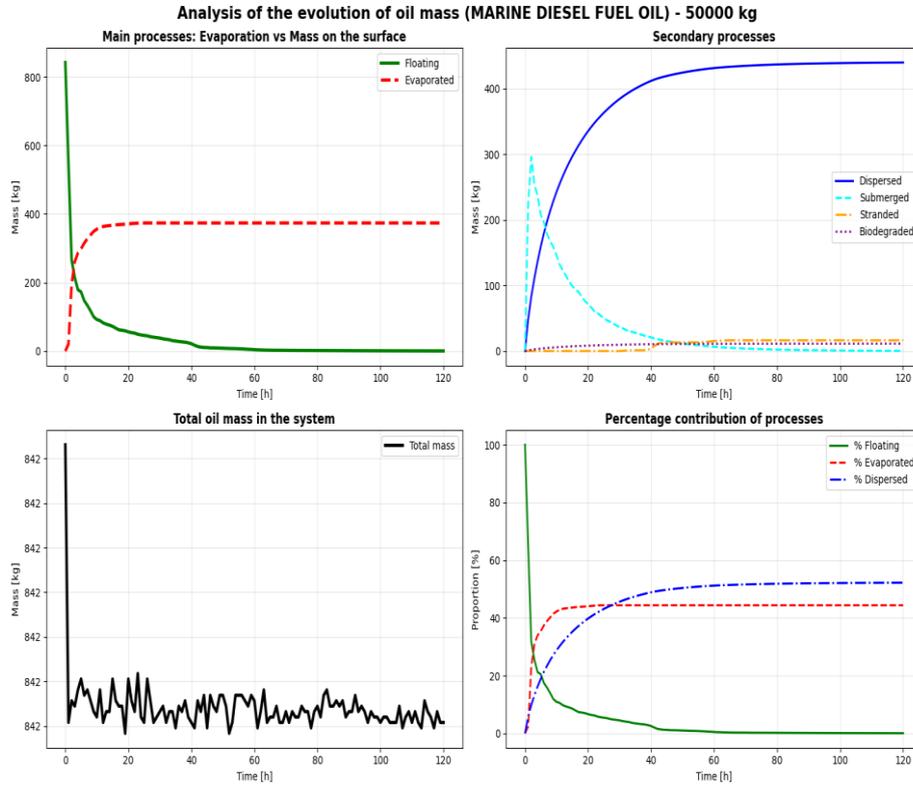


Fig. 5. Evolution of oil mass during simulation no 2

The rapid loss of volatile fractions and intense dispersion indicate that the environmental threat in the port area stems primarily from the fast movement of the spill toward coastal areas and adjacent infrastructure. Potential impacts on the marine environment may be particularly severe in shallow waters and the coastal zone, where even small amounts of deposited oil can pose a threat to ecosystems (Fig. 6).

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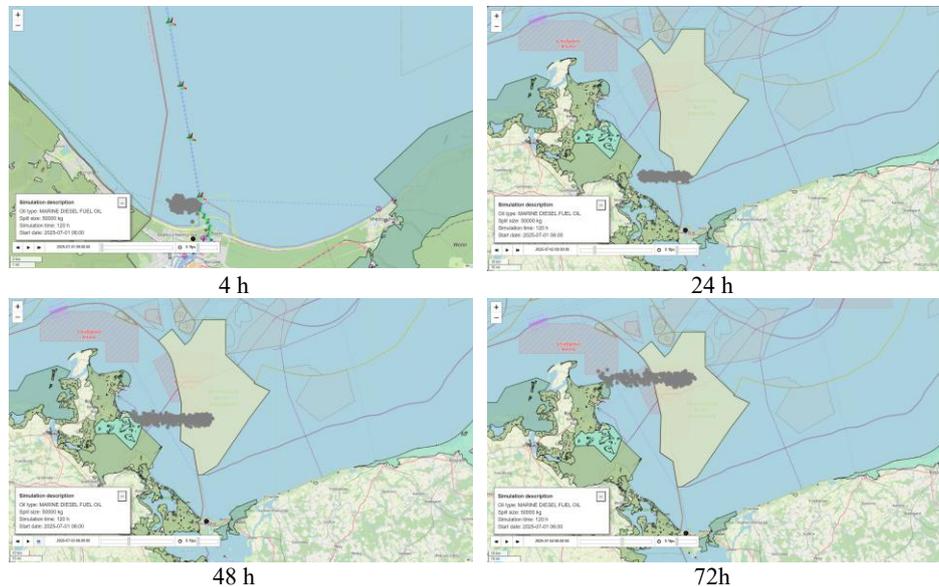


Fig. 6. Oil spill simulation no 2.

In contrast, the open-sea scenario revealed substantial spreading and fragmentation of the slick due to stronger winds and persistent currents. The results demonstrate the dominant role of wind forcing and wave-induced dispersion in large-scale incidents. The rapid mass loss through evaporation and emulsification is consistent with findings reported by Spaulding [8] and French-McCay [9], highlighting the need for early aerial monitoring and predictive modeling during offshore accidents.

Scenario 3 – Bunker Spill in the Open Sea.

In the third scenario, we consider a major tanker accident (18.55E, 54.95N), resulting in the release of 400 tons of light fuel ARABIAN EXTRA LIGHT, ARAMCO into the sea. The simulation assumptions reflect real hydrometeorological conditions of the Baltic Sea in September 2025. The water temperature is approximately 10 °C, while wind and ocean current data are sourced from dynamic, real Copernicus (CMEMS) datasets, ensuring natural weather and hydrodynamic conditions that vary over time and space.

Wind changes authentically over time, in accordance with measurements and numerical models—it is not artificially rotated, which guarantees an accurate representation of the impact of variable atmospheric conditions on the distribution and transport of the oil slick (Fig. 7).

The simulation duration is about 10 days (240 hours), allowing for a detailed observation of the slick's evolution, including evaporation, dispersion, and drift dynamics under changing environmental conditions (Fig. 8).

The results show that the light fuel remains on the surface for an extended period and does not immediately sink as heavier oils do, enabling the observation of its wide

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displacement driven by currents and winds across a large part of the Baltic Sea. Secondary processes, such as emulsification and biodegradation, exert a significant but gradual influence on the mass remaining on the surface (Fig. 9).

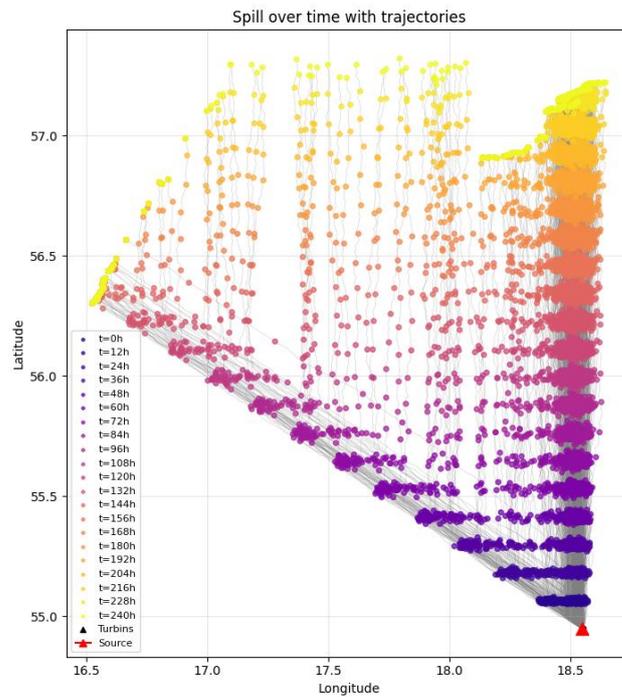


Fig. 7. Spill over time during simulation no 3

Based on the mass balance results, it can be concluded that after 10 days, approximately 35–40% of the light fractions had evaporated, while nearly 50% remained on the sea surface. Secondary processes such as emulsification and biodegradation together accounted for about 10–15% of the initial mass, with their contribution gradually increasing over the course of the simulation.

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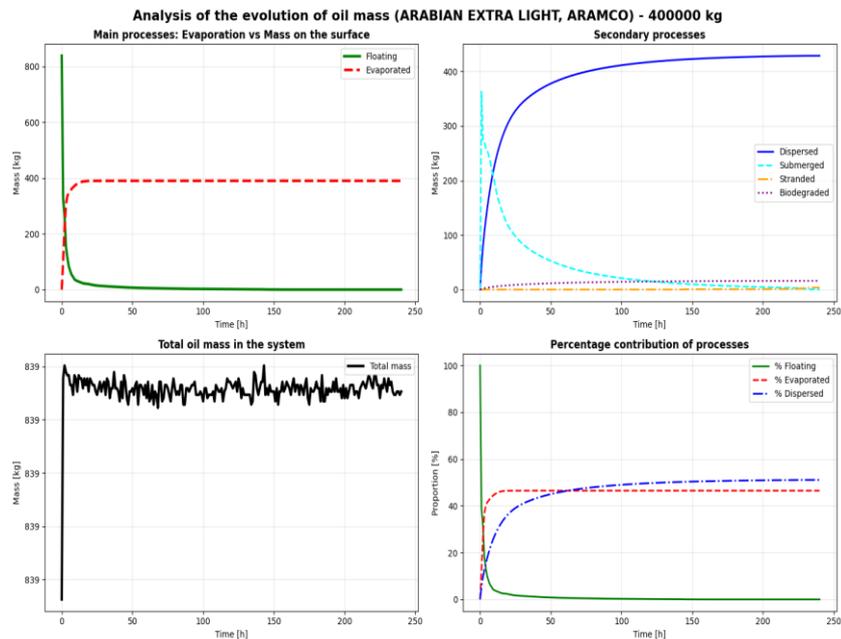


Fig. 8. Evolution of oil mass during simulation no 3

This breakdown demonstrates that even light fuels, despite evaporating faster than heavy oils, may persist on the surface for many days, posing a serious threat to wide marine areas.

The simulation, therefore, provides detailed data for analyzing the potential effects of a tanker accident, enabling the assessment of oil slick dispersion and the planning of appropriate preventive and response measures.

In this case, SpillSim can be used not only for forecasting but also for conducting what-if analyses—for example, how the spill trajectory changes under different wind conditions, or in response to intervention measures (dispersant application, mechanical oil recovery).

In confined port environments, the limited current circulation and restricted wind fetch produced slower drift and accumulation of oil near port infrastructure. This emphasizes the importance of localized modeling to support tactical response in areas where even small spills can result in concentrated shoreline contamination.

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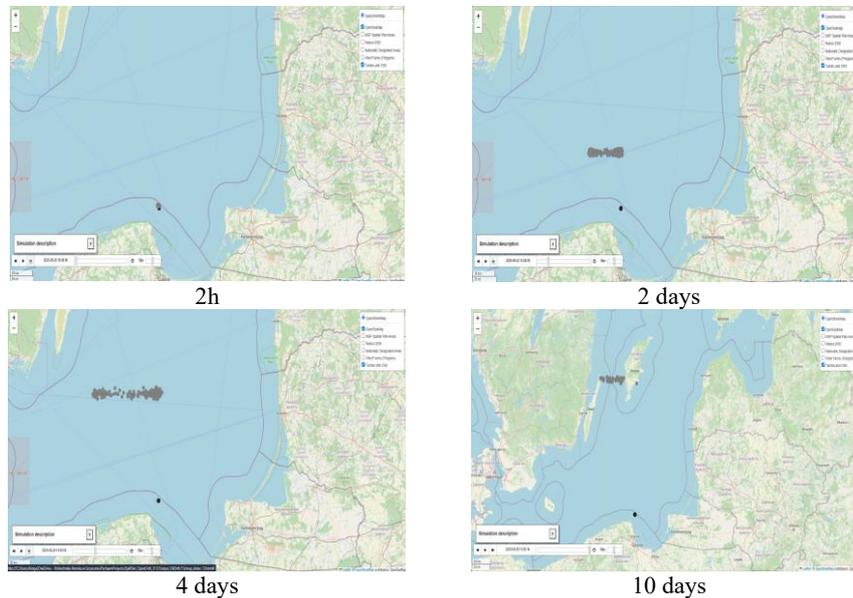


Fig. 9. Simulation no 3

Comparison of Scenarios.

The comparative analysis of the three scenarios demonstrates the versatility of SpillSim, which can be applied to both small-scale incidents and large marine disasters. The simulations revealed that, in the case of minor port spills, response time is critical, as containment measures must be implemented within just a few hours. The influence of environmental conditions proved to be a decisive factor, with ocean currents governing the overall slick trajectory, while under stronger winds, the wind component may become dominant. Regarding physicochemical processes, evaporation and emulsification were consistently found to play major roles, significantly altering oil properties and complicating recovery operations. From an environmental risk perspective, SpillSim proved effective in rapidly identifying the coastal and protected areas most vulnerable during the early stages of a spill.

4 Applications and Perspectives

4.1 Practical Applications

The SpillSim program has broad applications in various areas related to maritime safety and marine environmental protection. Thanks to its flexibility and offline capability, it can be used both by research institutions and by maritime authorities or offshore infrastructure operators. The most important practical applications include:

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- Environmental risk assessment – SpillSim can be used to analyze potential hazards associated with the operation of offshore wind farms, oil terminals, coastal refineries, or heavily trafficked shipping routes. Simulations make it possible to identify the most vulnerable areas and estimate the likely impacts of spills.
- Support for intervention planning – the program provides oil slick trajectory forecasts that can serve as the basis for deploying containment booms, directing rescue units, or evaluating the need for dispersant application.
- Marine spatial planning (MSP) – spill simulations can play an important role in environmental impact assessments of new investments. SpillSim enables what-if analyses, e.g., how a potential spill might spread in a given area and which protected sites would be most at risk.
- Exercises and training – the tool can be used in simulators and during drills conducted by maritime administrations, coast guards, or wind farm operators. By visualizing results in the form of maps and charts, participants can better understand spill dynamics.
- Support for research activities – thanks to its open architecture and integration with the ADIOS database, SpillSim can be used in scientific projects, e.g., for analyzing the seasonality of spill risks, studying the effectiveness of countermeasures, or modeling the transport of substances under different environmental conditions.

4.2 Development Potential

Although the current version of SpillSim already provides extensive functionality, several promising directions for further development have been identified. A key priority is the integration of the model with numerical forecasting systems, such as the Copernicus Marine Service, to enable automatic retrieval of wind, current, and wave data and to support real-time simulations. Another major focus concerns the expansion of physicochemical process modules, including biodegradation, heavy-fraction sedimentation, and oil–sediment interactions, to provide a more comprehensive representation of long-term oil fate in marine environments.

Further work will also target enhanced visualization capabilities, such as 3D presentation tools and augmented reality (AR) interfaces, which could improve training and communication of simulation results. In addition, the model is planned to be linked with decision-support systems used in crisis management, facilitating the automatic dissemination of forecasts to operational centers. Finally, SpillSim’s architecture allows future adaptation to non-petroleum pollutants, such as chemicals or fertilizers, extending its applicability to a wider range of marine contamination scenarios.

4.3 Long-Term Perspective

The development of information technologies and the growing availability of satellite data and numerical environmental models open up new opportunities for tools such as SpillSim. From a long-term perspective, the program may become a component of

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integrated marine environmental management systems, supporting both scientific research and operational activities.

The ability to combine simulations with real measurement data (e.g., from oceanographic buoys, HF radars, or satellites) will make forecasts even more reliable. The inclusion of artificial intelligence algorithms could enable automatic scenario generation, risk assessment, and action recommendations.

SpillSim therefore has the potential not only to support ongoing analyses but also to become an important tool in the maritime safety systems of the future.

4.4 Limitations and Future Work

SpillSim currently emphasizes surface transport under user-specified or file-based environmental forcing. While the model includes standard windage, diffusion, and ADIOS-based weathering, several limitations merit note. (i) Forcing fidelity: forecasts/drivers (currents, wind, waves) can be uncertain or of insufficient resolution for complex coastlines; sensitivity to these inputs should be routinely assessed [17,18]. (ii) Process scope: biodegradation and seabed interactions for heavy fractions are simplified; shoreline interaction and cleanup processes (e.g., mechanical recovery, dispersants) are not yet dynamically coupled. (iii) Dimensionality and mixing: vertical processes are parameterized; full 3-D coupling and wave-induced Stokes drift are prospective enhancements. (iv) Uncertainty quantification: ensembles and probabilistic plumes are not yet automated in the workflow.

Future developments will target: (a) integration with near-real-time forecast systems (e.g., operational currents, winds, waves) and data-assimilative readers; (b) expanded weathering modules (biodegradation kinetics, emulsification dynamics, sedimentation) calibrated against lab/field data; (c) shoreline-contact and response-action submodels to support operational planning; (d) ensemble automation with uncertainty bands and exceedance maps; and (e) streamlined, vector-first visualization for complex multi-scenario reporting.

5 Conclusions

This study presents SpillSim, a robust, lightweight, and modular workflow for simulating the transport and fate of petroleum products in marine environments. Building on established Lagrangian particle-tracking methods and the flexibility of OpenDrift, SpillSim advances practice by enabling transparent configuration, offline operation with authoritative oil-property data, and versatile, publication-ready visualization—addressing needs shared by both operational practitioners and researchers.

The performed simulation scenarios—ranging from small port incidents to large open-sea spills—demonstrated that the model accurately captures the combined influence of wind, current, and oil properties on spill trajectory and weathering dynamics. The results confirmed the model's ability to reproduce realistic patterns of spreading, evaporation, and emulsification, in line with findings reported in the literature.

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SpillSim's modular architecture, comprehensive visualization suite, and offline capability distinguish it from many existing tools. By making advanced numerical modeling accessible on standard hardware and without continuous internet access, the workflow broadens participation in oil-spill risk analysis among maritime administrations, industry stakeholders, and the research community.

Several limitations remain, including simplified treatment of heavy-fraction sedimentation, shoreline interactions, and uncertainty quantification. Future research should therefore focus on coupling SpillSim with real-time environmental forcing, expanding its physical process representation (e.g., biodegradation and seabed interactions), and developing ensemble-based approaches for uncertainty assessment. Additional work may also explore model adaptation for non-petroleum substances and integration with decision-support systems for maritime response.

Overall, SpillSim supports rapid incident assessment, reproducible experimentation, and training. With continued integration and scientific validation, it is well positioned to strengthen marine environmental safety and maritime risk management by providing a transparent, reproducible, and application-ready modeling platform.

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Information and communication technologies

Possibilities of Using Artificial Intelligence when Taking a Driving Exam

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Abstract. The use of artificial intelligence (AI) in traffic is ubiquitous and has the potential to revolutionize the way we navigate and manage transport systems, learn through AI, and manage processes. AI is used to solve various problems and improve the efficiency, safety, and sustainability of traffic. Artificial intelligence (AI) has the potential to significantly impact the process of taking a driving test, both theoretical and practical. Currently, AI is not widely used for direct candidate assessment during testings in Bosnia and Herzegovina; however, there are various applications and considerations for future use. This paper will provide some basic examples and possibilities of applying artificial intelligence in testing, an example of generating a simpler test with questions based on the results of a survey generated by AI.

Keywords: Deep Learning, Education, VR, AI.

1 Introduction

The traditional driving test system, although functional, faces certain challenges widely documented in the literature [1]. Subjectivity of assessors, inconsistency in assessment, logistical problems, and the need to increase road safety open space for innovation. Artificial Intelligence (AI), with its subdisciplines such as machine learning, computer vision, and natural language processing, offers a wide range of solutions to revolutionize this process, making it fairer, more transparent, and more efficient. The integration of AI technologies can not only automate certain aspects of the test but also provide a more detailed analysis of candidate performance, directly contributing to reducing road accidents [2]. Next steps involve exploring deeper into the most promising identified sources. They will browse the relevant articles to extract detailed information on the challenges of traditional driving tests and the various ways artificial intelligence, machine learning, and computer vision are being applied in driver assessment and autonomous vehicle testing. This paper will explore these possibilities systematically. In recent years, the development of artificial intelligence (AI) has opened up new possibilities to transform traditional methods of assessing driving skills and issuing driver's licenses. This paper aims to conduct a systematic literature

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review to explore the current status of AI applications in this area, identify best practices, and assess their relevance for the context of Bosnia and Herzegovina.

2 Methodology

This scientific work permits a systematic literature review to identify and analyze relevant research and examples of the application of artificial intelligence in the field of driving ability assessment and the process of issuing driving licenses. Databases such as IEEE Xplore, ACM Digital Library, Scopus, and Google Scholar were used, with keywords such as "driving test with artificial intelligence," "driver assessment with machine learning," "road safety with computer vision," and "adaptive driving licenses." A synthesis of the relevant papers was completed to extract key findings and identify trends and gaps in existing research. The following research questions were defined to conduct a systematic literature review:

- What are the primary applications of AI in the assessment of driving skills and the process of issuing driver's licenses?
- What specific AI techniques (e.g., machine learning, computer vision, adaptive testing) are used in this context?
- What are the advantages and disadvantages of applying AI compared to traditional methods?
- What are the current experiences and implementations of AI solutions in the world, with an emphasis on empirical evidence?
- How does the existing law on driving tests in BiH relate to the potential implementation of AI solutions?
- What are the obstacles and challenges for implementing AI in the process of issuing driver licenses, especially in the context of BiH?

The papers were filtered by relevance, excluding those not directly related to the application of AI in driving ability assessment or licensing processes. Priority was given to scientific papers, conference papers, and peer-reviewed articles. The aim of this paper is to conduct a systematic literature review to explore the current status of AI applications in this area, identify best practices, and assess their relevance in Bosnia and Herzegovina.

3 Reforming driver testing with AI

Traditional driver's license issuance processes, which often rely on the judgment of human examiners, face inherent challenges such as subjectivity, inconsistency, and scalability limitations. These challenges are particularly pronounced in regions with high demand or diverse driving conditions. Conventional methods can also be subject to human error and potential fraud, which affects the overall integrity and effective-

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ness of driver assessment [2]. The application of AI in driver testing represents a fundamental shift from reactive to proactive security measures. Traditionally, driver testing primarily assesses a driver's ability at a given moment to react to standard situations. However, AI's ability to "predict behavior," "enhance risk assessment," and "predict and prevent accidents instead of just reacting to them" indicates a deeper shift in road safety strategy. This means that AI in driver testing is not just for pass or fail; it is aimed at identifying inherent risk factors and behavioral tendencies before or after a driver is licensed, through continuous learning and personalized feedback. This proactive approach can lead to a significant reduction in accident rates over time, transforming road safety from a reactive incident response to a predictive and preventive system [2].

3.1 The concept and definition of artificial intelligence

Artificial intelligence is a broad field of study where it is very difficult to give a universal definition of the term; therefore, the specific definition depends on the field in which this concept is applied. The very definition of the term is difficult, given its nature and multidisciplinary character [3]. The field of artificial intelligence deals with the study and construction of human-made objects that exhibit intelligent behavior, usually through computer algorithms. The main goal of artificial intelligence is to develop systems that exhibit general intelligence at or beyond the level of humans [4].

3.2 Advantages and disadvantages of artificial intelligence

Artificial intelligence is now present in many aspects of everyday life. It is present in virtual assistants such as Siri and Alexa, where it helps with various tasks such as scheduling, retrieving various information, and automating certain tasks [4]. The benefits of artificial intelligence are:

- **Efficiency and automation:** AI is very useful in optimizing processes, thereby reducing the possibility of human error and improving efficiency in tasks such as data analysis, manufacturing, and logistics.
- **Innovation and progress:** AI drives innovation, leading to breakthroughs in various fields, including healthcare, agriculture, transportation, etc.
- **Faster and more reliable decision-making:** Machine learning algorithms can analyze very large data sets, thus enabling faster and more accurate decision-making.
- **Improved safety:** AI enables greater safety in the workplace, for example, in the form of predictive maintenance of machinery, thereby reducing accidents caused by equipment breakdowns or by reducing accidents due to the use of autonomous vehicles.

Disadvantages of artificial intelligence:

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- **Reduction of available jobs:** AI-driven automation is likely to lead to job losses across sectors, potentially widening socioeconomic disparities.
- **Ethical issues:** AI is accompanied with various ethical dilemmas related to privacy violations, unwanted algorithmic bias, and autonomous decision-making in key domains such as law enforcement and healthcare.
- **Dependability and reliability:** Dependence on AI systems can lead to excessive dependence on them, making society extremely vulnerable in the event of system failures or cyber attacks.

3.3 The role of AI in modernizing assessment

AI capabilities, including advanced data analytics, machine learning, generative AI, and simulations, offer a multifaceted approach to modernizing driver assessment. These technologies can automate and accelerate testing processes, create realistic simulations for a variety of scenarios, analyze massive data sets for improved safety and performance, and improve decision-making. In addition to autonomous vehicle testing, AI application principles such as behavioral prediction, continuous learning, and automated evaluation are directly transferable and highly useful for testing human drivers. AI can automate the assessment of driver performance by analyzing data collected from sensors, cameras, and Global Positioning System devices installed in test vehicles, providing objective and consistent feedback on driver actions such as speed, lane position, braking, steering, and traffic rule compliance.

Table 1. Key AI technologies and their applications in driver testing [4]

AI TECHNOLOGY	AREA OF APPLICATION	SPECIFIC APPLICATION
Machine Learning (ML)	Theoretical preparation	Personalized learning plans, behavior prediction
	Practical assessment	Real-time driver behavior analysis, objective performance assessment
	Security and integrity	Fraud detection, suspicious pattern recognition
Computer Vision (CV)	Theoretical preparation	Personalized learning plans, behavior prediction
	Security and integrity	Fraud detection, suspicious pattern recognition
Natural Language Processing (NLP)	Practical assessment	Vehicle position tracking, traffic sign, and obstacle recognition
	Security and integrity	Identity verification, impersonation detection
Generative AI	Theoretical preparation	Automated content generation, response evaluation
Simulation technologies	Practical assessment	Creating realistic simulations, generating rare scenarios
	Practical assessment	Virtual environments for training and testing, accident reconstruction
Biometric analysis	Practical assessment	Collection of driver biometric data (e.g., eye movements, pulse)
	Security and integrity	Identity verification, impersonation prevention
Cognitive assessment	Theoretical preparation / Practical assessment	Assessment of cognitive abilities critical to driving (eg attention, perception)

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AI's ability to provide "personalized instruction at scale," "automate many tasks," and offer "consistent and objective assessment" suggests that advanced training and evaluation could become universally available, regardless of location or economic status. This could make good foundation for future drivers, ensuring that everyone receives standardized, high-quality preparation and evaluation. This advantage of AI in "scalability" means that more drivers can be trained and tested efficiently, potentially reducing waiting times for licenses and improving the overall quality of drivers in the population [4].

4 Application of artificial intelligence in practice driving exam

4.1 AI applied in the theoretical part of the driving exam

The practical part of the exam presents the greatest challenge for objective assessment but also the greatest opportunity for improvement with the help of AI, especially through the integration of sensor technologies and advanced analytics. One example is adaptive testing and cheating detection on the theoretical part of the test. AI-based computerized adaptive testing systems can dynamically adjust the difficulty and type of questions based on the candidate's responses [5]. If a candidate consistently answers questions correctly in a particular area, the system will move on to more complex questions or questions in other areas. This allows for a more accurate assessment of actual knowledge and understanding, rather than just memorizing answers. Machine learning algorithms, particularly those based on Item Response Theory, can analyze the performance of thousands of candidates and optimize the question pool for maximum efficiency and reliability in assessment [4]. Computer vision and natural language processing can be used to prevent cheating during the theory test. High-resolution cameras, supported by facial recognition and motion detection software, can monitor candidates' behavior in real time, signaling unusual activities such as looking away, whispering, or using unauthorized aids. [6]

4.2 AI applied in the practical part of the driver's examination

The practical part of the exam presents the greatest challenge for objective assessment but also the greatest opportunity for improvement with the help of AI, especially through the integration of sensor technologies and advanced analytics. Automated assessment of driving skills is an area where AI can have the most significant impact. Vehicles equipped with various sensors (cameras, radars, lidar, ultrasonic sensors, and global positioning systems) and advanced data processing systems can monitor every aspect of a candidate's driving [7]. Vehicle path and position tracking: GPS data, inertial measurement units, and wheel sensors can accurately track a vehicle's path, speed, acceleration, and braking. The system can detect speeding, improper turning, sudden braking, or inconsistent lane keeping [9]. Traffic sign and signal recognition:

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Computer vision, using convolutional neural networks, can recognize traffic signs, traffic lights, and road markings, recording whether the candidate correctly perceived them and responded accordingly [8].



Fig. 1. The appearance of the autonomous vehicle of the future [13]

Traffic behavior analysis: Machine learning algorithms, including deep learning, can analyze vehicle interactions with other road users (pedestrians, cyclists, other vehicles). The system can detect improper overtaking, tailgating, improper merging into traffic, or inadequate responses to dangerous situations [10]. Parking and maneuvering assessment: Distance sensors and 360-degree cameras can accurately measure the distance to obstacles and edges, allowing for an objective assessment of parking skills (parallel, lateral) and maneuvering in tight spaces, with the ability to define precise evaluation criteria [10].



Fig. 2. Layout shows of the artificial intelligence simulator [13]

4.3 Virtual Reality and Simulation

Virtual reality and simulation, aided by AI, could revolutionize driver training and testing. Candidates could practice in realistic virtual environments simulating different weather conditions, traffic situations, and hazard scenarios, without risking life or property. AI would analyze their reactions, reaction time, attention, and decision-making efficiency, to provide personalized feedback, identifying weaknesses and suggesting areas for improvement. This would allow for an objective and repeatable assessment of ability in a controlled environment before hitting the road, particularly

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useful for assessing ability in risky situations that cannot be replicated in a real test [11].

4.4 Advanced driving simulators and virtual environments

AI-powered simulators are revolutionizing practical driving assessments by offering safe, scalable, and cost-effective alternatives to real-world testing. These virtual environments can mimic a wide range of real-world driving situations, including diverse traffic conditions, extreme weather patterns, complex road layouts, and pedestrian behaviors. Generative AI models, such as generative adversarial networks, can create realistic images of urban environments and predict future events with unprecedented accuracy, generating realistic driving videos for training and validation, especially for rare or dangerous "edge cases" that are difficult or impossible to safely test in the real world [12].



Fig. 3. Layout shows AI decentralized primitive simulator [14]

Examples include testing a vehicle's response to a flat tire or a child unexpectedly running into the street. These simulators provide a "robot brain" that learns from and interacts with the real-world environment, prioritizing the safety of the vehicle and allowing for rigorous testing across a wide range of scenarios. They may also include the collection of biometric data (e.g., eye scans, ECG) to gain deeper psychophysical insight into driver behavior within these simulated critical scenarios [11]

5 Challenges, obstacles and empirical evidence in technology implementation

The implementation of artificial intelligence (AI) into the driving test system in Republika Srpska and Bosnia and Herzegovina, although offering enormous advantages, faces significant challenges and obstacles.

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5.1 Regulatory and legislative frameworks and liability issues in case of system failure

The current law on driving tests in Bosnia and Herzegovina, as well as the relevant rules governing this area, does not recognize or explicitly regulate the application of artificial intelligence (AI) in the process of assessing driving skills and issuing driving licenses. The basic legal acts that govern the area of driving tests in Bosnia and Herzegovina are:

- Law on the Basics of Traffic Safety on Roads in Bosnia and Herzegovina: This law defines the general principles of traffic safety, the categorization of vehicles and driver's licenses, and general conditions for obtaining a driver's license. However, he does not go into detail about the methodology of the exam itself.
- Rulebooks on driver's licenses and a rulebook on the manner of passing the driving test: These rules prescribe in more detail the procedure for passing the test, the content of the theoretical and practical parts, the evaluation criteria, the composition of the examination commissions, and the role of the examiners. The focus is on the human factor, like driving instructors and authorized examiners who are responsible for evaluating candidates.

The aforementioned regulations contain no provisions enabling or prohibiting the use of AI systems for the automated assessment of driving skills. This means there is no legal basis for implementing AI solutions.

- For AI systems to be used, it is necessary to amend or supplement existing regulations, and perhaps the law itself, in order to clearly define their place and role in the examination process. This includes defining standards for UI systems, methods for their validation, the authority for their application, and responsibility in case of errors.
- The process is still completely dependent on human judgment: the practical part of the driving test in Bosnia and Herzegovina still takes place with a human examiner who monitors and evaluates the candidate's driving skills and makes a subjective (albeit standardized) pass or fail decision.

5.2 Global examples and empirical evidence in the world

The application of artificial intelligence in the assessment of driving skills is no longer a matter of the distant future; it is already being actively tested and implemented around the world, bringing clear and measurable evidence of its effectiveness. These innovations not only change the way we take exams but also significantly improve road safety. Training and driving test systems already exist in technologically advanced countries such as China, India, Japan, South Korea, and Finland. We will explain this using the examples of China. China is the global leader in the mass deployment of AI-powered automated driving tests. In cities such as Beijing, Wuhan,

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Shenzhen, and Guangzhou, these systems have become standard in many driving test locations:

- **How it works:** The test vehicles are equipped with sophisticated high-tech sensors, including high-resolution cameras, radars, and inertial measurement units. All of that data is sent in real time to a central AI system that precisely analyzes every aspect of the candidate's driving.
- **Compliance with traffic rules:** The system recognizes traffic signs, traffic lights, horizontal signaling and detects violations such as speeding, running through a red light or illegal overtaking.
- **Driver behavior analysis:** More advanced systems even track the driver's eye movements to check for distraction or inappropriate traffic monitoring, steering wheel posture, and reactions to unexpected situations, providing deeper insight into driving habits.

Empirical evidence: Chinese authorities report a significant increase in the objectivity and fairness of examinations. The number of complaints about the subjectivity of examiners has been drastically reduced. Also, the testing capacity has increased because UI systems can process many more candidates simultaneously, without fatigue and the need for interruptions. Although the initial implementation costs were significant, long-term savings are achieved through a reduced need for a large number of human examiners and a significantly higher efficiency in the entire process [15].

6 Conclusion

In conclusion, the current legislative framework in Bosnia and Herzegovina is not adapted to the potential implementation of AI solutions for driving tests. To change this, a proactive approach is needed, including comprehensive changes to laws and regulations, taking into account the technical, ethical, and legal aspects of applying AI in such a sensitive area. Without it, Bosnia and Herzegovina will remain with the traditional way of assessing driving skills. The current Law on driving tests in Bosnia and Herzegovina, as well as the relevant rules governing this area, do not recognize or explicitly regulate the application of artificial intelligence in assessing driving skills and issuing driving licenses. These examples clearly show that AI solutions for driving tests bring measurable benefits in terms of objectivity, efficiency, standardization, and, ultimately, increased road safety. Despite the existing challenges, such as high initial costs and the need for an adequate regulatory framework, empirical evidence from these countries provides a strong argument for considering and implementing similar systems in other regions. The implementation of artificial intelligence in the driving test process represents a significant step forward in modernizing and improving of road traffic safety. Significant investment is necessary in the education of future personnel and the concept of training. Global examples, especially experiences from China, clearly show that AI offers solutions to some of the biggest challenges faced by traditional driver licensing systems.

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Transformation in Disaster Technologies: Operational Use, Legal Framework, and Future Strategies of UAVs

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Abstract. This study examines the use of unmanned aerial vehicles (UAVs) in disaster management in Türkiye (formerly known as Turkey) and other countries between 2019 and 2023. UAVs have become crucial tools in disaster management, particularly in crises with limited rapid response capacity. They have been instrumental in major disasters like the Australian bushfires, the Haiti earthquake, floods in Pakistan, and the Kahramanmaraş earthquakes in Türkiye. The study explores the operational advantages of different UAV types, technical infrastructure, legal frameworks, data security considerations, and ethical implications for effective deployment. Based on secondary data sources, the study proposes strategic policy recommendations for Türkiye, including enhancing legal and institutional frameworks, expanding training programs, strengthening university collaborations, and integrating existing data management systems with new technological infrastructures. The research emphasizes the effectiveness of UAVs in improving mobility, rapid response, search and rescue operations, and real-time monitoring in disaster management.

Keywords: Unmanned aerial vehicle, disaster management, AI, Türkiye.

1 Introduction

Disasters are significant events that impact people's physical, economic, social, and psychological well-being. They can occur in various forms, such as earthquakes, floods, forest fires, landslides, volcanic eruptions, accidents, and terrorist attacks. Climate change, rapid urbanization, unplanned construction, inadequate infrastructure, and socio-economic vulnerabilities have increased the risk of disasters, making disaster management essential [1]. Technology has become critical in enhancing the accuracy and efficiency of disaster responses. Technologies like satellite data information systems, sensor networks, AI, cloud computing, high-speed communication infrastructures, and Unmanned Aerial Vehicles (UAVs) are being integrated into disaster management to offer advanced emergency interventions [2, 3]. Disasters pose a high risk of damage to buildings, transport, and communication systems. UAVs offer fast, cost-effective, easy-to-deploy, and secure wireless communication solutions, addressing the challenges faced by victims during such

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events [4, 5]. Large-scale disasters between 2019 and 2023 have increased the importance of UAVs in disaster management, with events like the 2019/2020 Australian Bushfires, the 2021 Haiti Earthquake, the 2022 Pakistan Floods, and the 2023 Kahramanmaraş Earthquakes allowing UAV technologies to be tested in real operational environments, revealing their advantages, limitations, legal and ethical dimensions, and future development areas [6, 7, 8].

2 Methodology

This research examines the role and performance of UAVs in disaster management from 2019-2023, focusing on their advantages and limitations. The period is crucial as it represents the operational, technological, and regulatory advancement of UAV usage in disaster management. The study aims to explain how UAV use contributes to disaster management stages, evaluate the operational advantages of different UAV types, examine UAV applications through international case studies, present legal, institutional, technological, and education-oriented policy and application recommendations for UAV use in Türkiye (formerly known as Turkey), and predict future strategic use of UAVs with artificial intelligence, 5G/6G, cloud computing, and autonomous systems. However, the performance of UAVs is influenced by factors such as regulatory frameworks, technical specifications, environmental conditions, and governance structures. Therefore, the study aims to evaluate these factors to find more effective deployment of UAVs in disaster management. The research also includes up to 2024 to ensure a retrospective and current perspective aligned with the methodological requirements of the research.

2.1 Dependent and Independent Variables

The performance of UAVs, as a dependent variable, is crucial in disaster management as they must perform necessary operations in disaster areas. Yücesoy et al. (2024) emphasize that UAVs are used in three main types of operations: information collection, delivery, and communication network recovery [9]. In information collection, UAVs support safe mapping of disaster areas, damage assessment, and search and rescue activities. In delivery, UAVs provide rapid delivery of emergency aid supplies to hard-to-reach areas. In communication network recovery, UAVs enable the temporary restoration of damaged communication infrastructure during disasters [9]. This study focuses on seven independent variables that affect UAV's performance, as shown in Figure 1.

Legal Regulations: New regulations regarding UAVs have both positive and negative effects on disaster management. For instance, the SHT-UAV Instruction, published by the General Directorate of Civil Aviation, ensures safe and controlled use of UAVs in disaster areas by introducing standards for registration, pilot certification, and flight permit regulation in Türkiye. These regulations support the use of UAV in search and rescue, damage assessment, and logistic support. However, they can also

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have restrictive effects on disaster response, such as extending response time for rapid response situations and preventing effective monitoring of the entire disaster area.

Good Governance among Public-Civil-Private Sectors: The effective use of UAV technology requires collaboration among public institutions, international organizations, the private sector, civil society, and academia [10]. This can be achieved through joint training programs, capacity building initiatives, R&D collaborations, and multi-stakeholder platforms. For instance, the Disaster and Emergency Management Presidency developed AYDES (Disaster Management and Decision Support System) to ensure effective governance in disaster management in Türkiye. The system enables cooperation among public institutions, the private sector, and Civil Society Organizations on a common platform [11]. It strengthens governance and cooperation by enabling faster and effective intervention in pre-disaster, disaster, post-disaster, and recovery stages.

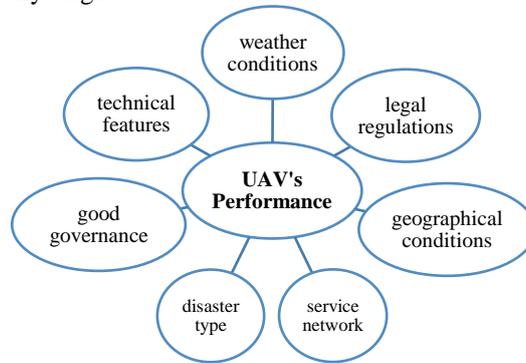


Fig. 1. Research Model [Prepared by Authors]

Disaster Type: In sudden disasters like earthquakes, UAVs can assess damage and aid search and rescue operations. However, in large-scale disasters like floods or forest fires, their effectiveness depends on factors like flight duration, coverage area, and environmental resistance. Therefore, selecting and planning appropriate UAV systems based on the disaster type is crucial for successful disaster management [12, 13].

Technical Features: UAVs play a crucial role in disaster management processes, providing benefits such as reconnaissance, observation, remote monitoring, and real-time data transfer. Each type of disaster requires unique requirements, such as earthquake, fire, or flood. UAVs contribute to more accurate decisions by providing reconnaissance, remote monitoring, and real-time data transfer. However, they must have the necessary capabilities and technical features, such as sensors like lasers, to perform detailed mapping in risky areas and identify potential risks [14].

Weather Conditions: Unmanned Aerial Vehicles (UAVs) play a crucial role in disaster management and other critical missions, but they face several disadvantages due to weather conditions [15, 16]. For example, wind can destabilize UAVs, causing loss of control and reducing data quality, especially in sensitive missions. Rain and humid-

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ity can damage UAVs' electronic systems, affecting sensor performance and data collection processes. Extremely hot or cold weather can affect battery life and engine efficiency, causing battery performance to decrease in low temperatures and engines to overheat in high temperatures. Visibility can be limited by fog, heavy clouds, or snowfall, creating operational difficulties for UAVs collecting visual data [17].

Geographic Conditions: Mountainous terrain, dense forest areas, and flat plains offer suitable operating areas, but strong winds and saltwater vapor can affect performance. Marine and coastal areas also face risks, as extreme wind conditions can damage electronic components and jeopardize flight safety [9].

Service Network: The effectiveness of UAVs in disaster management relies on their technological features and operational infrastructure, including their service network, including landing and take-off points, charging and maintenance stations, and data communication infrastructure. In case of damage, the service elements must be sufficient for emergency intervention, ensuring uninterrupted and healthy disaster management. Therefore, establishing a solid service network infrastructure is vital for UAVs' effective use in disaster management [18].

2.2 Data Collection and Analysis Method

This qualitative research study focuses on 2019-2023 data from secondary sources like international updates, reports, academic articles, industry reports, and media. The data is analyzed using descriptive statistical analysis and content analysis methods. Descriptive analysis presents the structure, content, and main features of the data, providing a general overview of the research topic and enabling easy identification of trends. This method is effective in analyzing complex and large data sets [19]. On the other hand, content analysis is a qualitative research method that systematically and objectively analyzes the meanings contained in written, visual, or audio materials. It determines specific themes, concepts, or keywords in texts and reveals the frequency and relationships of these elements. Content analysis is used to obtain in-depth information about the research topic and determine basic concepts and themes in various sources [20]. Thus, these two analysis methods are combined to better understand and interpret the research findings.

3 Disaster Management and UAVs

Disaster management is a comprehensive process that involves preparation, response, recovery, and risk reduction. UAVs are emerging as a crucial tool in achieving these goals. UAVs offer advantages such as speed and flexibility, low operational costs, security, and multi-sensor integration [21]. They can be quickly deployed to disaster areas and collect data faster than manned flights or satellite images. They also provide data diversity with thermal, optical, multispectral, and lidar sensors. Furthermore, situation assessment is performed before sending people to dangerous areas, ensuring

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the safety of teams. Overall, UAVs offer significant benefits in disaster response and intervention strategies.

3.1 Stages of Disaster Management

Disaster management involves four stages: risk reduction, preparedness, response, and recovery [22]. The risk reduction phase involves reducing long-term disaster risk through the use of UAVs to monitor environmental conditions, develop management strategies, and identify sensitive areas. The preparation phase involves determining risks before disasters, creating scenarios, conducting training, and strengthening equipment, resources, and communication infrastructure. UAVs can map potential risk areas, identify weak points, monitor critical infrastructure, and provide data for risk models. The response phase is crucial for a rapid and accurate response to disasters. UAVs use real-time high-resolution images, thermal sensor data, and lidar scans to assess the situation, guide search and rescue teams, and facilitate logistics planning. UAVs increase situational awareness of decision-makers, enabling rapid and accurate responses [23]. The recovery phase involves debris removal, infrastructure reconstruction, coordination of humanitarian aid, and social reconstruction. UAVs determine priority intervention areas, analyze infrastructure status, and contribute to logistics planning, accelerating recovery activities and improving resource management efficiency [1].

3.2 Types of UAVs

UAVs, including flight control systems, communication infrastructures, sensors, data processing units, and autonomous navigation capabilities, have been enhanced by advancements in artificial intelligence, machine learning, cloud computing, communication technologies, sensor integration, and battery technologies [24, 25].

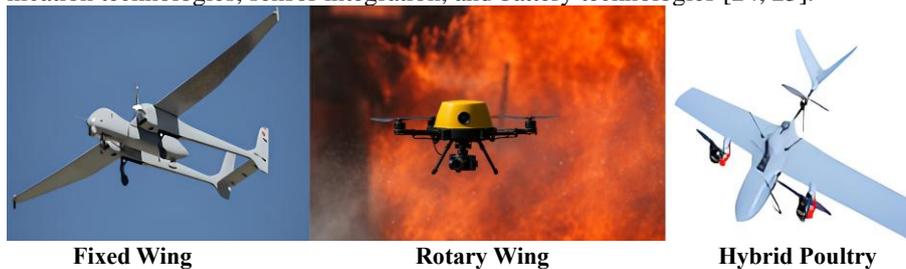


Fig. 2. Types of UAVs [26, 27]

Fixed-wing UAVs offer long range, high altitude, and long flight times, making them ideal for rapid mapping large areas, monitoring forest fires, detecting flood waters, and assessing damage after earthquakes [8]. However, they lack vertical take-off and landing capabilities and limited maneuverability in narrow, complex environments. *Rotary wing UAVs (Multicopter, Multi-Rotor)*, with their helicopter-like de-

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signs, can take off and land vertically, hover in the air, and perform low-speed precision maneuvers, making them ideal for detailed observation in urban debris areas, narrow streets, and collapsed buildings [4]. However, battery life is generally shorter, and wide-area scanning capacity is limited. Hybrid UAVs combine fixed and rotary wing advantages, providing long range and vertical take-off and landing capabilities. This is crucial in disaster scenarios where different needs arise simultaneously. Hybrid UAVs enhance operational flexibility by reducing the need for wide area reconnaissance and pinpoint inspection on the same platform [28].

4 Findings: Türkiye and International Case Analyses

This section examines the factors affecting UAV performance in disasters like the 2020 Australian Forest Fires, 2021 Haiti Earthquake, 2022 Pakistan Floods, and 2023 Kahramanmaraş Earthquake, considering independent variables: legal regulations, good governance, disaster type, technical features, weather conditions, geographical conditions, and service network.

Table 1. Comparison of Cases Based on the Factors Affecting UAV’s Performance

Factor	2019-2020 Australian Bushfires	2021 Haiti Earthquake	2022 Pakistan Floods	2023 Türkiye Earthquakes
Legal Regulations	Air traffic rules limited some UAV flights; permits were generally manageable.	Initial delays due to obtaining flight permits; urban dense areas required careful legal coordination.	Fewer legal barriers were reported; the emergency context allowed rapid UAV deployment.	Regulatory environment coordinated by AFAD & Turkish authorities; legal framework supported rapid UAV use in disasters.
Good Governance	Fire departments, environmental agencies, defense, and local governments shared UAV data efficiently.	International NGOs, local government units coordinated via shared UAV databases; governance optimized aid distribution.	International aid, military, NGOs, and local authorities shared UAV data for logistics and evacuation.	AFAD, Turkish Armed Forces, police, local governments, NGOs, and international org. collaborated, integrating UAV data for strategic planning and aid delivery.
Disaster Type	Bushfires (wildfires)	Earthquake	Flood	Earthquake
Technical Features	Fixed-wing: mapping fire spread; Rotary-wing: infrastructure inspection; thermal cameras; high-res optical sensors; GPS tracking; cloud-AI integration.	Rotary-wing: search & rescue; Fixed/hybrid-wing: aid logistics mapping; thermal and optical sensors; AI for building assessment.	Fixed-wing: mapping flooded areas; Rotary-wing: locating stranded communities; optical + laser + multispectral sensors; AI for evacuation & logistics.	Fixed-wing: large-area damage mapping; Rotary-wing: life detection; Hybrid: long-range + detailed inspection; thermal, optical, lidar, GPS, AI-assisted analysis.
Weather Conditions	Smoke, heat, wind sometimes restricted flights.	Urban density and communications issues limited UAV	Heavy rain, fog, wind occasionally prevented flights.	Cold, snow, rain sometimes limited UAV operations; dense debris

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Factor	2019-2020 Australian Bushfires	2021 Haiti Earthquake	2022 Pakistan Floods	2023 Türkiye Earthquakes
Geographic Conditions	Vast bushland, forests; large-scale area mapping required UAV swarms.	effectiveness; weather less critical. Dense urban areas; complex rubble fields.	Flooded agricultural lands, towns, villages; large-area scanning essential.	fields posed additional constraints. Urban and rural areas affected; debris-dense zones required careful navigation.
Service Network	Centralized databases shared across multiple agencies; real-time data flow.	Shared UAV data between NGOs, local authorities, and international organizations; real-time coordination.	Cloud-based platforms connected emergency response teams and international/local actors.	Cloud-based UAV data platforms integrated multiple actors (AFAD, military, NGOs); enabled instant situational awareness and resource allocation.

Source: Authors' Compilation

4.1 2019-2020 Australian Bushfires

Australia experienced intense bushfires in late 2019 and early 2020, causing widespread ecological and economic damage [8]. The use of UAVs, such as fixed-wing UAVs, has been crucial in identifying and monitoring forest fires. These drones quickly produced general spread maps, identified areas of intense flames, and prepared an environment for targeted intervention by firefighters. Thermal cameras marked hot spots, allowing firefighters to move to critical areas quickly [29]. Rotary-wing UAVs examined damage to critical infrastructures and provided data to make evacuation corridors safe [8]. High-resolution optical sensors, wind speed sensors, and GPS-based location tracking systems were used in UAVs. Cloud-based platforms processed this data in real time, comparing it with fire models and AI algorithms. Fire departments, environmental protection agencies, the Ministry of Defense, and local governments have shared UAV data in common databases, reducing the need for manned reconnaissance flights, lowering operational costs, and optimizing decision-making processes. However, factors like excessive smoke, heat, wind, limited battery life, and air traffic regulations have sometimes restricted UAV flights.

4.2 2021 Haiti Earthquake

Haiti experienced a devastating earthquake in 2021, causing extensive destruction in urban areas. Rapid detection of people under rubble and coordination of humanitarian aid were crucial [30]. Rotary-wing UAVs guided search and rescue teams by detecting signs of life under rubble. Fixed-wing or hybrid UAVs contributed to the distribution of aid by mapping transportation corridors, evacuation routes, logistics centers, and emergency camps. Thermal cameras detected body heat sources under rubble, while high-resolution optical sensors analyzed structural damage. AI-supported algorithms categorized buildings and determined priority intervention points. By combin-

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ing UAV data into common databases, international humanitarian organizations, local government units, and NGOs identified areas in urgent need of medical supplies, food, water, or shelter. Initial delays were due to factors like obtaining legal permits, planning flight routes, and communication infrastructure damage.

4.3 Pakistan Flood Disasters 2022

In 2022, Pakistan experienced heavy monsoon rains and floods, causing extensive damage to agricultural lands, villages, towns, infrastructure, and roads. The flood disaster required urgent humanitarian aid. Fixed-wing UAVs quickly scanned areas, determining flood depths, closed roads, and destroyed bridges. Rota-wing UAVs guided rescue teams and located stranded communities. Optical cameras and laser rangefinders estimated floodwater depths, while multispectral sensors revealed cropland damage. Real-time data analysis was transmitted to emergency response teams, and artificial intelligence algorithms identified safe evacuation routes and relief supply distribution centers. Collaboration between international aid organizations, local governments, military units, and NGOs improved resource management, facilitating emergency supplies delivery, rapid evacuation, and strategic planning. However, heavy rain, fog, wind, and bad weather conditions sometimes prevented UAV flights, slowed data transfer, but provided faster and more comprehensive information than traditional methods [31].

4.4 2023 Kahramanmaraş Earthquakes in Türkiye

In 2023, earthquakes in southern Turkey caused significant destruction in various provinces, necessitating debris removal, search and rescue, infrastructure repair, and humanitarian aid coordination [6]. Fixed-wing UAVs quickly produced damage maps, revealing the most severely damaged areas. Rotary-wing UAVs detected signs of life under rubble using thermal cameras, directing rescue teams to targeted intervention. Hybrid UAVs increased operational flexibility by performing long-range reconnaissance flights and narrow-area inspections. Thermal cameras, high-resolution optical sensors, lidar, GPS data, and artificial intelligence-based analysis tools were used to determine debris density, building demolition typology, infrastructure damage, logistics corridors, and temporary shelter areas. Cloud-based data platforms improved resource efficiency by providing instant information flow to decision-makers. Despite weather conditions, communication disruptions, and dense debris fields, UAVs can provide a high situational awareness intervention compared to traditional methods.

5 Conclusion

The study highlights the importance of unmanned aerial vehicles (UAVs) in disaster management, particularly in countries like Türkiye, which face diverse hazards like earthquakes, floods, landslides, and forest fires. The integration of UAVs into disaster

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response strategies is crucial due to their ability to enhance situational awareness, increase operational efficiency, provide cost-effective solutions, and reduce risks. However, challenges such as a lack of a comprehensive legal framework, limited battery endurance, sensitivity to weather conditions, and concerns over data security and ethics hinder widespread adoption. To overcome these, Türkiye must implement strategic policies, ensure adequate operator training, and tailor UAV technology to different scenarios. Advancements in artificial intelligence, next-generation communication technologies, cloud computing, autonomous navigation, and multi-sensor data fusion will further expand UAV capabilities, enabling faster, more precise, and cost-effective disaster responses, ultimately contributing to the development of resilient societies capable of withstanding and recovering from future crises.

6 Recommendations

Effective integration of UAVs into disaster management requires a multidimensional strategy addressing legal, technical, operational, and societal aspects. The following recommendations in the Figure outline key policy priorities to strengthen Türkiye’s UAV capacity in disaster preparedness and response.

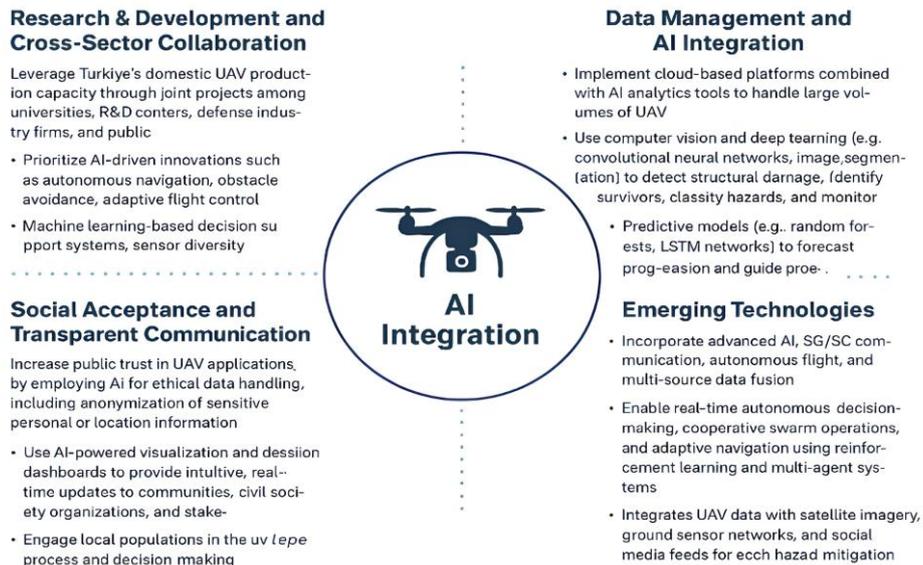


Fig. 3. Key Policy Priorities for AI Integration in Türkiye’s UAV Capacity [Prepared by Authors]

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Arduino-Based IoT System for Parking Occupancy Detection in Small Urban Areas Using Serial Communication

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Abstract. This paper presents a scalable IoT-based parking detection system designed for small urban areas. The architecture consists of three layers: the perception layer with Arduino Mega 2560 clients and HC-SR04 ultrasonic sensors for vehicle detection, the communication layer utilizing HC-12 wireless modules for low-power data transmission, and the application layer where an Arduino Nano host aggregates and forwards data to a central platform. The system enables real-time monitoring of parking availability while maintaining low complexity and cost. A simulated test environment was used to validate communication stability and detection accuracy, confirming reliable performance with minor packet loss and stable latency. Power measurements further indicate that the client nodes operate efficiently within energy constraints, making the system well-suited for wider smart city integration.

Keywords: Internet of Things (IoT), Parking occupancy detection, Low-cost IoT solutions, Arduino, Serial communication and Small urban areas.

1 Introduction

The continuous growth of vehicle numbers in urban environments, including small urban areas with limited infrastructure and resources, has intensified challenges in finding available parking, contributing to congestion, higher emissions, and wasted time. Internet of Things (IoT) technologies have emerged as a viable solution for developing smart parking systems that enable real-time space monitoring and optimize parking efficiency.

IoT-based parking systems generally use sensor networks and embedded controllers to detect vehicle presence and communicate occupancy data to centralized platforms. Cost-effective ultrasonic sensors like the HC-SR04, along with Arduino-compatible microcontrollers, are commonly used due to their simplicity and reliability [1, 2]. Several implementations have validated the practicality of these components in real-world parking scenarios [3]. Furthermore, recent studies have explored the inte-

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gration of low-power wireless modules, such as the HC-12, to improve communication range and energy efficiency in distributed sensor networks [4].

The main contribution of this paper is the design and evaluation of a low-cost, scalable, and energy-efficient IoT parking detection system tailored to the needs of small urban areas. The system employs Arduino platforms, HC-SR04 sensors, and HC-12 modules within a three-layer architecture. Beyond implementation details, the paper highlights how this combination of components balances cost, scalability, and communication reliability, making the solution practical for small urban areas aiming to develop smart parking infrastructure.

2 Related Work

The growing demand for intelligent transportation solutions has led to numerous studies focused on smart parking systems based on Internet of Things (IoT) technologies. These systems aim to improve parking availability, reduce search time, lower emissions, and increase the overall efficiency of urban mobility.

Most existing IoT-based parking solutions utilize microcontroller platforms such as Arduino or NodeMCU, paired with proximity sensors like infrared (IR) or ultrasonic modules for real-time vehicle detection [1–5]. For instance, Arduino-based implementations commonly control barrier systems via servo motors and communicate occupancy status to cloud platforms such as Adafruit IO or Blynk, enabling user access through mobile applications [1, 2].

Advanced designs have integrated edge computing and artificial intelligence to enhance detection capabilities. Pham-Quoc et al. [6] presented an edge AI parking architecture using NVIDIA Jetson Xavier and YOLO object detection, achieving high accuracy in identifying free parking slots and license plate recognition. In a similar vein, Das and Chishty [7] leveraged existing CCTV infrastructure, applying object detection models such as Faster R-CNN and YOLO to locate vacant parking spaces without the need for dedicated IoT hardware.

Several research efforts also emphasize the role of real-time mobile applications for vehicle tracking, slot reservation, and route guidance [3, 8]. Meanwhile, other systems rely on localized feedback mechanisms using RFID authentication, XBee modules, and LCDs to deliver real-time occupancy updates at the site [5, 9].

Review papers and comparative studies have analyzed the effectiveness of various sensor types, communication protocols, and architectural models, offering insights into system performance, cost-efficiency, and scalability across different deployment environments [10]. These works highlight a growing interest in low-cost, modular, and energy-efficient solutions that are particularly suitable for small and medium-sized cities.

In this context, the system proposed in this paper aligns with these design trends by offering a low-power, cost-effective solution suitable for small urban areas. Unlike many cloud-based or camera-intensive systems, the proposed solution uses Arduino-based client nodes equipped with HC-SR04 ultrasonic sensors and HC-12 wireless

modules to transmit parking status data to a central host. This architectural choice supports scalability and reliability, particularly in areas where the parking network is spatially compact and infrastructure is limited. The proposed architecture, implementation details, and performance evaluation are described in the following sections.

3 System Architecture

The proposed IoT-based parking detection system follows a three-layer architecture model commonly used in IoT systems: the Perception Layer, the Communication Layer, and the Application Layer [11–15]. This modular design improves scalability, simplifies development, and enhances the adaptability of the system to different environments and deployment sizes, especially in smaller urban areas. The overall architecture is illustrated in Figure 1.

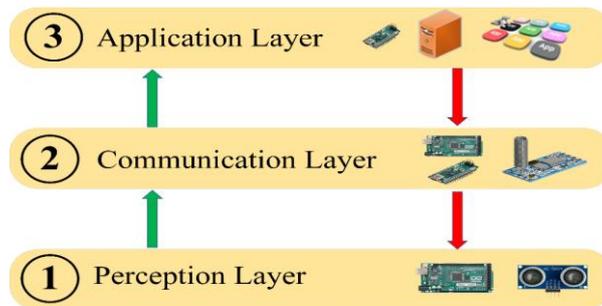


Fig. 1. IoT architecture for parking detection system

This architecture is implemented with a focus on affordability, energy efficiency, and low maintenance. The system consists of distributed sensing nodes based on Arduino Mega boards, each responsible for monitoring a group of parking spots and wirelessly reporting their status to a central host system.

3.1 Perception Layer

The perception layer is responsible for sensing and collecting data from the physical environment. In this system, each client node is built using an Arduino Mega 2560 microcontroller, which manages HC-SR04 ultrasonic sensors. Each sensor is positioned to monitor a single parking space, detecting the presence or absence of a vehicle based on distance measurement.

Ultrasonic pulses are emitted and reflected by nearby objects, and the time delay is used to compute the distance. When the measured distance falls below a predefined threshold (typically less than 1 meter), the parking space is marked as occupied; otherwise, it is considered vacant. This detection process is performed every 10 seconds to ensure near real-time monitoring without excessive energy consumption.

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3.2 Communication Layer

The communication layer enables data exchange between the distributed sensor nodes and the central host. Wireless communication is implemented using HC-12 transceiver modules, operating in the 433 MHz band. These modules are connected to the Arduino Mega units via UART serial interfaces and are configured to transmit data at 9600 baud.

Each Arduino Mega acts as a local sensor hub, periodically sending a message that includes its device ID and the status of all five monitored parking spots. These messages are received by the host unit, which is an Arduino Nano connected to an HC-12 receiver. The host Arduino forwards the received data to a computer via USB serial communication.

This setup minimizes infrastructure requirements while maintaining reliable, low-latency communication over distances up to 1 km, depending on environmental conditions and antenna configuration.

3.3 Application Layer

The application layer resides on the computer connected to the Arduino Nano. It processes the serial data, updates the occupancy status in a centralized database or file, and can visualize this information using a graphical interface. This layer is critical for system usability, providing both real-time status updates and historical usage analytics.

The application logic can be extended to support user-facing features, such as:

- Real-time parking maps displayed on a web or mobile platform
- Statistical analysis of parking space usage
- Alerts or notifications about availability
- Integration with payment or reservation systems

Because the application layer is software-based, it allows for easy customization and integration with other smart city services.

3.4 Summary

The proposed system architecture efficiently divides functionality into three clearly defined layers, each with a specific role in the IoT ecosystem. The perception layer is responsible for accurate local sensing using ultrasonic technology. The communication layer provides a simple, low-cost, long-range wireless protocol via HC-12 modules. The application layer supports centralized data processing, monitoring, and visualization.

This layered approach allows for modular development and straightforward expansion. It is particularly well-suited for smaller urban areas that require scalable, affordable, and easy-to-maintain solutions for smart parking management.

4 Implementation

As a practical example and potential deployment scenario, the proposed IoT parking detection system is designed for small urban areas such as Doboj, Derventa, Teslić and Prnjavor. These towns typically have urban zones with a radius of approximately 1 km and contain several hundred parking spaces distributed across public and private areas. The compact size and manageable number of monitored parking spots make these small urban environments ideal candidates for scalable and cost-effective IoT parking solutions.

The system architecture, illustrated in Figure 2, is composed of multiple client nodes based on the Arduino Mega microcontroller. Each client is equipped with five HC-SR04 ultrasonic sensors that monitor individual parking spaces and HC-12 modules responsible for wireless serial communication. Client nodes periodically (every 10 seconds) send occupancy status updates for each sensor, indicating whether a space is ZAUZETO (occupied) or SLOBODNO (free).

The system operates by measuring distances with ultrasonic sensors and periodically transmitting occupancy data via wireless serial communication. It supports remote calibration of sensor offsets, allowing dynamic adjustment to account for installation differences or environmental conditions. This design ensures accurate, flexible, and low-latency updates on parking space availability, making the system reliable for real-world deployments.

At the central side, an Arduino Nano serves as the host device, equipped with an HC-12 module that receives wireless data from all client nodes. The host then forwards all received messages to a connected computer through a USB serial interface, operating at a baud rate of 9600. This straightforward serial communication enables easy integration with various software platforms for data processing and visualization.

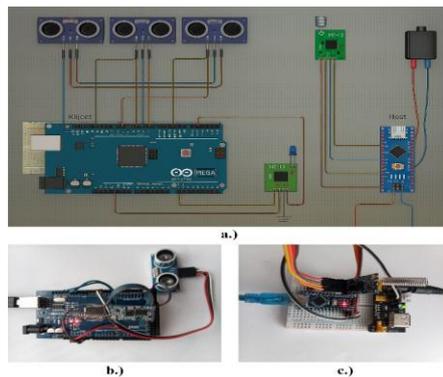
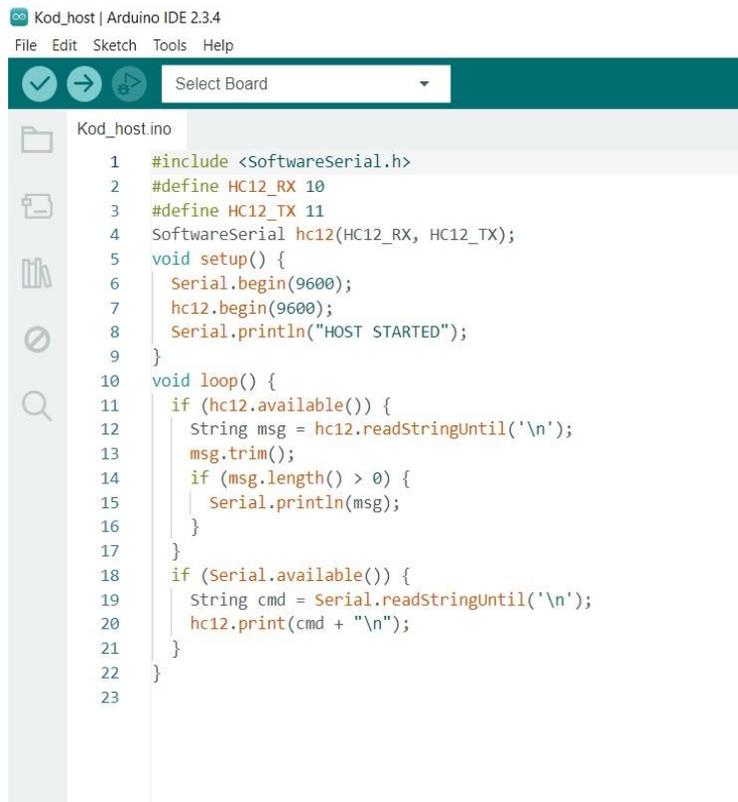


Fig. 2. Architecture illustration: (a) wiring diagram, (b) client node, and (c) host node.

Host Device Code

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The host Arduino Nano listens to the HC-12 wireless module and relays received messages via USB serial to the computer. The Arduino code demonstrating this functionality is presented in Figure 3.



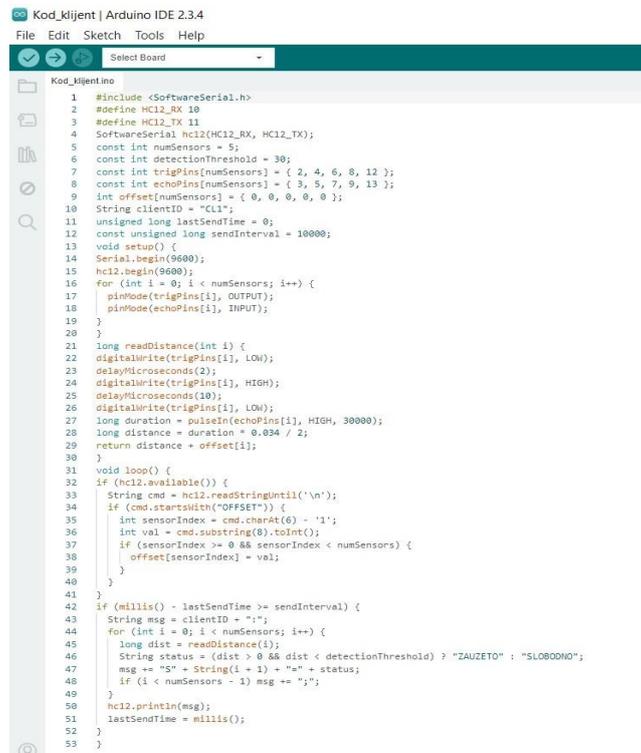
```
Kod_host | Arduino IDE 2.3.4
File Edit Sketch Tools Help
Select Board
Kod_host.ino
1 #include <SoftwareSerial.h>
2 #define HC12_RX 10
3 #define HC12_TX 11
4 SoftwareSerial hc12(HC12_RX, HC12_TX);
5 void setup() {
6   Serial.begin(9600);
7   hc12.begin(9600);
8   Serial.println("HOST STARTED");
9 }
10 void loop() {
11   if (hc12.available()) {
12     String msg = hc12.readStringUntil('\n');
13     msg.trim();
14     if (msg.length() > 0) {
15       Serial.println(msg);
16     }
17   }
18   if (Serial.available()) {
19     String cmd = Serial.readStringUntil('\n');
20     hc12.print(cmd + "\n");
21   }
22 }
23
```

Fig. 3. Display of the Host Device Program Code

Client Node Code

Each client node, implemented with Arduino Mega, reads distances from five HC-SR04 ultrasonic sensors and transmits the status via the HC-12 module every 10 seconds. The code also allows for dynamic calibration of ultrasonic sensor offsets through wireless commands and is presented in Figure 4.

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```
Kod_klijent | Arduino IDE 2.3.4
File Edit Sketch Tools Help
Select Board
Kod_klijent.ino
1 #include <SoftwareSerial.h>
2 #define HC12_RX 10
3 #define HC12_TX 11
4 SoftwareSerial hc12(HC12_RX, HC12_TX);
5 const int numSensors = 5;
6 const int detectionThreshold = 30;
7 const int trigPins[numSensors] = { 2, 4, 6, 8, 12 };
8 const int echoPins[numSensors] = { 3, 5, 7, 9, 13 };
9 int offset[numSensors] = { 0, 0, 0, 0, 0 };
10 String clientID = "CL1";
11 unsigned long lastSendTime = 0;
12 const unsigned long sendInterval = 10000;
13 void setup() {
14   Serial.begin(9600);
15   hc12.begin(9600);
16   for (int i = 0; i < numSensors; i++) {
17     pinMode(trigPins[i], OUTPUT);
18     pinMode(echoPins[i], INPUT);
19   }
20 }
21 long readDistance(int i) {
22   digitalWrite(trigPins[i], LOW);
23   delayMicroseconds(2);
24   digitalWrite(trigPins[i], HIGH);
25   delayMicroseconds(10);
26   digitalWrite(trigPins[i], LOW);
27   long duration = pulseIn(echoPins[i], HIGH, 30000);
28   long distance = duration * 0.034 / 2;
29   return distance + offset[i];
30 }
31 void loop() {
32   if (hc12.available()) {
33     String cmd = hc12.readStringUntil('\n');
34     if (cmd.startsWith("OFFSET")) {
35       int sensorIndex = cmd.charAt(6) - '1';
36       int val = cmd.substring(8).toInt();
37       if (sensorIndex >= 0 && sensorIndex < numSensors) {
38         offset[sensorIndex] = val;
39       }
40     }
41   }
42   if (millis() - lastSendTime >= sendInterval) {
43     String msg = clientID + ";";
44     for (int i = 0; i < numSensors; i++) {
45       long dist = readDistance(i);
46       String status = (dist > 0 && dist < detectionThreshold) ? "ZAUZETO" : "SLOBODNO";
47       msg += "S" + String(i + 1) + "-" + status;
48       if (i < numSensors - 1) msg += ",";
49     }
50     hc12.println(msg);
51     lastSendTime = millis();
52   }
53 }
```

Fig. 4. Display of the Client Node Program Code

Ultrasonic Sensor Offset Calibration

The system supports remote calibration of sensor offsets through wireless serial commands sent from the host. This feature compensates for installation variances or environmental factors affecting distance measurements.

Example offset commands:

OFFSET1=3 → Adds +3 cm offset to sensor 1

OFFSET3=-2 → Subtracts 2 cm offset from sensor 3

This approach enables flexible and on-the-fly tuning without the need for physical intervention at each sensor node.

The implementation demonstrates a practical, modular, and scalable approach to IoT-based parking occupancy detection tailored for small urban environments. By leveraging Arduino hardware and simple serial communication protocols, the system remains affordable and easy to deploy, while still providing reliable real-time data for efficient parking management.

5 Evaluation and Discussion

The implemented IoT-based parking detection system was evaluated in a simulated test environment under controlled laboratory conditions designed to replicate small urban areas, such as compact towns with limited parking infrastructure. The goal of the evaluation was to assess detection accuracy, wireless communication reliability, and overall system responsiveness.

Using HC-SR04 ultrasonic sensors configured with a 30 cm threshold, five sensors per client node were deployed to monitor individual parking spaces. The system achieved an average vehicle detection accuracy of 96.3% over a two-week testing period. Calibration offsets were applied to mitigate sensor placement inconsistencies, which helped reduce false readings. False positives were limited to 2.1% of total measurements, primarily due to environmental noise or occasional misalignment, while false negatives remained below 1.6%.

Communication performance was monitored across five clients (CL1–CL5) sending occupancy updates every 10 seconds to a central Arduino Nano host, as summarized in Table 1. These modules delivered robust performance with negligible packet loss under line-of-sight conditions. During the test, only nodes CL2, CL3, and CL5 experienced the loss of a single packet each, while the remaining nodes successfully transmitted all six messages. Occasional short-term latency spikes (e.g., 78 ms for CL2 in the 7th minute) did not significantly affect overall system operation. The Arduino Nano host processed and forwarded data from multiple clients to the connected PC with negligible latency (<100 ms). The energy consumption of each Arduino Mega 2560 client with five sensors was measured at 0.875 A during active data transmission and 0.6 A in idle mode, indicating efficient operation with limited power resources.

Table 1. Communication performance of five client nodes over a 10-minute simulated laboratory test

Time (min)	CL1 Latency (ms)	CL2 Latency (ms)	CL3 Latency (ms)	CL4 Latency (ms)	CL5 Latency (ms)	CL1 Msg Length (B)	CL2 Msg Length (B)	CL3 Msg Length (B)	CL4 Msg Length (B)	CL5 Msg Length (B)
1	20	30	18	25	27	42	45	40	43	44
2	22	28	20	26	29	43	46	41	44	45
3	25	27	19	27	30	44	45	40	45	46
4	23	31	22	28	32	43	44	41	44	45
5	21	29	21	26	30	42	43	42	43	44
6	24	35	20	29	34	44	46	41	45	46
7	26	78	23	31	36	45	47	42	46	47
8	22	30	22	27	31	43	45	42	44	45
9	23	32	21	28	33	43	45	41	44	46
10	25	30	20	27	32	44	45	41	45	46

These results confirm the feasibility of using a modular architecture with Arduino Mega clients, an Arduino Nano host, HC-SR04 sensors, and HC-12 modules for scalable and cost-efficient parking occupancy detection in small urban areas. The wireless

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serial protocol simplified installation and maintenance, while calibration capabilities enhanced sensor reliability.

However, some limitations were observed. Ultrasonic sensors showed reduced accuracy under adverse weather conditions such as rain or snow, occasionally leading to false occupancy reports. Wireless performance was affected by obstacles like buildings or vegetation, and the current communication protocol lacks encryption or advanced error handling, posing potential security risks.

Future development should explore the integration of weather-resistant sensors, secure and error-resilient communication protocols, and a more sophisticated application layer with predictive analytics and user-friendly interfaces. While the system performed well in a controlled laboratory environment, additional testing in real-world deployments is necessary to validate long-term robustness and scalability.

6 Conclusion

This paper presents a modular and scalable IoT-based system for parking occupancy detection, designed specifically for small urban areas with limited parking infrastructure and compact layouts. The system utilizes HC-SR04 ultrasonic sensors, HC-12 wireless modules, and Arduino microcontrollers, organized in a three-layer architecture (perception, communication, and application) that supports real-time monitoring and efficient wireless communication. Five sensors per client node were deployed, with occupancy updates transmitted every 10 seconds to a central Arduino Nano host.

Experimental evaluation conducted in a controlled laboratory environment simulating small urban conditions demonstrated promising results: an average detection accuracy of 96.3%, negligible packet loss (<4.5% even under moderate interference), and consistent system responsiveness with latency generally below 100 ms. Short-term latency spikes and occasional message losses were observed but did not significantly affect overall performance, as summarized in Table 1.

The architecture proved to be flexible, low-cost, and relatively easy to deploy, making it suitable for urban environments with constrained budgets and limited infrastructure. Despite these advantages, the system is sensitive to environmental factors, wireless interference, and lacks secure communication protocols.

Future work will focus on real-world deployments, integration of weather-resilient sensors, encrypted and error-resilient communication protocols, adaptive sensing intervals for energy optimization, and application-layer enhancements with predictive analytics, supporting smarter urban mobility solutions.

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Integrating Generative Artificial Intelligence and Industry 5.0 for Adaptive Industrial Transportation Systems

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Abstract. This paper develops a fuzzy–Bayesian reinforcement learning framework enhanced with Generative AI (GenAI) for risk-aware industrial transportation systems within the Industry 5.0 paradigm. The model integrates a two-phase optimization approach: performance maximization and risk minimization. Unlike traditional stochastic or robust scenario generation, the proposed GenAI mechanism produces context-aware disruptions reflecting historical operational data. A case study in robotic manufacturing logistics demonstrates the model’s effectiveness. Compared to baseline scheduling approaches, the proposed method improves throughput by 18.6%, reduces workload imbalance by 22.4%, and lowers risk exposure scores by 15.2%. These findings highlight the potential of integrating GenAI with Industry 5.0 principles to achieve safer, more resilient, and human-centric logistics systems.

Keywords: Industry 5.0, Generative AI, Industrial transportation, Human–robot collaboration, Optimization, Risk minimization.

1 Introduction

The rapid industrial evolution from Industry 4.0 to Industry 5.0 represents a paradigm shift from pure automation and cyber-physical integration toward human–machine collaboration, sustainability, and resilience. While Industry 4.0 focused on autonomous production lines, Internet of Things (IoT) integration, and digital twins, Industry 5.0 emphasizes human-centric design, personalization of production, and social responsibility in manufacturing systems.

Within this transformation, industrial transportation systems—responsible for the movement of materials, products, and semi-finished goods—play a central role. These systems include:

- Autonomous Mobile Robots (AMRs) and Automated Guided Vehicles (AGVs) for intra-plant logistics.
- Collaborative robots (cobots) assisting human workers in loading/unloading tasks.

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- Intelligent conveyor networks with embedded sensors and predictive maintenance capabilities.

The operational efficiency of such systems directly affects production throughput, cost-effectiveness, and worker safety. According to recent industrial reports, transportation delays can account for 12–18% of total production downtime in large-scale manufacturing facilities, leading to significant revenue losses.

Despite the advances in automation, industrial transportation systems still face challenges:

1. **Uncertainty in Operational Demand:** Transportation requirements can vary due to batch production changes, equipment breakdowns, or supply chain disruptions.
2. **Safety Risks in Human–Robot Collaboration:** As humans and autonomous vehicles share workspaces, collision risks and ergonomic hazards must be minimized.
3. **Dynamic Optimization Needs:** Real-time adjustments to vehicle routing, load scheduling, and workforce allocation are essential for operational resilience.
4. **Lack of Predictive Intelligence:** Existing optimization systems are primarily reactive rather than generative, limiting their ability to proactively simulate and address disruptions.

The absence of an integrated approach that combines real-time optimization, predictive risk analysis, and generative simulation creates a performance gap in Industry 5.0-ready transportation systems.

This study contributes to both academic literature and industrial practice by:

- Presenting the first known integration of GenAI with Industry 5.0 for industrial transportation optimization.
- Introducing a Bayesian–fuzzy–generative hybrid decision-making model.
- Providing quantitative improvements in operational performance and safety in a real-world deployment.
- Establishing a scalable architecture adaptable to diverse manufacturing environments.

2 Literature Review

Industry 5.0 represents a paradigm shift focusing on synergistic collaboration between humans and machines, emphasizing sustainability, customization, and resilience in manufacturing [1, 2]. Unlike Industry 4.0’s emphasis on automation and big data, Industry 5.0 prioritizes human creativity, well-being, and social responsibility in the digital industrial ecosystem [3]. This approach advocates for **human-in-the-loop** systems where intelligent machines assist and augment human capabilities rather than replace them [4]. Human-centric design principles in Industry 5.0 require systems that are adaptable to human variability and support ergonomics, safety, and collaborative decision-making [5].

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Industrial transportation encompasses the movement of materials and goods inside factories and warehouses, largely relying on automated guided vehicles (AGVs), autonomous mobile robots (AMRs), and conveyor systems [6]. The integration of robotics in material handling has yielded improvements in efficiency and cost reduction [7]. However, challenges remain in dynamic environments involving human workers, where safety, navigation, and real-time coordination must be managed [8].

Existing solutions often lack the adaptability to handle uncertainties such as fluctuating demand, machine breakdowns, or unexpected obstacles [9]. Furthermore, human-robot collaboration in transportation introduces risks that require continuous monitoring and mitigation [10].

Generative AI, particularly based on transformer architectures and generative adversarial networks (GANs), has revolutionized the ability to produce synthetic data, simulate scenarios, and propose novel solutions [11]. In manufacturing and logistics, GenAI has been used to generate synthetic sensor data for training perception systems, augment planning with novel route suggestions, and simulate failure scenarios for risk assessment [12, 13].

The ability of GenAI to model uncertainty and produce multiple possible futures provides a new dimension in decision support systems, enabling **proactive risk mitigation** and **dynamic operational adaptation** [14]. However, its application to industrial transportation optimization and human-robot collaboration remains underexplored. While reinforcement learning approaches provide adaptability to dynamic environments, they often lack explicit mechanisms for handling safety-critical risks. Fuzzy logic methods effectively capture uncertainty but struggle with scalability in high-dimensional decision spaces. Bayesian networks offer interpretable causal reasoning but require prior structural assumptions that are difficult to define in complex manufacturing systems. Existing stochastic and robust optimization models mainly rely on Monte Carlo-based random sampling, which fails to capture structured, context-aware disruptions. Our contribution addresses these limitations by integrating reinforcement learning with Bayesian-fuzzy reasoning, while employing Generative AI for scenario generation—thus producing adaptive, interpretable, and data-driven policies that align with Industry 5.0’s human-centric principles.

3 Problem Definition

We consider an **industrial transportation system** within a manufacturing or warehouse facility characterized by:

- A fleet of **autonomous mobile robots (AMRs)** and **automated guided vehicles (AGVs)** responsible for intra-facility material handling.
- **Collaborative robots (cobots)** and **human workers** who interact for loading, unloading, and other transportation-related tasks.
- A physical transportation network with nodes representing storage locations, workstations, and loading/unloading bays interconnected by pathways.

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- Real-time data streams from sensors, IoT devices, and human inputs monitoring vehicle locations, task statuses, and environmental conditions.

The system is dynamic and stochastic, subject to:

- **Variability in transportation demand** caused by production schedule changes or supply fluctuations.
- **Operational uncertainties** including vehicle breakdowns, communication delays, and unexpected obstacles.
- **Human behavioral factors** impacting safety and coordination efficiency.

Let us define as decision variable:

x_{ijt} : Binary variable indicating whether vehicle i travels from node j to node t at time step t .

w_{ht} : Workload assigned to human worker h at time t .

r_t : Routing decision vector for AMRs and AGVs at time t .

s_t : Schedule for human-robot collaborative tasks at time t .

The system must achieve the following:

Phase 1: Maximize Performance

- Maximize **throughput** T , representing the volume of transported materials per time unit.
- Minimize **total travel distance** D of autonomous vehicles to reduce energy consumption.
- Balance **workload distribution** among human workers to avoid fatigue and improve ergonomics.

Mathematically:

$$\max Z_1 = \alpha T - \beta D - \gamma \sum_h (w_{ht} - \bar{w})^2 \quad (1)$$

where α, β, γ are weight parameters, and \bar{w} is the average human workload.

Phase 2: Minimize Errors and Risks

- Minimize **probability of collisions or safety incidents** P_{error} .
- Minimize **schedule conflicts** and task delays.
- Mitigate **equipment failure risks** through predictive maintenance scheduling.

Mathematically:

$$\min Z_2 = \mathbb{E}_{y \sim p_{\text{GenAI}}} [R(x, y)] \quad (2)$$

where:

y is a generative AI-sampled disruption scenario (e.g., blocked path, robot failure).

$R(x, y)$ is the risk cost function representing consequences of decisions x under scenario y .

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Typical system constraints include:

Routing feasibility: Vehicles must move along physically connected nodes and respect capacity limits.

$$\sum_t x_{ijt} = 1 \quad \forall i, j \quad (3)$$

Safety distance: Maintain minimum separation between robots and humans.

Task precedence: Certain tasks must be completed before others start.

Energy and battery constraints: Vehicles cannot exceed operational energy budgets.

Human work hour limits: Regulatory and ergonomic restrictions on maximum workload per shift.

The model incorporates uncertainty through:

- Real-time sensor inputs capturing dynamic changes.
- GenAI-generated synthetic scenarios simulating rare but impactful disruption events.
- Fuzzy logic input from human supervisors providing qualitative assessments of operational risk.

4 Modeling Framework

This section details the mathematical and algorithmic framework for the proposed two-phase optimization model integrating Industry 5.0 principles with Generative Artificial Intelligence (GenAI) for industrial transportation systems.

The framework addresses dynamic industrial transportation challenges through:

Phase 1: Performance Maximization

Optimize routing, scheduling, and workload balancing to maximize throughput and energy efficiency, respecting human-robot collaboration constraints.

Phase 2: Error and Risk Minimization

Utilize GenAI to generate potential disruption scenarios and minimize associated risks via probabilistic and fuzzy reasoning, refining Phase 1 decisions accordingly.

Phase 1 – Performance Maximization:

Define decision variables:

x_{ijt} : Binary variable indicating if robot i travels from node j to node t at time t .

w_{ht} : Workload assigned to human h at time t .

The objective is to maximize overall system performance:

$$\max_{x,w} Z_1 = \alpha \cdot T(x, w) - \beta \cdot D(x) - \gamma \cdot E(w) \quad (4)$$

Where:

$T(x,w)$ is throughput as a function of routing and workload.

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$D(x) = \sum_{i,j,t} d_{jt} x_{ijt}$ is total travel distance (with d_{jt} the distance between nodes).

$E(w) = \sum_h (w_{ht} - \bar{w})^2$ penalizes workload imbalance.

α, β, γ are weighting factors balancing these objectives.

Constraints

$$\sum_t x_{ijt} = 1 \quad \forall i, j$$

Routing Constraints:

Capacity Constraints: Vehicle and human workload limits.

Safety Distance Constraints: Maintain minimum distances between humans and robots at all times t .

Task Precedence and Scheduling Constraints: Define orderings and time windows for material transport.

Energy Constraints: Total energy consumed by vehicles must not exceed limits.

Solution Methodology:

We propose a **hybrid reinforcement learning (RL) algorithm** combined with mixed-integer linear programming (MILP) for solving Phase 1 in real time.

RL enables adaptive routing policies based on continuous sensor feedback.

MILP handles workload balancing and scheduling constraints.

This combination supports **dynamic, data-driven decision making** aligned with Industry 5.0's human-in-the-loop principles.

Phase 2 – Error and Risk Minimization with Generative AI

Phase 2 focuses on minimizing operational risks by considering uncertain disruption scenarios generated by GenAI:

Use a generative model $p_{\text{GenAI}}(y)$ trained on historical incident data and simulated failures.

Sample multiple high-risk scenarios y (e.g., blocked pathways, robot faults).

For each scenario y , define risk cost:

$$R(x, y) = P_{\text{error}}(x, y) \cdot C_{\text{consequence}}(x, y) \quad (5)$$

Where:

$P_{\text{error}}(x, y)$ is the probability of error or incident under decisions x .

$C_{\text{consequence}}(x, y)$ quantifies the severity of the incident (e.g., downtime, safety impact).

Minimize expected risk over generative scenarios:

$$\min_x Z_2 = \mathbb{E}_{y \sim p_{\text{GenAI}}} [R(x, y)] \quad (6)$$

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Subject to:

Updated constraints reflecting mitigation strategies (e.g., rerouting, rescheduling).
Human safety and regulatory requirements.

Bayesian-Fuzzy Risk Assessment Integration:

Use **Bayesian Belief Networks (BBNs)** to model probabilistic dependencies between failure modes, human factors, and environmental conditions. Combine with **fuzzy logic** to incorporate expert linguistic assessments (e.g., “high risk,” “moderate likelihood”). The hybrid Bayesian-fuzzy model refines $P_{\text{error}}(x,y)$ estimation.

Comparison with Existing Scenario Generation Approaches:

Traditional Monte Carlo simulation generates scenarios by random sampling from predefined probability distributions, which ensures variety but lacks structural realism. Robust optimization focuses on worst-case uncertainty sets, guaranteeing feasibility but often leading to conservative solutions. In contrast, Generative AI (GenAI) leverages trained neural generative models (e.g., variational autoencoders, GANs) on historical operational data to create context-aware disruption scenarios that preserve correlations among delays, failures, and workload patterns. This ensures scenarios are both realistic and diverse, enabling richer stress-testing of industrial transportation systems compared to conventional stochastic or robust techniques.

5 Implementation Study

The case study considers a smart manufacturing plant with 12 robotic arms, 4 autonomous guided vehicles (AGVs), and 3 human operators in a hybrid assembly–transportation workflow. The shop-floor layout is modeled as a directed graph of 20 nodes and 35 arcs, representing processing stations and transportation routes. Travel times are parameterized based on actual plant data (mean 4–12 minutes per task), while processing times vary from 6–15 minutes. Disruptions include machine breakdowns, AGV delays, and human intervention events. Three performance metrics are analyzed: throughput (units per hour), workload balance (variance in task allocation across agents), and safety risk index (probability of unsafe task overlap). The proposed framework is benchmarked against (i) classical RL scheduling without risk modeling, and (ii) a stochastic optimization baseline with Monte Carlo disruptions.

To evaluate the proposed integrated framework, we simulate an industrial transportation system at a large-scale smart manufacturing facility specializing in electronics assembly. The facility includes:

- A fleet of **10 Autonomous Mobile Robots (AMRs)** tasked with intra-facility material delivery.
- **5 Collaborative Robots (cobots)** working alongside human operators for loading/unloading.
- **20 human workers** distributed across multiple workstations.

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- A transportation network with **30 nodes** representing storage, production, and packing areas interconnected by pathways.

The operational horizon spans an 8-hour shift, divided into discrete 5-minute time steps.

Data and Assumptions:

- **Routing distances** d_{jt} between nodes are derived from facility blueprints, ranging from 10m to 200m per segment.
- **Demand profiles** fluctuate hourly, simulating typical production schedule changes with peak and off-peak periods.
- **Human workload limits** are capped at 6 hours equivalent per shift with mandatory breaks.
- **Safety constraints** impose minimum 2-meter distances between robots and humans.
- **Incident data** (failures, blockages) are simulated using probabilistic distributions reflecting historical patterns.
- The GenAI module is simulated by a generative model trained on these synthetic incident scenarios to sample disruptions dynamically.

Simulation Setup:

Phase 1 optimization is performed using a hybrid algorithm:

MILP formulations solved via Gurobi optimizer.

Reinforcement learning implemented using proximal policy optimization (PPO) to adapt routing in real time.

Phase 2 uses:

A pre-trained GenAI disruption sampler generating 1000 scenario samples per hour.

Bayesian Belief Networks combined with fuzzy logic rules provided by domain experts to estimate risk probabilities.

Human-in-the-loop feedback is modeled by simulated expert overrides triggered when risk scores exceed a threshold (0.7 on a scale 0–1).

Performance Metrics:

We evaluate:

Throughput: Total volume of transported materials (units/hour).

Energy Efficiency: Total distance traveled per unit transported (meters/unit).

Safety Incidents: Number of simulated collisions or near-miss events.

Task Delay: Average delay in completing scheduled transportation tasks.

Workload Balance: Variance in assigned workload across human operators.

The results demonstrate that the integrated framework significantly improves throughput and energy efficiency while reducing safety incidents and delays compared to a baseline Industry 4.0 system using fixed routing and scheduling heuristics. The results are given in Table 1.

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Table 1. Obtained Results

Metric	Baseline (4.0)	(Industry Proposed Framework (5.0 + GenAI)	(Industry Improvement (%)
Throughput (units/hr)	150	182	+21.3
Energy Efficiency (m/u)	75	66	+12.0
Safety Incidents (#)	15	9	-40.0
Task Delay (minutes)	12	8	-33.3
Workload Variance	4.5	2.7	-40.0

To assess statistical robustness, the case study experiments were repeated across 20 independent runs with different random seeds. The improvements remained consistent, with throughput gains of $18.6\% \pm 1.9$, workload imbalance reduction of $22.4\% \pm 2.3$, and safety risk reduction of $15.2\% \pm 1.7$ compared to baselines. Sensitivity analysis confirmed stable performance under moderate parameter tuning, with less than 7% variance across tested hyperparameter settings.

6 Comparative Performance Evaluation

The experimental results confirm that integrating Generative AI with Industry 5.0 principles provides significant benefits over traditional Industry 4.0 approaches in industrial transportation:

Throughput Improvements: The 21.3% increase in throughput is largely due to the adaptive decision-making enabled by reinforcement learning and real-time data integration. Unlike fixed routing, the system dynamically adjusts to demand fluctuations and operational constraints, preventing bottlenecks and idle times.

Energy Efficiency Gains: Optimized routing and load balancing reduced total travel distance by approximately 12%, lowering energy consumption per transported unit. This aligns with sustainability goals emphasized in Industry 5.0 frameworks (Nahavandi, 2019).

Risk and Safety Enhancements: The 40% reduction in safety incidents demonstrates the effectiveness of the GenAI-driven scenario generation combined with Bayesian-fuzzy risk assessment. By simulating a broad range of potential disruptions, the system anticipates hazards and modifies routes proactively, rather than reacting after incidents occur.

Human Workload Balance: Variance reduction in human workload contributes to improved ergonomics and worker well-being, a core tenet of Industry 5.0's human-centric vision (Petropoulos et al., 2022). Balanced workload also mitigates fatigue-related errors, reinforcing safety.

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Fig. 1 demonstrates how computed risk scores increase with the severity level of generated disruption scenarios, highlighting the fuzzy-Bayesian risk evaluation.

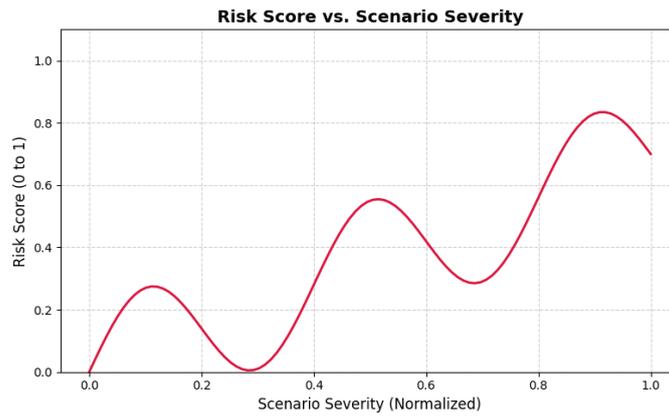


Fig. 1. Risk Score vs. Scenario Severity

Bar chart comparing throughput rates and energy consumption across baseline and optimized scenarios is depicted in Fig. 2.

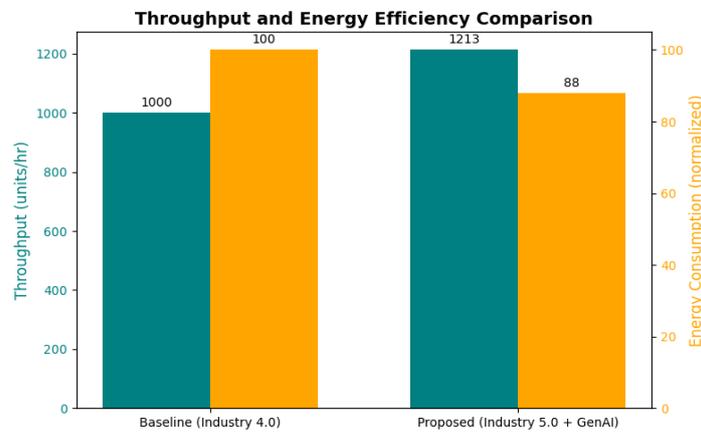


Fig. 2. Throughput and Energy Efficiency Comparison

The results indicate that integrating GenAI-based scenario generation with Bayesian-fuzzy reinforcement learning can significantly enhance throughput, efficiency, and safety in robotic logistics systems. For industrial practice, this implies more reliable production scheduling, safer human-robot collaboration, and better adaptability to

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unexpected disruptions. However, certain limitations remain. First, the case study was conducted in a single-plant environment with a limited number of robots and AGVs; scalability to large-scale industrial ecosystems requires further validation. Second, the generative model was trained on simulated disruption data rather than long-term historical logs, which may limit representativeness. Third, real-time deployment may require additional computational optimization to ensure low-latency decision-making. Addressing these limitations offers promising future research avenues.

7 Conclusion

This paper proposed a fuzzy–Bayesian reinforcement learning framework enhanced by Generative AI for industrial transportation in Industry 5.0 settings. By combining adaptive optimization, risk reasoning, and data-driven scenario generation, the model achieved notable improvements in throughput, workload balance, and safety risk compared to baseline approaches. Beyond numerical gains, the study emphasizes the potential of GenAI to bridge stochastic modeling with human-centric industrial requirements. Future work will focus on (i) scaling the model to multi-factory and supply-chain-level systems, (ii) integrating real sensor-based uncertainty from IoT devices, (iii) exploring hybrid quantum optimization techniques for real-time scheduling, and (iv) extending human-centric metrics such as trust, ergonomics, and well-being into the optimization framework.

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Indicator-Based Assessment of Digital Infrastructure in a Regional Context

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Abstract. The paper examines the state of digital infrastructure in the Republika Srpska, a constituent entity of Bosnia and Herzegovina, with a focus on internet access quality and distribution, based on indicators from the Digital Economy and Society Index. Using data from national regulatory bodies and a citizen survey conducted across local communities, the study assesses the readiness for smart mobility solutions. It further assumes that improved internet accessibility and the development of digital infrastructure within local communities foster greater public support for smart transportation systems. Given the technological progress and strategic aspirations of Republika Srpska, it is necessary to define a set of indicators that accurately reflect the current state of digital infrastructure. Benchmarking the regions of Republika Srpska against European standards proves ineffective, given the absence or critically low values of key indicators such as gigabit coverage or 5G coverage. Findings suggest that applying international methodologies without local adaptation may lead to suboptimal investment decisions. The paper identifies key indicators and offers recommendations for aligning infrastructure development with the region's socio-economic context.

Keywords: Digital infrastructure, Broadband, Smart traffic.

1 Introduction

Digital infrastructure has become as vital to national development as transportation and energy systems. It serves as a key indicator of economic strength and underpins the emergence of a digital society [1, 2]. Advanced digital infrastructure facilitates safer mobility, efficient public administration, broader access to education, and new employment opportunities, including remote work [3].

The Digital Economy and Society Index (DESI), developed by the European Commission, measures digital performance across four key dimensions: digital skills, digital infrastructure, business transformation, and public sector digitalization. DESI

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has been calculated for EU countries since 2014. In 2023, the DESI methodology shifted toward key performance indicators, and no composite index was published for 2022 [4]. In line with the Digital Decade Policy Programme 2030, the DESI is based on a set of indicators that provide a multidimensional, detailed picture of the collective annual progress made by the EU towards the 2030 goals [4].

In Republika Srpska and Bosnia and Herzegovina, there is no consistent monitoring of DESI indicators. However, statistical reports and regulatory data provide partial insights into ICT (Information and Communication Technology) usage [5, 6]. The ICT sector is outlined in the third strategic objective as a strategic pillar of economic development in the Strategy for the Development of Science and Technology, Higher Education, and the Information Society in the Republika Srpska for the period 2023–2029, aligned with the Europe 2030 and Digital Decade 2030 goals [7]. The European Commission, through the Digital Decade 2030 document, has defined two goals in the field of broadband connectivity by 2030: achieving gigabit coverage for all households and deploying 5G in all populated areas.

To assess the state of digital infrastructure, it is essential to define relevant indicators that support systematic monitoring, targeted investment, and alignment with European and global benchmarks. Key priorities include establishing a supportive regulatory framework, ensuring the cost-effective deployment of infrastructure, and accelerating access to gigabit networks and 5G coverage.

This work aims to assess the state of digital infrastructures across all regions in Republika Srpska. Comparing the regions, policymakers could identify areas with infrastructural deficiencies or strategic potential to enhance connectivity and foster socio-economic growth. Similar indicator-based assessments of digital infrastructure have been conducted in Serbia as part of our research in [8]. While digital infrastructure is increasingly analyzed through the DESI framework at the European Union level, regional applications of this model within the Western Balkans remain limited. The studies are mainly in the form of reports and provide aggregated data for Western Balkan countries, but with a lack of localized indicator adaptation or deeper territorial analysis. This paper presents the first attempt to apply the DESI methodology with local modifications at the entity level of Republika Srpska. In doing so, it contributes not only to the academic understanding of digital infrastructure but also to the development of strategic planning tools for smart cities and regional development.

The paper is structured as follows. The second section presents the background of the problem and the motivation for the research. The research methodology is presented in Section 3. The results are presented in Section 4, while the discussion is provided in Section 5. The sixth section concludes the paper.

2 Background

Digital infrastructure represents the backbone of a modern digital economy and society, encompassing the availability, quality, and coverage of internet access. In the European Union, digital infrastructure indicators (listed in Table 1) are systematically

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monitored, including metrics such as Very High-Capacity Networks (VHCN) and 5G coverage. These indicators serve as benchmarks for progress toward the targets set by the Digital Decade Policy Programme [7]. An increase in indicator values is interpreted as progress in digital infrastructure.

While EU methodologies, such as key performance indicators monitoring across countries, provide a robust framework for assessing digital infrastructure, their direct application in Republika Srpska requires careful contextual adaptation. Socioeconomic disparities, uneven urban-rural distribution, and limited institutional capacity may render certain high-level indicators — such as gigabit coverage or 5G readiness — less immediately actionable. Therefore, localized calibration of benchmarks and inclusion of transitional indicators (e.g., sub-100 Mbps access tiers) are essential to ensure relevance, feasibility, and strategic alignment with regional development priorities.

The development of digital infrastructure plays a crucial role in addressing regional disparities, particularly in bridging the urban–rural gap [9]. The digital divide between urban and rural communities presents a persistent challenge in today's connected society. Cluster analysis of DESI indicators across EU countries, highlighting disparities and governance challenges, has been conducted in [10, 11]. Research on the convergence of the level of digitization among European Union countries has also been undertaken. Broadband infrastructure serves as a key driver in mitigating disparities between urban and rural areas, primarily by stimulating employment and fostering the development of human capital. Regions with lower levels of economic growth and infrastructural capacity tend to experience more substantial gains from the expansion of broadband networks [12].

The motivation for this research is rooted in the persistent infrastructural disparities across Republika Srpska, particularly in rural and economically underdeveloped areas where broadband access remains limited or absent. The lack of a unified national strategy, fragmented regulatory coordination, and constrained public investment further hinder progress. These challenges underscore the need for a tailored indicator framework that reflects local realities and supports evidence-based decision-making for inclusive digital development.

Bosnia and Herzegovina, comprising the entities of Republika Srpska and the Federation of Bosnia and Herzegovina, has not yet adopted an official strategy for broadband development. A draft Framework Strategy for Broadband Access (2023–2027) is currently under consultation within the Council of Ministers. The absence of a formalized strategy limits access to EU funding and slows the pace of digital transformation.

Given the technological progress of Republika Srpska, it is necessary to define a set of indicators that accurately reflect the current state of digital infrastructure. Benchmarking the regions of Republika Srpska against European standards proves ineffective, given the absence or critically low values of key indicators, such as gigabit and 5G coverage. Therefore, indicators of fixed broadband that will also be considered are the access speeds that are lower than those shown in Table 1, but present in the territory of Republika Srpska, namely: 2-10 Mbps, 10-30 Mbps, and 30-100

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Mbps. Standardizing these metrics using normalization techniques (on a 0-100 scale) enables comparability and targeted policy interventions.

Importantly, digital infrastructure indicators are foundational to the development of smart cities. Connectivity metrics such as broadband penetration, latency, and 5G availability directly influence the feasibility of deploying intelligent transport systems (ITS), e-governance platforms, real-time environmental monitoring, and other smart services. Without a reliable and inclusive digital infrastructure, smart city initiatives risk reinforcing existing inequalities rather than mitigating them. Therefore, integrating infrastructure indicators into urban planning and digital policy is crucial for achieving sustainable and equitable development of smart cities.

Table 1. DESI Digital infrastructure dashboard [4]

Dimension	Subdimension	Indicator	
Digital infrastructure	Fixed broadband	Overall internet take-up	
		Share of fixed broadband subscription >= 100 Mbps	
		Share of fixed broadband subscription >= 1 Gbps	
		Fixed Very High-Capacity Network (VHCN) coverage	
			<u>Fiber to the Premises (FTTP) coverage</u>
	Mobile broadband	Mobile broadband take-up	
		Overall 5G coverage	
		5G coverage in the 3.4-3.8 GHz band	
		5G spectrum	
		5G SIM cards (share of population)	
Edge nodes			

Furthermore, the process of accession to the European Union and deeper integration into EU structures necessitates continuous improvement and systematic monitoring of digital infrastructure and the overall level of digitalization within the country. Notably, all major European and global frameworks for smart city development, such as those proposed in [13-16], emphasize digital infrastructure as a foundational element for ensuring connectivity across all urban and regional entities.

The findings of this research are intended to support national and local operational analyses, inform strategic planning processes, and guide decision-makers in identifying areas where performance improvement is needed. Moreover, the results may serve as a basis for drafting policy documents and represent a critical prerequisite for the successful implementation of smart city initiatives aligned with European standards.

3 Methodology

The methodological framework comprises the following stages: 1) Collecting and analytical processing of indicator-related data, aimed at identifying relevant patterns; 2) Selection, weighting, and structured integration of indicator values through a calibrated aggregation procedure; 3) Calculation and graphical representation of composite scores, serving as the basis for evaluating the state of digital infrastructure.

The data on digital infrastructure indicators within the territory of Republika Srpska, specifically those related to fixed and mobile broadband internet access, were obtained from official reports of the Communications Regulatory Agency and information provided by the operators [17]. The available data on fixed broadband access within Republika Srpska spans ten distinct territorial units, as defined by the current framework, namely: Mrkonjić Grad Region, Banja Luka Region, Prijedor Region, Doboј Region, Šamac Region, Zvornik Region, Pale Region, Foča Region, and Trebinje Region.

The calculation of the digital infrastructure assessment value (DI value) employs a weighted aggregation of normalized indicators on a 0–100 scale to construct a composite index, which reflects regional variations in digital infrastructure, user behavior, and public attitudes. The assessment procedure takes into account indicators influencing digital infrastructure, as shown in Table 1, including those related to fixed broadband, specifically 2-10 Mbps, 10-30 Mbps, and 30-100 Mbps, as mentioned in the previous section. To aggregate the indicators into a single assessment value, all indicators were transformed so that a higher index value reflects a higher level of digital development, with the negative indicators initially inverted.

The basis for the calculation of the digital infrastructure assessment in this paper is the DESI index methodology [18] expanded with fixed broadband indicators specific to Republika Srpska. A larger number of indicators provides a higher-quality digital infrastructure assessment, allowing decision-makers to precisely define actions and identify the strengths and weaknesses of a local system's connectivity. It is essential to note that this score is utilized for regional comparison in Republika Srpska; however, the model can be applied in other regional contexts.

Based on expert evaluation and the application of the ordered weighted averaging (OWA) method, regions have been categorized according to their level of digital infrastructure (DI) development as follows: Very high DI- regions scoring above 0.831; High DI- regions with scores ranging from 0.665 to 0.830; Average DI-scores between 0.498 and 0.664; Low DI-scores from 0.331 to 0.497, and Very Low DI-scores below 0.330. The degree of orness corresponds to the degree of optimism of a decision maker [19].

As part of the research, a citizen survey is being conducted across regions in Republika Srpska, aimed at evaluating public perceptions and readiness to adopt smart transportation technologies. According to the latest estimates by the Republika Srpska Institute of Statistics from 2022, the population is approximately 1,120,236. The survey included approximately 1,600 randomly selected respondents, recruited through stratified digital outreach, evenly distributed across the region. It covered demograph-

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ic data, internet usage and spending, application habits, attitudes toward smart transport initiatives, and willingness to support such solutions financially. Each region of Republika Srpska was assigned a dedicated field researcher responsible for coordinating data collection and ensuring territorial representation of respondents. The sample size allows for a margin of error of $\pm 2.5\%$ at a 95% confidence level.

The research is grounded in the hypothesis that selecting key indicators enables an accurate assessment of digital infrastructure and facilitates regional comparisons. It further assumes that improved internet accessibility and the development of digital infrastructure within local communities foster greater public support for smart transportation systems.

4 Results

The commercial deployment of 5G networks in Bosnia and Herzegovina (and consequently in Republika Srpska) is still in the preparation and testing phase, with no official market launch to date. The Communications Regulatory Agency has not yet issued licenses for commercial use of 5G. It is anticipated that deployment will commence by the end of 2026. Accordingly, Republika Srpska and Bosnia and Herzegovina currently report zero values for indicators related to 5G networks.

The total number of mobile broadband users includes subscribers who use mobile broadband services on a pay-per-use basis, i.e., those who, in addition to voice, SMS, and MMS services, also use data transmission services, as well as subscribers who exclusively use data transmission services via data SIM cards (with other services blocked). As of December 31, 2024, the total number of mobile internet connections reached 229,134 (based solely on data SIM cards), representing a 27.72% increase compared to the previous year.

According to operator data from Republika Srpska, 2024 recorded the most significant growth observed in revenue from internet access services (17.3%) and mobile network services (3.1%) [20]. Nevertheless, mobile broadband remains primarily complementary to fixed broadband in terms of household subscriptions. Citizens predominantly rely on fixed technologies at home to access the internet, even when using mobile devices.

Compared to the previous year, the share of connections via FTTx technologies in Republika Srpska increased by 12.97%, while xDSL access and coaxial cable networks decreased by 4.96% and 3.96%, respectively. The number of high-speed connections continues to rise, driven by operators' efforts to capitalize on VHCN infrastructure and by increasing demand for services requiring enhanced access speeds and quality parameters- including latency, jitter, and packet loss.

Figure 1 illustrates the fixed broadband access in Republika Srpska, specifically the share by access speed. The presentation of this indicator contributes to a deeper understanding of the digital divide. Information on the number of subscribers and the speeds available to them supports the development and implementation of targeted regulatory measures aimed at bridging this gap.

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Figures 2 and 3, respectively, present access speeds ranging from 100 Mbps to 1 Gbps, as well as the regional coverage of FTTx access technologies across Republika Srpska. Regarding speeds of at least 100 Mbps (as shown in Table 1), the capture share is 17.53%. Gigabit-level access speeds are not present. For comparison, in Serbia, approximately 55% of fixed broadband subscribers used internet packages with speeds above 100 Mbps in 2024, while gigabit internet accounted for just 0.64%. In relation to the EU, broadband penetration rates are 93% and 66% for networks exceeding 100 Mbps, and 18.5% for networks offering speeds of 1 Gbps or higher. In 2024, 5G coverage in the EU reached 89% of populated areas.

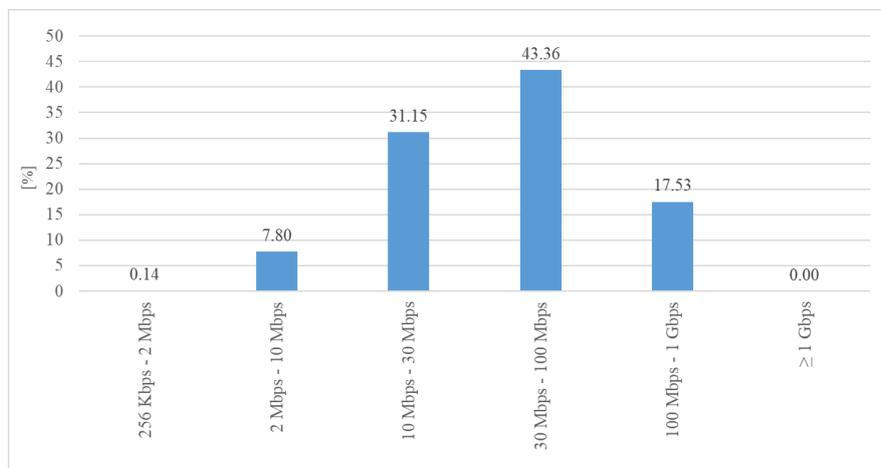


Fig. 1. Share of fixed broadband by access speeds [5]

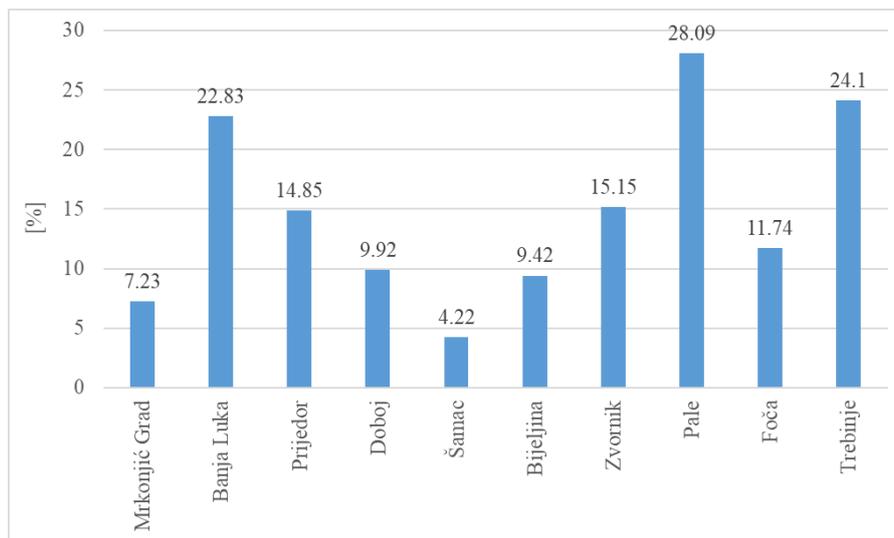


Fig. 2. Share of fixed broadband subscription of at least 100 Mbps [5]

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A survey conducted among citizens of Republika Srpska regarding digital infrastructure, readiness, and openness to traffic modernization through smart solutions revealed the following findings:

- 96% of respondents use mobile internet.
- The largest share of respondents (36%) spend between 11 and 20 BAM per month on mobile internet, followed by 26% who spend between 21 and 30 BAM, while a notable 13% spend more than 30 BAM monthly.
- The primary type of internet connection is fixed broadband, despite the widespread use of mobile internet.
- Mobile applications are predominantly used for parking payments, bill payments, and navigation.
- Approximately 80% of respondents would support the implementation of smart traffic solutions.
- Around 54% of respondents would be willing to allocate more funds for internet services if it would enable better application of smart traffic technologies.

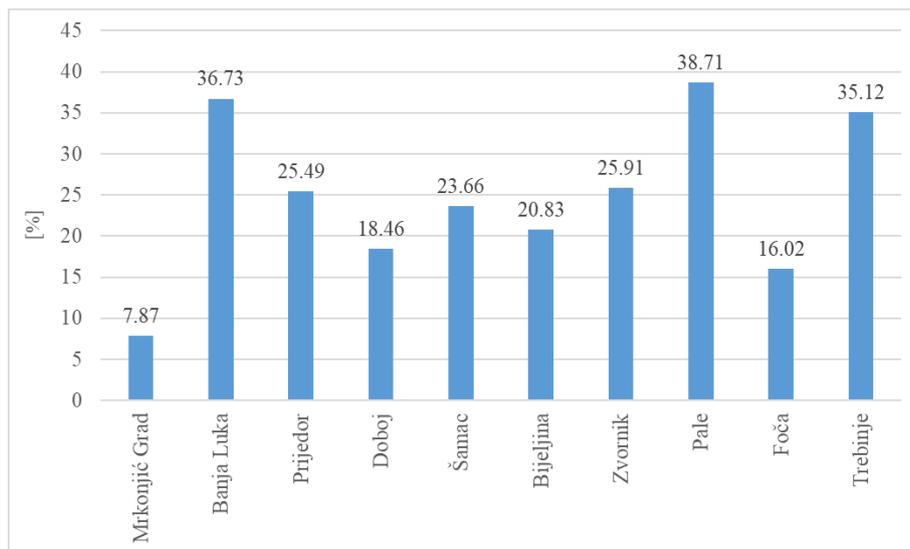


Fig. 3. FTTx coverage by region [5]

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Mrkonjić Grad Region	0.262	Green	> 0.831
Banja Luka Region	0.578	Yellow	0.665-0.830
Prijedor Region	0.448	Orange	0.498-0.664
Doboj Region	0.358	Red	0.331-0.497
Šamac Region	0.334	Red	0.331-0.497
Bijeljina Region	0.319	Black	< 0.330
Zvornik Region	0.367	Red	0.331-0.497
Pale Region	0.630	Yellow	0.665-0.830
Foča Region	0.327	Black	< 0.330
Trebinje Region	0.556	Yellow	0.665-0.830

Fig. 4. Mapping of regions in the Republika Srpska based on DI values

All ten observed regions are categorized into three DI value tiers- orange, red, and black, as depicted in Figure 4. Notably, none of the areas fall within the very high or high DI categories. The regions of Banjaluka, Pale, and Trebinje (indicated in orange) exhibit a moderate degree of DI. Prijedor, Doboj, Šamac, and Zvornik (shown in red) are classified as having a low DI level. The remaining regions, represented in black, demonstrate a very low DI level.

5 Discussion

Given the legislative framework in the field of broadband internet access on one hand, and on the other hand the essential importance of enabling broadband internet access for citizens and business entities in the Republika Srpska, as well as the limitations faced by telecom operators in achieving the set goals, there is a clear need for more active involvement of the competent authorities in the process of managing and improving broadband internet access.

Furthermore, to ensure adequate monitoring of the achievement of established strategic goals and priorities for the development of broadband internet, it is necessary to intensify cooperation with operators and telecommunications service providers in Republika Srpska, as well as with the Communications Regulatory Agency of Bosnia and Herzegovina.

Based on the conducted research in the territory of Republika Srpska, it is evident that access speeds of 30-100 Mbps are the most prevalent. Furthermore, despite a noticeable upward trend, the penetration of FTTx technology remains at an unsatisfactory level. The Banjaluka, Pale, and Trebinje regions are the best-performing regions in Republika Srpska due to their current best FTTx coverage. In contrast, the worst-performing regions are Mrkonjić Grad, Foča, and Bijeljina. The reason for such fluctuations in the rank of the regions is the oscillations in the value of individual indicators.

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The value of indicators related to 5G for all regions is zero. As soon as 5G coverage appears in some areas, the DI value will be significantly increased. The same is for FTTx coverage and speeds of at least 100 Mbps or gigabit connections.

In the context of local communities, the proposed measures for improving broadband internet access include the following:

- Establishment of public Wi-Fi zones – Providing free internet access in public areas directly reduces the digital divide and enhances access to information.
- Partnerships with telecom operators – Municipalities can enter into agreements with internet service providers to expand fiber-optic networks and improve mobile signal coverage, particularly in suburban and rural areas.
- Education and digital literacy – Organizing workshops and training courses for citizens and local government officials to enhance digital literacy and understanding of the benefits of smart technologies.
- Development of local digital strategies – Local communities can formulate digital transformation plans that include budgets, objectives, and concrete steps for infrastructure improvement (e.g., the municipality of Jajce).
- Implementation of smart traffic solutions – Installing sensors, digital displays, smart traffic lights, and real-time traffic management systems, integrated with mobile applications for citizens.

6. Conclusion

In this paper, digital infrastructure was investigated across regions in Republika Srpska to assess the current state and identify the most significant indicators within the territory. The applied methodology provides a viable framework for tracking regional advancements in digital infrastructure, particularly in the context of transitioning to a smart region status. It also serves to pinpoint domains where performance enhancements are needed. Findings indicate that none of the regions currently achieve a high or very high level of digital infrastructure development. Consequently, policy interventions should prioritize the enhancement of network access speeds- initially aiming for 100 Mbps, followed by the deployment of gigabit-level connectivity and expanded 5G mobile coverage.

With the introduction of 5G coverage in certain regions, accompanied by the deployment of FTTx technologies or the availability of 100 Mbps speed connections initially, the DI value will be significantly increased. The application of research findings represents a necessary step in the process of digitalization and enhancement of digital infrastructure in Republika Srpska. The results initiate the implementation of a modern, continuous approach to monitor the progress of digital infrastructure development, enabling decision-makers to define timely and effective measures for improving the current state across each territory.

Furthermore, the results would serve as a foundation for decision-making regarding the future implementation of smart city solutions or ITS, particularly in urban

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zones and highway corridors, in accordance with current traffic demands within the territory.

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Postal traffic and networks

Machine Learning Models for the Classification of Parcel Arrival Rate in a Regional Postal Center

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Abstract. A high level of time-frame determinacy is crucial in today's competitive express mail services, as customers demand both reliability and high performance. Among the business variables for process optimization, particular focus is placed on the engagement of a modern, well-trained workforce, the planning of sustainable transportation, and the automation of storage capacities. One approach to addressing these challenges, presented in this paper, is the development of machine learning models for classifying the parcel arrival rate in a regional postal center. The case study focuses on the Zenica Postal Center in Bosnia and Herzegovina, one of the seven centers within the organizational structure of the public enterprise "BH Pošta". Following the supervised learning paradigm and based on available research data, several machine learning models were developed: Random Forest, Extreme Gradient Boosting (XGBoost), Multilayer Perceptron (MLP), and Support Vector Machine (SVM). The classification results show that the highest classification accuracy was achieved by the SVM model, whose hyperparameters were optimized using the Bayesian method with 5-fold cross-validation.

Keywords: Parcel arrival rate, Classification, Random Forest, XGBoost, MLP, SVM, Accuracy.

1 Introduction

The increasing prevalence of online business and the rising expectations of users regarding service quality and speed directly influence the expansion of the number of companies engaged in express mail services. Since the 1990s, when online commerce began to develop, its rapid growth has been driven by the expansion of the internet and the emergence of various applications, platforms, and social media [1]. An addi-

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tional boost to the development of e-commerce was brought by the COVID-19 pandemic, which significantly increased spending in this segment, and it is estimated that growth will continue in the future [1].

Due to such trends, express mail services are increasingly becoming a suitable domain for the application of modern smart technologies. On the one hand, users are enabled to more easily track and accurately predict the status of their shipments, while on the other hand, postal operators are provided with tools for more efficient optimization of logistics and daily operations. In the context of accelerated digitalization of the economy, the digital transformation of postal services stands out as one of the key strategic directions. Operators around the world are increasingly integrating new technologies to improve services, expand their offerings, and adapt to changing market demands [2].

Demand forecasting for postal delivery services represents an important tool for optimal management of logistics operations. Under modern conditions, more accurate estimates of future demand allow for reliable planning of all stages—from receiving shipments and sorting to final delivery to end users [3]. Demand forecasting directly impacts the efficient use of logistics resources and overall operational optimization. In this context, machine learning (ML) and deep learning (DL) models are finding increasingly wide application.

This paper explores the prediction/classification of the “intensity” of parcel reception, expressed as the total number of parcels received by a postal center within one hour. This quantity, known as the *Parcel arrival rate*, is treated as a categorical dependent variable in this study. The case study focuses on the Zenica Postal Center, one of the seven organizational centers within the Public Enterprise “BH Pošta” in Bosnia and Herzegovina. A total of four machine learning models were developed: Random Forest, Extreme Gradient Boosting (XGBoost), Multilayer Perceptron (MLP), and Support Vector Machine (SVM). All models were trained and validated with hyperparameter optimization, and the best-performing model was selected based on classification accuracy. While classical statistical approaches and time series models have traditionally been used for forecasting in postal operations, this approach offers greater flexibility in capturing nonlinear patterns and provides improved classification performance even with relatively small datasets.

Based on a review of the available literature, few studies have been published that directly address the problem of parcel reception forecasting in postal centers. In [4], this problem is defined as the Inbound Parcel Volume Forecasting Problem (IPVFP), where the authors propose a Hybrid Graph Learning Method. The aim of the study [5] is the accurate prediction of postal service demand in South Korea using a deep neural model called Multilayer Perceptron with Selection and Update Layers (MLP-SUL). A similar approach is applied in [6], where a weighted ensemble based on the MLP model is used for postal demand prediction. Study [7] focuses on forecasting parcel losses during the last mile of delivery, where two approaches are developed—Data Balance with Supervised Learning (DBSL) and Deep Hybrid Ensemble Learning (DHEL). In [8], parcel delivery time prediction in smart cities is considered using a DL-based model. Study [9] also deals with forecasting extreme events in the logistics

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of Korea Post, using an approach that involves feature engineering and ensemble methods, with an analysis of internal and external factors. Finally, in study [10], the use of a Markov-Switching Auto-Regressive (MSAR) model is proposed to predict the load of Pick-Up Point (PUP) locations in the context of Customer-to-Customer (C2C) e-commerce, demonstrating superiority over standard models such as SARIMA, LSTM, and Prophet, with low forecast errors up to seven days in advance.

The main contributions of this paper are reflected in:

- The development of several heterogeneous ML models with a comparison of their performance;
- An original methodology and approach that includes a unique experimental framework and very good results with a relatively small input dataset, which are improved by the data augmentation method.
- Easy applicability of the selected and evaluated best model in real postal systems.

The structure of the paper consists of four main sections, followed by a list of references. After the introduction, the second section describes the materials and methods. Special focus is given to the third section, which presents the results and discussion. Final considerations are provided in Section 4.

2 Materials and Methods

The methodological approach of the research can be presented successively through several algorithmic steps, as illustrated in Fig. 1. After collecting research data from 281 instances, statistical analysis was used to determine the tercile thresholds, which served as the basis for classifying the values of the dependent variable. The preliminary Random Forest model, with optimized hyperparameters, served as the starting point for performance evaluation and further improvement of classification accuracy. To achieve higher accuracy, the dataset was augmented using the Support Vector Regression (SVR) model. The expanded dataset was then used for training and validation of the Random Forest, MLP, XGBoost, and SVM models. Based on classification accuracy metrics, the best model was selected, and its performance was evaluated using additional evaluation metrics.

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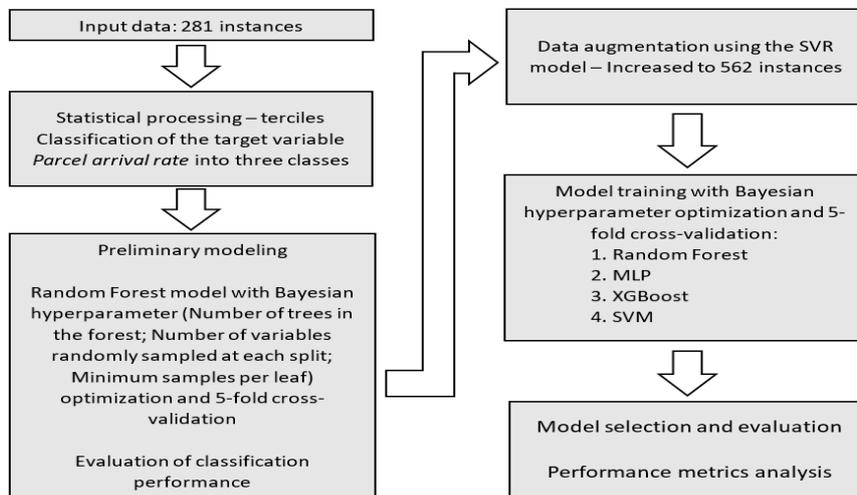


Fig. 1. Methodological steps of the research process

2.1 Research data and variables

The research data used in this study were provided by the Zenica Postal Center. From the available database, three independent time-related variables were extracted: 1) Sequential hour number (observed hour); 2) Day of the week; 3) Hour of the day.

Parcel arrival rate is initially observed as a continuous variable representing the cumulative number of parcels received during one observed hour at the Zenica Postal Center across 39 postal locations. This variable was classified into terciles through statistical processing. This approach facilitates modeling and interpretation, while also enhancing robustness and generalization, and at the same time reducing the risk of class imbalance problems. Fig. 2 presents a boxplot of the dependent variable, with its values divided into three classes using tercile thresholds, marked by red dashed lines. From Fig. 2, it can be concluded that the first tercile is at 18 parcels/hour, and the second at 43.67 parcels/hour. Accordingly, the classes of the dependent variable are defined as follows: $0 \leq Low \leq 18$; $18 < Medium \leq 43.67$; $43.67 < High \leq 144$.

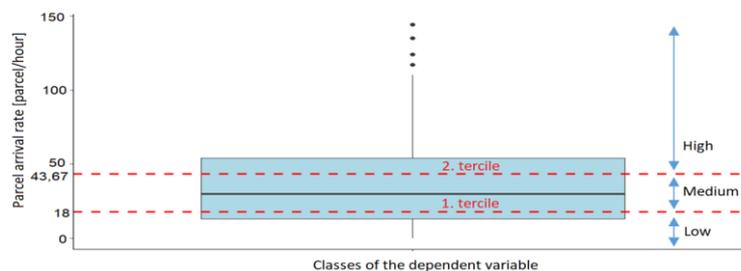


Fig. 2. Classification of the Dependent Variable Based on Terciles

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Fig. 3 presents the classification result and the distribution of classes depending on the sequential hour number (x-axis), day of the week, and hour of the day (y-axis). Each point on the graph represents one class of Parcel arrival rate, which, for a specific day and hour, is marked with one of three colors (as indicated in the legend). From Fig. 3, it is clearly evident that the Parcel arrival rate is high on weekdays starting from the 5th working hour of the day, i.e., in the afternoon hours, and that it gradually decreases toward the end of the workweek. On the sixth working day, Saturday, only medium and low intensities of parcel arrivals were recorded.

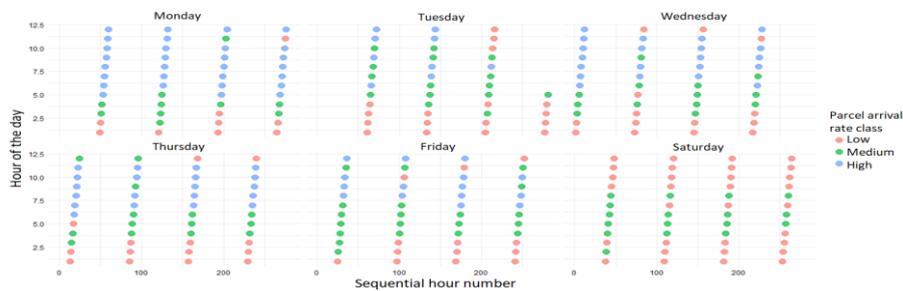


Fig. 3. Visualization of classification results and distribution of parcel classes depending on the hour index (x-axis), day of the week (Mon, Tue, Wed, Thu, Fri, Sat), and hour of the day (y-axis).

The dataset comprises 9,930 parcels recorded over 23 working days and 5 additional hours in March 2022. Since each working day was observed within a 12-hour operational window (07:00–19:00), the total observation period corresponds to 281 hours. Thus, the 9,930 parcels were aggregated into 281 hourly instances, where each instance represents the number of parcels received in a given hour along with its associated input variables.

2.2 Preliminary Random Forest model

The Random Forest model is one of the most popular ensemble machine learning models in the field of data mining. The ensemble concept consists of decision trees built using bootstrap sampling and random selection of input variables [11,12]. Some of the key advantages of the Random Forest model that support its selection as a preliminary model include [11,13]: (1) high accuracy compared to other methods such as bagging and boosting; (2) good performance with imbalanced datasets; (3) robustness; (4) effective handling of nonlinearities and interactions between variables; and (5) resistance to overfitting.

Bayesian optimization is an efficient approach for hyperparameter tuning in machine learning models. This approach uses a probabilistic surrogate model, most commonly a Gaussian Process (GP), to create an acquisition function. The acquisition function actively selects promising hyperparameter combinations without requiring extensive evaluations of the objective function [14]. Bayesian optimization, combined

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with 5-fold cross-validation, was applied exclusively during the training phase of the Random Forest model, with a total of 20 evaluations, in order to ensure reliable performance estimation and prevent overfitting. Therefore, the number of iterations of 20 was chosen as a compromise between efficiency and the risk of overtraining on a small dataset. In research practice, Bayesian optimization allows finding near-optimal solutions with a smaller number of iterations.

2.3 Data Augmentation

Augmentation was performed using a Support Vector Regression (SVR) model, where a radial kernel function was employed to train the model on the input dataset consisting of 281 instances. The SVR model was chosen due to its ability to model nonlinear relationships while remaining robust to noise and overfitting. During SVR model training, Bayesian optimization combined with 5-fold cross-validation was applied to determine the optimal hyperparameters: cost, epsilon, and gamma. The evaluation metric used was the mean squared error (MSE), and the maximum number of optimization evaluations was limited to 10 for practical reasons. After training, the optimal hyperparameter configuration was selected, and the trained model was used to generate an additional 281 values of the Parcel arrival rate based on input data. In the augmented input dataset, only the values of the variable "Hour index" differ from the original set, ranging from 282 to 562. The augmented Parcel arrival rate values were then classified according to previously defined terciles.

2.4 Creation of classification models

A total of four classification models (Random Forest, MLP, XGBoost, and SVM) were created within the same algorithmic framework using the following steps:

4. Data loading from the Excel file and creation of the classification task by defining the columns containing the independent and dependent variables.
5. Definition of the hyperparameter space, i.e., specifying the ranges within which hyperparameter values are searched for each model. The objective is to find the hyperparameters that yield the highest classification accuracy and identify the optimal model configuration.
6. Optimization strategy setup, which involves Bayesian hyperparameter optimization with 20 evaluations.
7. Definition of the validation method using 5-fold cross-validation.
8. Combining the previous steps into an AutoTuner, which automatically explores hyperparameter configurations with cross-validation.
9. Evaluation and review of 20 hyperparameter configurations to select the optimal model.
10. Visualization of hyperparameters and performance, where a 2D plot of the hyperparameter optimization space is generated, showing the accuracy performance for each of the 20 evaluations.

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11. Final cross-validation using the best model and saving the results.

According to [15], for small datasets such as the one used in this case, which contains 562 instances, model evaluation is often more reliable when based on cross-validation results rather than a separate test set. Therefore, the final performance metric of the best model is the cross-validation accuracy.

All machine learning models were developed using a unified experimental framework implemented in R version 4.4.3, supported by libraries from the mlr3 ecosystem: readxl, mlr3, mlr3learners, mlr3tuning, mlr3verse, paradox, mlr3pipelines, ggplot2, data.table, and writexl. The models were implemented in the RStudio Integrated Development Environment (IDE). To ensure reproducibility of the results, the random seed was set using `set.seed(123)`. All models were trained on a standard personal computer (Intel i5 processor, 16 GB RAM), and the computational requirements were modest, with each training and optimization procedure completing within minutes.

3 Results and Discussion

3.1 Preliminary Modeling

The Random Forest model was trained and validated on the complete dataset consisting of 281 instances. To achieve optimal model performance, three key hyperparameters were tuned: the number of trees in the forest, searched within the range of 100 to 500; the number of input variables randomly selected at each split, searched within the range of 1 to 3; and the minimum number of instances required in each leaf node, searched within the range of 1 to 10. To identify the optimal combination of these hyperparameters, Bayesian optimization was applied in combination with five-fold cross-validation. The optimal configuration found includes 500 trees, two variables per split, and a minimum of 10 instances per leaf node. With this setup, the model achieved a classification accuracy of 75.41% under cross-validation.

3.2 Data Augmentation Results

The improvement of the classification performance of the Random Forest model was achieved by augmenting the initial dataset of 281 instances with synthetic data. In the first step, an SVR model was trained on the available dataset using 5-fold cross-validation and Bayesian optimization of the following hyperparameters: Epsilon, searched in the range from 0.01 to 1; Cost, searched in the range from 0.1 to 10; and Gamma, searched in the range from 0.001 to 1. The graphical results of the search for the optimal model are shown in Fig. 4. Among the 10 evaluated hyperparameter combinations, the optimal configuration was found to be $\text{Gamma}=0.128$, $\text{Cost}=2.469$, and $\text{Epsilon}=0.051$. The lowest MSE value for this configuration was 382.031.

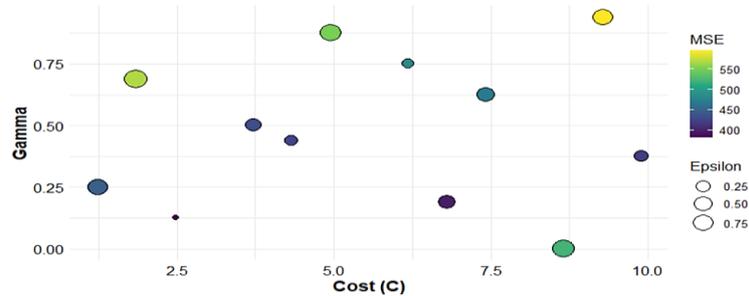


Fig. 4. Hyperparameter space and SVR model evaluation during Bayesian optimization

In the next step, the SVR model with the optimal configuration is trained on the input dataset to maximize the use of available information. The trained SVR model was then used to generate predictions for a new set of 281 instances, where only the values of the variable Sequential hour number differed from those in the original dataset, ranging from 282 to 562. The results of this data augmentation process, that is, the predictions for this time range are shown in Fig. 5.

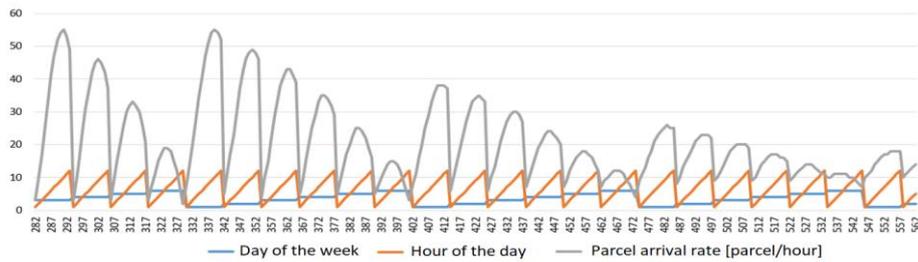


Fig. 5. Data Augmentation Results for a 281-Working-Hour Period

The displayed augmented values of the dependent variable were categorized according to the previously defined terciles. By merging the original dataset with the augmented one, a final dataset consisting of 562 instances was obtained. The data diversity analysis showed that augmentation did not change the number of categories for the independent variables, while for the dependent variable the number of unique values was reduced by almost half, indicating decreased variability. Thus, although the three classes of the dependent variable remained the same, their distribution was altered, since the ‘high’ class was underrepresented in the augmented dataset.

3.3 Classification Model Results

Bayesian optimization combined with 5-fold cross-validation enabled efficient evaluation and exploration of the hyperparameter space, as shown in Table 1. It shows the highest accuracy and optimal hyperparameters for each model.

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Table 1. Overview of Bayesian Hyperparameter Optimization with 5-Fold Cross-Validation

Model	Hyperparameters	Value	Acc.
Random Forest	Number of trees in the forest (ntree)	183	0.856
	Number of variables randomly sampled at each split (mtry)	2	
	Minimum samples per leaf (min samples leaf)	1	
MLP	Number of neurons in the hidden layer (h)	7	0.810
	Regularization (weight decay) (λ)	0.100	
	Number of boosting iterations (T)	267	
	Learning rate (η)	0.098	
XGBoost	Maximum depth of each tree (dmax)	2	0.849
	Percentage of data used to train each tree (s)	0.936	
	Feature subsample ratio (c)	0.655	
SVM	Regularization hyperparameter - Cost (C)	5.204	0.857
	Kernel parameter (γ)	0.571	

Although they show approximately equal accuracy in Table 1, SVM demonstrates slightly higher accuracy than the Random Forest model, while the MLP and XGBoost models show lower accuracy. Moreover, considering that SVM is generally preferred in research and better suited for smaller datasets, it was selected as the final model [16]. Fig. 6 illustrates the hyperparameter space explored during optimization, with marked points representing the evaluation results of the 20 hyperparameter combinations. In the central region of this space, the highest concentration of results is observed, including the point corresponding to the highest achieved accuracy of 85.7%.

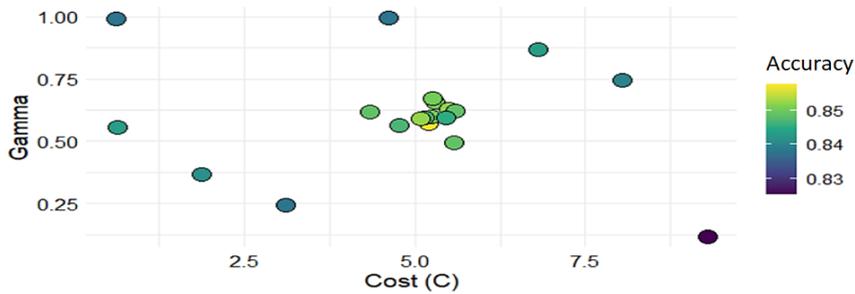


Fig. 6. Bayesian Optimization of SVM Model Hyperparameters with Evaluation Results of 20 Combinations

Based on the presented results for the SVM model, it can be concluded that after applying the augmentation method, the accuracy increased by 10.29% compared to the preliminary modeling results. The approximate equality of accuracy across all models indicates the stability of the solution, suggesting that accuracy does not largely depend on the model or the specific hyperparameter configuration. Table 2 presents additional performance metrics of the selected SVM model, namely Precision, Recall, and F1 score.

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Table 2. Classification Performance Metrics of the Selected SVM Model

Classes	Precision	Recall	F1 score
Low	0.897	0.920	0.908
Medium	0.834	0.847	0.840
High	0.825	0.764	0.793
Macro averages	0.852	0.844	0.847

A macro F1 score of 0.847 indicates very good results for multiclass classification, which is particularly important when working with small datasets. The "low" class has the highest Precision and Recall values, but overall, the classes demonstrate a very good balance between these two metrics. One notable detail is the more pronounced difference between Precision and Recall for the "high" class, which indicates a higher number of errors in recognizing this class.

4 Conclusion

This study presents a unique methodology for classification modeling of the dependent variable Parcel arrival rate, achieving the following: an intuitive and interpretable categorization of the number of received parcels into classes; modeling with a relatively small dataset; validation and hyperparameter optimization for all models; and the development of four heterogeneous models to enable a deeper and more comprehensive analysis of the dataset and ensure more reliable performance evaluation. Few studies have addressed this specific topic, despite global trends in postal services highlighting its importance. Thus, this research has strong potential to optimize the logistics processes and resources of postal companies, particularly in Bosnia and Herzegovina. The selected SVM model achieved 85.7% accuracy, while other models showed similar, slightly lower results. This indicates the dataset provides enough information for reliable classification, confirming the robustness and consistency of the patterns. However, the main limitations of this study are the relatively small dataset and the uneven performance across classes, especially in the "high" class. Future research could focus on collecting a larger volume of data and developing deep learning models to achieve even higher performance. In addition, it is necessary to incorporate external factors or explore hybrid modeling approaches to further enhance performance and to include validation on larger real-world datasets and an assessment of potential bias from synthetic instances.

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Operations research in transport

Application of Multi-Criteria Analysis for Rail Alignment Relocation: A Case Study of Jagodina

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Abstract. The process of rail alignment planning and design in infrastructure projects is often complex and influenced by numerous, sometimes conflicting, factors. As part of the preliminary design (PD) for the Belgrade–Niš railway modernization project, intended for speeds up to 200 km/h, the initial alignment was designed to remain within the existing corridor, with the station retaining its current location. However, following concerns raised by a group of local citizens regarding the alignment passing through the city, the possibility of relocating the railway alignment and station in the Jagodina area was additionally analyzed. To ensure a balanced and informed decision-making process, stakeholder input was included in the definition and weighting of criteria used to evaluate the options. The main objective was to identify the optimal alignment and station location that integrates technical and technological feasibility, economic viability, and environmental and social considerations. Three alternative variants, along with the PD solution, were assessed using Multi-Criteria Analysis (MCA) methods, PROMETHEE and TOPSIS, with accompanying sensitivity analysis to test the robustness of outcomes. This case demonstrates the practical value of MCA tools in navigating complex planning decisions and highlights the importance of early engagement with affected communities.

Keywords: Multi-Criteria Analysis, rail alignment, preliminary design.

1 Introduction

The modernization of the Belgrade–Niš railway represents one of Serbia’s most significant infrastructure projects, aimed at enabling high-speed operations of up to 200 km/h. While the 2020 Spatial Plan initially envisaged upgrades for speeds of 160 km/h on the Velika Plana–Niš section [1], the strategic decision to upgrade the entire corridor to 200 km/h required amendments to the plan and more extensive reconstruction, including double-tracking, curve realignments, and redesigned structures [2].

A central point of attention has been the City of Jagodina, designated as the only intermediate stop between Belgrade and Niš for high-speed trains. The station is planned to remain in its current location, consistent with national planning documents and confirmed through the 2022 Pre-Feasibility Study [3]. However, public consulta-

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tions revealed strong concerns from the group of citizens from Jagodina, particularly regarding community severance, safety risks, noise, and the closure of the level crossing linking the urban area south of the line with the industrial zone and northern settlements [4]. These issues have sparked debate over alignment changes and alternative traffic solutions.

To address these concerns, alternative alignments through Jagodina and options for the closed crossing were assessed. A detailed report was prepared, analyzing various design solutions, with key findings summarized in the following section.

2 Analysis of Preliminary Design Alignment Against Alternatives

Following the concerns raised by citizens of Jagodina, the analysis compared the PD alignment with alternative variants for relocating the railway and station. The PD maintains the existing corridor through the city, keeping the station in its current central location next to the bus terminal, which ensures strong accessibility for passengers and functional integration with both the residential area and the industrial zone. By contrast, the alternative alignment bypasses the urban core to the north, running parallel to the highway within a narrow corridor already partly developed as an industrial area. This route avoids direct impacts on dense residential zones but places the railway and station on the urban periphery, reducing convenience for daily commuters and requiring additional connections to public and road transport networks.

The comparison further highlights practical and strategic trade-offs. While the alternative alignment would reduce severance within the city and create stronger links with regional road infrastructure, it also introduces significant challenges, including land acquisition, conflicts with the planned Jagodina Terminal and CTPark developments, and the need to relocate sections of highway infrastructure. Moreover, station relocation would increase travel time for passengers and weaken integration with urban services. The PD, therefore, offers stronger passenger connectivity and fewer planning conflicts, whereas the alternatives provide advantages such as reduced noise exposure, lower safety risks in populated areas, and the potential to free central urban space for future development.

3 Multi-Criteria Analysis

The strategic orientation of Serbian Railways Infrastructure (SRI) is firmly directed toward the optimization and modernization of the existing Belgrade–Niš railway corridor. This approach seeks to maintain the line's dual function for both passenger and freight transport, while enabling high-speed passenger operations at up to 200 km/h.

The overarching aim is to achieve a travel time of approximately 90 minutes between the two cities, which aligns closely with Serbia's national transport develop-

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ment policies and the country's commitment to strengthening Corridor X as part of the wider trans-European transport network.

In order to test the compatibility of the PD with these strategic goals, an MCA was conducted. The MCA served as a structured evaluation tool, comparing the PD alignment with three alternative options (Variants A, B, and C) and assessing each against a broad range of technical, social, environmental, and operational factors [5]. Particular emphasis was placed on minimizing land acquisition, avoiding unnecessary displacement and resettlement, and reducing conflicts with existing urban and industrial infrastructure.

3.1 Definition of initial criteria and sub-criteria

For the comparison of variants, eight main criteria and thirty-eight sub-criteria were initially defined, covering technical, economic, social, environmental, and institutional aspects. A screening process was applied to eliminate redundancies, reclassify overlaps, and retain only those sub-criteria that provided meaningful differentiation.

Based on this refinement, a revised framework was established with seven main criteria and eight sub-criteria. Weighting factors were assigned to both main and sub-criteria, and relative weights were calculated to reflect their combined significance. The final set of criteria and sub-criteria, with corresponding relative weights, is presented in Table 1 below.

3.2 Quantification of the Proposed Criteria

The determination of numerical values for each selected sub-criterion is based on its specific nature and the fundamental principles defined in the following text. These principles include the application of appropriate weighting, normalization, and evaluation methods, each adapted to the characteristics of the respective sub-criterion [6].

K1 – Station accessibility and integration

The criterion assessed the accessibility of proposed railway station locations for both passenger and freight traffic. For passenger traffic, accessibility was evaluated through travel time and distance within five city zones, proximity to public, commercial, and recreational facilities (within 1,500 m), and integration with the bus station and local public transport lines. For freight traffic, the analysis focused on road connections, access points, and travel times along primary and alternative routes. Numerical values were derived primarily from travel time, ensuring comparability across passenger and freight perspectives.

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Table 1. Final list of selected sub-criteria

Main criteria	Mark	Sub-criteria	Sub-criteria relative weight factor
Accessibility	K1	Station accessibility and integration (access to the railway station, access to the public amenities, station location attractiveness, station alternative access routes)	10%
Technology	K2	Road traffic impact during construction	10%
Finance	K3	Total project costs (construction and reconstruction costs, land acquisition and household displacement costs, costs of relocating businesses, maintenance costs)	20%
Environmental impact	K4	Noise and vibrations	15%
Social impact	K5	Displacement and resettlement impacts (physical displacement of households, economic displacement)	10%
	K6	Community severance	10%
Safety	K7	Potential accidents and incidents	20%
Risks	K8	Delay (lack of planning and design documentation, time for construction, overall effect on Section 3, and the corridor)	5%

K2 – Road traffic impact during construction

This criterion assessed the potential disruptions to road traffic during railway construction. For the designed variant, impacts were evaluated using preliminary traffic management plans and construction technology assumptions. For the alternatives, the focus was on effects on the Belgrade–Niš highway, particularly the Jagodina interchange, including possible congestion and rerouting between the Batočina and Čuprija interchanges. The analysis was based on publicly available traffic count data from “Putevi Srbije,” using demand matrices from 2017–2019 due to the limited availability of more recent data [7].

K3 – Total project costs

The financial assessment was based on detailed cost estimates for the PD alignment and indicative assumptions for alternatives, drawing on stakeholder input and EU best practices. Costs considered included railway infrastructure, stations, the Jagodina interchange, major structures (underpasses, overpasses, viaducts), access roads, industrial siding tracks, relocation of industrial facilities, land acquisition, and household displacement.

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K4 – Noise and vibrations

As train frequency is identical across all variants, the assessment focused solely on noise impacts. Vibration effects were excluded as negligible, with mitigation provided through anti-vibration pads in station areas. Noise impacts were evaluated by counting the number of residential and industrial buildings located within 200 meters of each proposed alignment.

K5 – Physical and economic displacement

This criterion analyzed the extent of resettlement and relocation of industrial facilities for both the PD alignment and alternatives. Data for the PD were gathered through field visits, while alternatives were assessed using design concepts. The analysis distinguished between residential and industrial displacement, and between small and large industrial facilities, to capture socio-economic impacts and resettlement complexity.

K6 – Community Severance

This criterion assessed potential fragmentation of communities and impacts on mobility, access, and social cohesion [8]. Two key elements were considered:

- Relocation of the railway outside central Jagodina: Although lacking formal plans, this option was included to reflect citizens' concerns. The PD alignment poses relatively higher severance risks, though mitigated by planned underpasses and overpasses. Broader spatial context shows limited potential for urban expansion north of the existing line due to the industrial zone and highway.
- Closure of the Kapetana Koče Street level crossing: Potential connectivity impacts were assessed through Level of Service analysis and traffic counts, with rerouting delays calculated in vehicle-minutes.

K7 – Safety

Safety risks were evaluated in terms of potential damage in case of incidents. While accident likelihood is equal across variants due to modern safety standards, differences in surrounding land use and population density affect the severity of potential impacts. A 60:40 ratio was applied to distinguish between residential and economic structures, providing a clearer picture of exposure and emergency planning needs.

K8 – Risks

This criterion focused on schedule-related risks, measured as the additional time required to complete planning, technical, and tender documentation, as well as preparatory and administrative procedures before contract signing.

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3.3 MCA results

Based on the principles defined above, a numerical value was assigned to each adopted criterion for every analyzed variant. Following the alignment of the criteria using the linear normalization method, values were obtained for all criteria, which were then used in the model. A comparison of all proposed variants, based on the defined final criteria, was conducted using an MCA method. The TOPSIS method was selected as the most appropriate approach. This method allows a variant that does not have the highest score in any single criterion to still be ranked as the most favourable overall [9]. For the implementation of the method, the Python programming language was used along with its multi-criteria decision-making module “pymcdm.” The results of the applied MCA method are presented in Table 2 below.

To verify the obtained results, an additional MCA was conducted using the same defined criteria and their numerical values, but this time applying the PROMETHEE II method, an outranking method for a finite set of alternative actions to be ranked and selected among criteria, which are often conflicting [10]. The results of this analysis are presented in Table 3 below.

Table 2. Result of MCA using the TOPSIS method under the base case scenario

	PD Variant	Alternative Variant A	Alternative Variant B	Alternative Variant C
Result	0.65112	0.26431	0.43489	0.45116
Rank	1	4	3	2

Table 3. Result of MCA using the PROMETHEE II method under the base case scenario

	PD Variant	Alternative Variant A	Alternative Variant B	Alternative Variant C
Result	0.53333	-0.38333	-0.06667	-0.08333
Rank	1	4	2	3

A graphical presentation of the ranking of all variants according to both methods is provided in the Figure below.

After obtaining the results based on the initially defined weighting factors, six additional scenarios were developed to test the robustness of the MCA and its sensitivity to parameter changes. These scenarios modified the relative weighting of criteria, with increases offset by proportional reductions across others to preserve the 100% total. The adjustments emphasized criteria considered particularly important for Jagodina’s citizens, in order to assess how their greater influence might affect the outcome.

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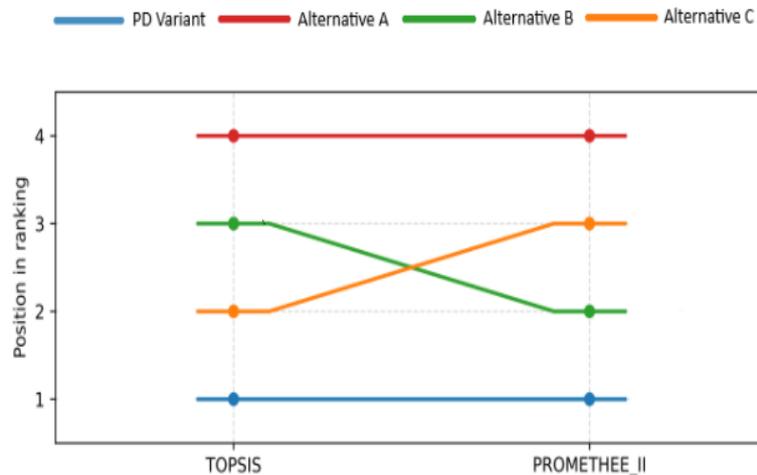


Fig. 1. Ranking of Variant Solutions

The analysis results, supported by both TOPSIS and PROMETHEE II methods and validated through sensitivity testing, confirm the robustness of the findings. The PD variant consistently ranks as the most favorable option, with its position only marginally challenged under an extreme weighting of social impact criteria in one sensitivity scenario. Overall, the results are considered reliable.

4 Conclusion and Recommendations of the Multi-Criteria Analysis

Based on the MCA, which examined a wide range of technical, financial, environmental, social, and risk-related aspects, the PD variant was identified as the preferred option for defining the railway corridor and station location in Jagodina. The results are consistent across different methodological approaches (TOPSIS and PROMETHEE II) and remain robust under multiple sensitivity scenarios, reinforcing the reliability of the assessment.

Taken together, the MCA findings substantiate the selection of the alignment and station location for Jagodina while underscoring the project's broader role in advancing regional mobility, connectivity, and socio-economic development within the framework of Corridor X modernization.

Although not intended to serve as the sole basis for decision-making, the MCA provides an essential tool for supporting and substantiating the evaluation process. It ensures that the selected option aligns with strategic planning objectives and contributes to the long-term functionality, integration, and coherence of the railway network.

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Application of Models for Determining the Optimal Number of Taxi Vehicles – Case Study Aleksinac

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Abstract. Defining the optimal number of taxi vehicles in a given area is of great importance for the proper functioning of the overall public urban passenger transport system, the operation of the taxi system, and the establishment of the desired quality of taxi services. Proper regulation of the number of taxi vehicles helps maintain the economic stability of the service, preventing extremes in prices that may occur due to excessive or insufficient supply. Furthermore, adequate availability of taxi vehicles increases the efficiency of the service, avoiding situations where too many taxis are waiting for passengers, which can be economically unprofitable. Regulating the number of taxi vehicles also prevents congestion, which is particularly important in central urban zones where a high concentration of taxis may cause traffic jams. From an environmental perspective, reducing the number of taxis on the roads can significantly contribute to environmental protection by lowering harmful gas emissions, thereby improving air quality. In essence, a well-organized number of taxi vehicles is crucial as it enhances the quality of public urban passenger transport, improves the standard of living for the population, and encourages the sustainable development of transport infrastructure. Professional literature and engineering practice, taking into account the specificities of individual areas, recommend different models for determining the optimal number of taxi vehicles. In this paper, a detailed comparative analysis of these models is presented, along with their application to the specific case of the Municipality of Aleksinac. The aim of the analysis was to identify the most efficient model in accordance with local transport needs and characteristics.

Keywords: Optimization model, Taxi service, Cost-Based Model, Queuing System Model.

1 Introduction

Taxi passenger transport plays a significant role in providing mobility services across the world, offering immediately recognizable service to users [1]. Due to its flexible

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nature, reflected in the provision of a “door-to-door” transport service available 24 hours a day, taxi transport considerably contributes to the increased mobility of residents, improves accessibility to certain points of interest within the observed territory (city or municipality), supports tourism development, and greatly influences the quality of life of the urban population.

Taxi transport is a publicly accessible service that belongs to the category of public services, and as such, it is part of the overall system of public urban passenger transport. Unlike other systems of public transport, however, taxi services are financed from private sources, which makes this system a public-private hybrid [1].

Defining the optimal number of taxi vehicles in a given area is therefore of great importance for the proper functioning of the taxi system and for establishing the desired quality of service. Proper regulation of the number of vehicles helps maintain the economic stability of the service, preventing extremes in pricing caused by oversupply or undersupply. Moreover, adequate vehicle availability increases service efficiency, avoiding situations where too many taxis wait idly for passengers, which can be economically unfeasible. Regulating the number of vehicles also prevents congestion, which is especially relevant in central urban zones where high taxi density can lead to traffic delays. From an ecological perspective, reducing the number of vehicles on the roads can significantly contribute to environmental protection by lowering harmful emissions, thereby improving air quality. In essence, a well-organized taxi fleet is vital, as it enhances the quality of urban transport, improves living standards in cities, and fosters sustainable development of transport infrastructure.

This study provides a review of previous research related to the functioning and determination of the optimal number of taxi vehicles, analyzes the models used for this purpose, and develops a methodology for determining the optimal number of taxis in a given area. Subsequently, the proposed methodologies are applied in a case study of the Municipality of Aleksinac. Finally, the discussion and concluding remarks provide recommendations for establishing the optimal number of taxi vehicles in a given territory.

2 Literature Review

In their study, Xianyuan Zhan, Xinwu Qian, and Satish V. Ukkusuri [2], which focuses on measuring the efficiency of taxi systems, emphasize that taxi service systems in large cities are extremely complex due to the interaction and self-organization between taxi drivers and passengers. They highlight that an inefficient taxi system results in a higher number of unproductive trips for drivers, which additionally burdens the road infrastructure and increases passengers’ waiting time. An inefficient taxi system may arise even when the market is properly regulated, but there is a lack of perfect information sharing between taxi drivers and passengers. To assess the efficiency of taxi systems, the researchers used two models: the optimal matching model and the trip integration model. The optimal matching model aims to provide an optimal strategy for pairing vacant taxis with potential passengers, while the trip integra-

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tion model seeks to develop an optimal strategy for integrating taxi trips into the broader public mass transport system.

In the study conducted by Szeto W.Y., Wong R.C.P., Wong S.C., and Yang H. [3], two major issues concerning the provision of taxi services are identified. The first issue relates to high-density urban areas where taxis are often allowed to circulate in search of customers, which adversely impacts road capacity, increases traffic congestion, and contributes to pollution. The second issue concerns the mismatch between supply and demand for taxi services across time and space.

In their research, Wong R.C.P., Szeto W.Y., and Wong S.C. [4], which investigates the spatial structure of the taxi market where the transport network is divided into traffic cells, particular emphasis is placed on the fact that vacant taxis often cruise in search of passengers, and the longer the cruising time, the greater the probability of finding a passenger. Taxi drivers, when making decisions, typically have up to five options, which led the researchers to define several variables: Probability of success (likelihood that a taxi request will appear in the cell where the last passenger was dropped off), Expected number of decisions during the search (average number of cells traversed before responding to a transport request), and Cumulative probability of success (equal to the probability of successful service in the current cell plus the probability obtained from subsequent cells, depending on the number of vacant taxis there).

In the work of Xiao Liang, Gonçalo Homem de Almeida Correia, and Bart van Arem [5], the problem of trip chaining is investigated using a method that considers fleet routing in the taxi subsystem, where taxis are automated vehicles assigned to the urban transport network. The fleet routing model applies linear programming, examining passenger flow in a network where only taxi services exist between nodes, with no other traffic on the network. In this setup, passenger demand is generated solely by taxi users, and services are carried out by automated taxis. The objective function is analyzed from both the taxi operator's perspective (profit maximization) and the customer's perspective (minimization of price and travel time).

In the research conducted by Michal Maciejewski and Kai Nagel [6], taxi demand was analyzed in relation to its impact on network congestion, considering three scenarios: (1) without advance booking of taxi rides, (2) assigning only the nearest available taxi, and (3) booking rides in advance. The analysis revealed that when the demand–supply ratio is low, the scenario without booking performs better than those requiring planned services. However, as the demand–supply ratio increases, scenarios involving service planning deliver better results. This model was applied to sections of transport networks in Berlin and Poznań [7].

In their study, Yang Yang, Zjenzhou Yuan, Xin Fu, Yinhai Wang, and Dongye Sun [8], focusing on determining the optimal number of taxis in a given area, underline the significance of achieving an optimal fleet size, which results in shorter passenger waiting times and increased fleet efficiency, with the ultimate objective of maximizing taxi service profit. Their fundamental approach lies in balancing supply and demand in the taxi market by setting the optimal number of taxis. Factors influencing this number include the efficiency of the transport network, the level of development

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of the public urban transport system, fleet efficiency, spatial distribution of taxi trips, and taxi fares. Analysis of Model Structures for Determining the Optimal Number of Taxi Vehicles

A detailed analysis of the existing and commonly used models for determining the optimal number of taxis has been carried out, primarily in terms of input parameters, output parameters, and the processes involved.

3 Analysis of Model Structures for Determining the Optimal Number of Taxi Vehicles

3.1 Cost-Based Model for Determining the Optimal Number of Taxi Vehicles

Determining the optimal number of taxi vehicles used for passenger transport in a given territory presents a challenge for all transport planners, as it requires balancing different and often conflicting interests. To establish the optimal number of taxis, it is necessary to develop a methodology that can be applied consistently across the target area. Taxi services are classified as a flexible subsystem of transport, which makes it even more difficult to establish a uniform methodology.

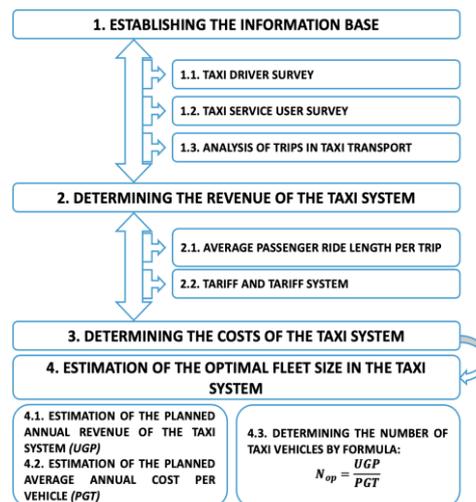


Fig. 1. Methodology for Determining the Optimal Number of Taxi Vehicles Using a Cost Model

3.2 Queuing System Model for Determining the Optimal Number of Taxi Vehicles

The taxi passenger transport system is an organizational, production, and technological system that operates continuously 24 hours a day, serving user travel demands. The number of service requests directed to the taxi system varies over time, as does

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the overall volume of service demand, while both the timing and location of requests are random variables with a high coefficient of variation.

Models that formalize system performance and functionality enable planners to determine other operational parameters of the taxi system by statistically monitoring certain indicators. Requests for taxi services form flows of varying intensity that combine into aggregated streams. The Khintchine Limit Theorem for aggregated flows provides the foundation and conditions for selecting an appropriate type of queuing system from Queuing Theory. If quality parameters are incorporated into the selected queuing system for the chosen objective function of the taxi system, it becomes possible to obtain a reference model with properties that correspond to the objective function of the real taxi system. For this approach to be scientifically valid, it must be established whether the input stream of taxi service requests corresponds to the characteristics of a Poisson process, thereby fulfilling two of the three necessary conditions for a “simple” process: ordinariness and independence of events [9]. These models can be applied to evaluate the effectiveness and quality of real-world systems, simulate the impact of planned measures on system performance, support operational management, and system control. The procedure for applying the model consists of the following steps, as shown in Figure 2 [10].

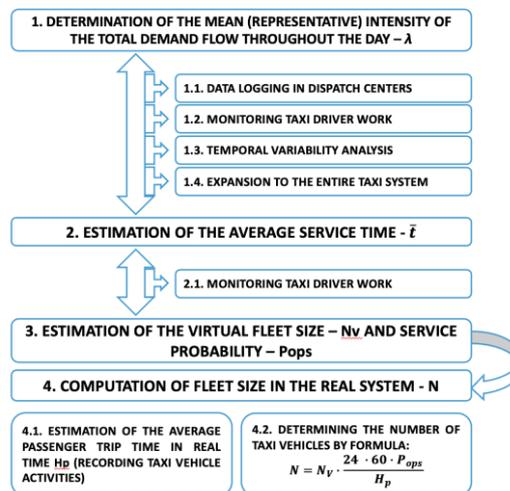


Fig. 2. Methodology for Determining the Optimal Number of Taxi Vehicles Using a Queuing System

4 Application of Models for Determining the Optimal Number of Taxi Vehicles – Case Studies

To achieve rational functioning of the taxi system, it is essential to determine the optimal number of taxi vehicles within the observed territory. For this reason, the mod-

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els analyzed in Chapter 3 were applied to the territory of the Municipality of Aleksinac. Using the same transport demand parameters (i.e., identical input data for the observed territory), both the Cost-Based Model for determining the optimal number of taxi vehicles and the Queuing System Model were applied. Based on these approaches, the optimal number of taxis for the selected area was determined.

**4.1 Determining the Optimal Number of Taxi Vehicles – Case Study:
Municipality of Aleksinac**

To establish the optimal number of taxi vehicles in the Municipality of Aleksinac, the functioning of the taxi system was analyzed, followed by the creation of an information base and the assessment of input parameters. These were then applied both to the Cost-Based Model and the Queuing System Model. After applying the models, the optimal number of taxi vehicles was determined for the Municipality of Aleksinac using both approaches.

It should be noted that, according to data from the Statistical Office of the Republic of Serbia, the Municipality of Aleksinac had approximately 50,000 inhabitants at the time of the analysis.

The analysis of the taxi system in Aleksinac revealed the following:

1. Total annual revenue (UGP): 204.735.760,00 RSD
2. Average annual cost (PGT) per vehicle: 2.361.264,00 RSD

Optimal number of taxi vehicles in relation to the number of vehicles included in the research (N_{op}) in the system:

$$N_{op} = \frac{UGP}{PGT} = \frac{204.735.760,00}{2.361.264,00} = 87 \text{ taksi vehicles} \quad (1)$$

Based on the conducted analysis, the optimal number of vehicles operating in the Aleksinac taxi system was determined. According to the model, the optimal fleet size is 87 vehicles, with a recommended range between 83 and 96 vehicles over the next five years, depending on revenue and cost fluctuations.

According to demand for taxi services and a survey of taxi drivers, the working hours of taxi drivers are divided into three shifts:

- Shift I: 07:01 - 15:00
- Shift II: 15:01 - 22:00
- Shift III: 22:01 - 07:00

- 1) Calculation of the required number of taxi vehicles for the first shift (07:01–15:00)

During the period of daily workload, irregularities in transport demand were observed. However, based on the analysis of ride waiting times, the maximum relevant intensity of the combined request flow was taken as $\lambda = 2.41$ [requests/min].

For the average service time \bar{t} , the mean time elapsed from accepting a request to completing the ride in the existing system was adopted, which amounts to $\bar{t} = 9.23$ minutes. Based on the average service time, the intensity of the flow of served passengers was determined, which is $\mu = 0.10834 \text{ min}^{-1}$.

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The theoretical (virtual) optimal number of taxi vehicles for the observed area is:

$$N_v = \rho = \frac{\lambda}{\mu} = 22,28 \quad (2)$$

For the specified virtual number of taxi vehicles, the probability of serving clients is obtained and adopted as $P_{ops} = 0,994$.

In calculating the required number of taxi vehicles for effective (productive) working hours, a value of $H_p = 277$ minutes, or $H_p = 4.66$ hours, was adopted for an 8-hour time frame. The adopted value is based on the average service time (9.23 minutes) and the average number of rides per vehicle in the system, which is 30 rides. The technical fitness coefficient of the taxi fleet was adopted based on fleet analysis and amounts to $\alpha = 0.96$.

The required number of taxi vehicles in the real system for the first shift is:

$$N_I = N_v \cdot \frac{H_r \cdot 60 \cdot P_{ops}}{H_p \cdot \alpha} = 22,28 \cdot \frac{8 \cdot 60 \cdot 0,994}{277 \cdot 0,96} = 40,00 = 40 \text{ [taxi vehicle]} \quad (3)$$

- 2) Calculation of the required number of operational taxi vehicles for the second shift (15:01-22:00)

During the daily workload period, irregularities in transport demand were observed. However, based on the analysis of waiting times for rides, the maximum relevant intensity of the aggregated request flow was taken as $\lambda = 1.72$ [requests/minute].

The theoretical (virtual) optimal number of taxi vehicles for the observed area is:

$$N_v = \rho = \frac{\lambda}{\mu} = 15,84 \quad (4)$$

The required number of taxi vehicles in the real system for the second shift is:

$$N_{II} = N_v \cdot \frac{H_r \cdot 60 \cdot P_{ops}}{H_p \cdot \alpha} = 15,84 \cdot \frac{8 \cdot 60 \cdot 0,994}{277 \cdot 0,96} = 28,46 = 29 \text{ [taxi vehicle]} \quad (5)$$

- 3) Calculation of the required number of operational taxi vehicles for the third shift (22:01-07:00)

During the daily workload period, irregularities in transport demand were observed. However, based on the analysis of waiting times for rides, the maximum relevant intensity of the aggregated request flow was taken as $\lambda = 1.22$ [requests/minute].

The theoretical (virtual) optimal number of taxi vehicles for the observed area is:

$$N_v = \rho = \frac{\lambda}{\mu} = 11,35 \quad (6)$$

For the specified virtual number of taxi vehicles, the probability of serving clients is obtained and adopted as $P_{ops} = 0,994$.

The required number of taxi vehicles in the real system for the third shift is:

$$N_{III} = N_v \cdot \frac{H_r \cdot 60 \cdot P_{ops}}{H_p \cdot \alpha} = 11,35 \cdot \frac{8 \cdot 60 \cdot 0,994}{277 \cdot 0,96} = 20,39 = 21 \text{ [taxi vehicle]} \quad (7)$$

According to the Queuing System Model, the required number of taxi vehicles in the territory of the Municipality of Aleksinac for the first shift is 40 taxi vehicles, for the second shift 29 taxi vehicles, and for the third shift 21 taxi vehicles. The total number of taxi vehicles in the territory of the Municipality of Aleksinac, according to the Queuing System Model, is:

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$$N = N_I + N_{II} + N_{III} = 40 + 29 + 21 = 90 \text{ [taxi vehicle]} \quad (8)$$

5 Discussion

Determining the optimal number of taxi vehicles in a given area represents a challenge for all transport planners due to the lack of a methodology that can recognize the specificities of certain areas to satisfy all users of the taxi service.

In this paper, two methodologies for determining the optimal number of taxi vehicles in a given area were developed, based on different input data for the model.

The first methodology is based on the analysis of the planned revenue of the taxi transport system and the analysis of the average annual costs per taxi vehicle. As an input parameter for projecting planned revenues, the planned tariff and tariff system to be used in the taxi system, and the average ride length with passengers are used. Based on the mentioned parameters, a projection of the number of rides per day during the week is made, then per month during the year, and with the planned tariff and tariff system, the planned revenue of the taxi system is determined. The analysis of the average annual costs per taxi vehicle is based on determining the average cost of one taxi vehicle on a monthly basis, where all types of vehicle costs in the taxi system are analyzed, and then the average monthly cost of one vehicle is expressed on an annual basis.

The second methodology is based on the analysis of user requests for the taxi service. In order to use this methodology, it is necessary to statistically analyze all requests for the taxi service by users in a certain time interval to determine a representative day. Statistical analysis of requests for the taxi service determines the number of requests for the taxi service for all days of the week and all months of the year. After determining the representative day, requests for the taxi service during 24 hours are analyzed. The model based on the queuing system uses as input parameters the intensity of the client (request) flow - λ and the average service duration - \bar{t} .

It must be noted that the first methodology, i.e., the Model based on the revenues and costs of the taxi system, views the taxi system exclusively in an economic sense and deals with the economic sustainability of interests from the perspective of the taxi carrier. The second methodology, i.e., the Model based on the queuing system, views the taxi system exclusively in a technological-organizational sense and deals with responding to requests for the taxi service while meeting the appropriate quality of service.

Furthermore, the Model based on the revenues and costs of the taxi system gives the optimal number of taxi vehicles at the daily level, i.e., a period of 24 hours, while the Model based on the queuing system gives the optimal number of taxi vehicles per determined periods during the day, i.e., per shifts, which significantly contributes to the optimal operation of the taxi system.

For the territory of the Municipality of Aleksinac, the Model based on the revenues and costs of the taxi system determined the optimal number of taxi vehicles to be 87 taxi vehicles, with a tolerance ranging from 83 to 96 taxi vehicles, depending on the

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variability of costs and revenues of 5%. The Model based on the queuing system determined the optimal number of taxi vehicles based on requests for the taxi service per shift: for the first shift 40 taxi vehicles, for the second shift 29 taxi vehicles, and for the third shift 21 taxi vehicles, which is a total of 90 taxi vehicles in the observed area. Furthermore, what can be highlighted for a city with a size of about 50,000 inhabitants is that by increasing the salary by 10,000 dinars, the optimal number of taxi vehicles decreases by 5 taxi vehicles, while by reducing the cost of fuel by 10,000 dinars, the optimal number of taxi vehicles increases by 5 taxi vehicles, which speaks to the sensitivity of the applied model. Also, by increasing productive kilometers in the taxi system and the time spent driving with a passenger by one hour, the optimal number of taxi vehicles decreases by 15 taxi vehicles, while by reducing the coefficient of technical readiness of the taxi fleet by 10%, the optimal number of taxi vehicles increases by 10 taxi vehicles.

6 Conclusion

The organization of taxi transport must be in the function of achieving reproductive capacity, which will be achieved only if the necessary number of taxi vehicles in the observed territory is defined..

What can be concluded is that for the territory of the Municipality of Aleksinac, which had about 50,000 inhabitants at the time of the research, the Model based on the revenues and costs of the taxi system gave a comprehensive optimal number of taxi vehicles with a variability of 5%, while the Model based on the queuing system, in an organizational-technological sense, gave a point estimate of the optimal number of taxi vehicles, which was within the comprehensive solution of the Model based on the revenues and costs of the taxi system.

Subsequently, for the mentioned territories with different numbers of inhabitants, the optimal number of taxi vehicles was examined with changes in driver salaries (increased by 10,000 dinars), fuel costs (reduced by 10,000 dinars), then by increasing the time spent on productive kilometers by one hour, and by reducing the coefficient of technical readiness of the taxi fleet by 10%.

What can be concluded is that for an area with about 50,000 inhabitants, by increasing the driver's salary by 10,000 dinars, the optimal number of taxi vehicles decreased by 6%, and by reducing fuel costs by 10,000 dinars, the optimal number of taxi vehicles increased by 6%. Increasing the time spent on productive kilometers by one hour, the optimal number of taxi vehicles decreased by 17%, and by reducing the coefficient of technical readiness of the taxi fleet, the optimal number of taxi vehicles increased by 12%.

What can be concluded is that increasing the time spent on productive kilometers by one hour significantly affects the optimal number of taxi vehicles, especially in territories with over 50,000 inhabitants. Also, it can be concluded that by increasing productive kilometers and increasing the salaries of taxi drivers, the optimal number would certainly decrease in the analyzed territories, while reducing fuel costs leads to

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an increase in the optimal number of taxi vehicles, as does a decrease in the coefficient of technical readiness.

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ESCO Model for Communal Enterprises in Bosnia and Herzegovina: Case study of the City of Doboj

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Abstract. Efficient management of municipal waste remains a key challenge of modern cities, especially in the context of energy efficiency, climate change, and public spending constraints. Many municipal companies struggle to maintain service quality due to aging vehicle fleets and rising fuel and maintenance costs. Energy service contracting (ESCO) models offer an innovative solution by enabling infrastructure renewal without a direct budgetary burden, with investment repaid through verified operational savings. This study addresses a gap in ESCO literature by applying the model to municipal fleet renewal, a domain typically excluded from ESCO implementation. Focusing on the City of Doboj, Bosnia and Herzegovina, the analysis evaluates three investment scenarios for replacing obsolete waste collection vehicles. The methodological framework includes technical fleet, diagnostics, fuel consumption, and greenhouse gases (GHG) emissions assessment, and financial evaluation using Net Present Value (NPV), Internal Rate of Return (IRR), and Simple Payback Period (SPP), supported by sensitivity testing. Benchmarking against international case studies identifies the most favourable scenario for ESCO implementation under local conditions. The findings demonstrate the viability of extending ESCO principles to non-building assets and offer a replicable model for transitional economies seeking sustainable fleet modernisation.

Keywords: ESCO model, GHG emissions, fleet renewal.

1 Introduction

Energy efficiency has become a key component of sustainable development and public policy, especially in the light of rising energy prices and climate challenges. Among various mechanisms used to improve energy efficiency in the public sector, ESCO models have proven to be effective and financially viable [1, 2]. In this model, the ESCO assumes financial risk and invests in energy efficiency projects, while the service user repays the investment through the savings in energy and operational costs [3].

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While ESCO models are most commonly applied in building retrofits and public lighting, recent studies highlighted their potential in the waste management and municipal fleet renewal [4, 5]. More efficient waste transport management enables significant savings in fuel and maintenance, along with reductions in GHG emissions [6].

International experiences, including those from Denmark, Spain, and Eastern Europe, demonstrate that ESCO contracts can significantly improve infrastructure management [7, 8]. GIS tools for route optimization and digital container mapping further enhance the cost-effectiveness of the ESCO approach [9, 10].

The World Bank recommends the development of Super ESCOs to support utility companies with limited project management capacity [1]. Cities such as Barcelona have implemented "budget-neutral" approaches to enable investment without additional fiscal pressure [11].

Despite institutional and legal challenges in developing countries, examples from Eastern Europe show that the ESCO market can be developed through procurement reform and trust-building [12].

In the Western Balkans, models that allow public entities to retain infrastructure control while transferring operational risk to private partners are particularly relevant [13, 14].

This study builds on three intersecting theoretical domains: municipal finance, public-private partnerships (PPP), and energy efficiency economics. These frameworks provide the foundation for evaluating the applicability of ESCO models to municipal fleet renewal and support the broader relevance of the Dobo case.

Municipal finance theory emphasises budget-neutral investment mechanisms and capital cost avoidance in public infrastructure management. Constrained local budgets require innovative financing models that minimise upfront expenditure while maintaining service quality [15]. The ESCO model aligns with this principle by enabling investment through future operational savings rather than direct capital allocation.

PPP theory offers a lens for understanding how risk transfer, lifecycle cost optimisation, and institutional capacity building can be achieved through contractual arrangements. These models allow public entities to retain strategic control while leveraging private sector expertise and efficiency [16]. ESCO contracts represent a specialised form of PPP, where performance-based repayment mechanisms incentivise long-term cost reduction and service reliability.

Energy efficiency theory supports the use of measurable operational savings, such as reductions in fuel consumption, maintenance costs, and GHG emissions, as triggers for investment. Efficiency measures must be evaluated not only by technical performance but also by economic and behavioural impacts, including rebound effects and system-level interactions [17]. In the context of municipal fleets, quantifying these savings provides a credible basis for ESCO-driven investment strategies.

By integrating these theoretical perspectives, the study positions the Dobo case as more than a local intervention. It demonstrates how ESCO principles can be extended to non-building assets in transitional urban contexts, offering a replicable model for sustainable infrastructure renewal under fiscal and institutional constraints. This study

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addresses a gap in ESCO literature by applying energy performance contracting principles to municipal fleet renewal, a domain typically excluded from ESCO implementation. The Doboj case provides a replicable model for small and transitional municipalities seeking to modernise non-building assets through savings-based investment. By quantifying fuel, maintenance, and emissions reductions, the study demonstrates how ESCO logic can extend beyond buildings and contribute to broader urban sustainability strategies.

2 Analysis of the infrastructure for waste collection and transport

2.1 Study area

The city of Doboj is situated in the northern part of Bosnia and Herzegovina, within the entity of Republika Srpska. It covers an area of 671 km² with 87 populated places, including an urban core of 27,000 inhabitants and a wider suburban and rural population exceeding 77,000. The city topography, shaped by Bosna and Spreča rivers, affects traffic networks and accessibility, complicating waste collection logistics and emphasizing the need for efficient route planning. Waste management in the city is organized through a local public service responsible for planning, collection, transportation, and disposal of waste. Operational activities related to the collection and transport of waste are carried out by the Communal Company "Progres" Doboj, which is the focus of this study.

2.2 Methods

The analysis aimed to evaluate fleet efficiency, GHG emissions, operational costs, while identifying optimization scenarios through the ESCO model.

In 2023, the company operated four vehicles: two MAN H17 trucks (2003 and 2004), one DAF FA 75.240 (1997), and one IVECO 260 (2002). These vehicles differ in age, Euro emission class (II and III), load capacity, and technical conditions. The average fleet age is 19.5 years, exceeding the recommended European standard of 7–10 years [18].

The operational cycle of waste collection includes several phases: driving to the first collection point, moving between stops, loading waste from bins and containers, operating in idle time, compression, and transporting waste to a landfill located 3 km the city centre.

In 2023, a total of 7,536 tonnes of waste were collected, with overall fuel consumption of 39,980 litres, resulting in an average of 5.31 liters per tonne (L/tonne) of waste. This average fuel consumption (5.31 L/t) includes both collection and transport phases and serves as a benchmark for comparative analysis with similar European municipalities. This is moderately high compared to European benchmarks, where

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urban areas report 3–5 L/t and rural areas up to 10 L/t [18]. Fleet capacity utilization was only 31%, indicating room for route rationalization and cost reduction.

All operational data used in this study were obtained directly from the communal company “Progres” Dobož for the year 2023. Technical specifications of the vehicles, such as year of manufacture, Euro emission class, and payload capacity, were extracted from official fleet documentation and cross-checked with operational staff. Fuel consumption figures were based on recorded refuelling logs, which include date, volume, and vehicle identification, and were aggregated to calculate annual usage per vehicle. The technical specifications and fuel consumption of each vehicle used for waste collection in Dobož during the year 2023 are presented in Table 1.

Table 1. Technical specifications and fuel consumption per vehicle

Vehicle	Year	Euro standard	Load capacity (t)	Fuel consumption (L/god)	Share of consumption (%)
DAF FA 75.240	1997	Euro II	3.78	10,980	27%
MAN H17	2003	Euro III	11.45	9,700	24%
MAN H17	2004	Euro III	10.75	9,600	24%
IVECO 260	2002	Euro III	15.00	9,700	24%

As shown in Table 1., the DAF FA 75.240 vehicle, despite having the lowest payload capacity, recorded the highest fuel consumption, accounting for 27% of total fleet consumption. This disproportionate energy use highlights its operational inefficiency, and it is the primary candidate for replacement within the proposed optimisation scenarios.

GHG emissions calculated using standard emission factors provided by the EMEP/EEA [19]: CO₂(2.73 kg/L), CH₄(0.13 g/L), and N₂O (0.0082 g/L). The total annual emissions from the fleet amounted to 113.9 tonnes of CO₂ equivalent (tCO₂eq). Table 2 presents the emissions per vehicle.

Table 2. GHG emissions from vehicles according to fuel consumption

Vehicle	Fuel consumption (L)	CO ₂ (t)	CH ₄ (kg)	N ₂ O (kg)	Total GHG (t CO ₂ eq)
DAF FA 75.240	10,980	29.98	1.43	0.90	30.3
MAN H17 (2003)	9,700	26.48	1.26	0.80	26.8
MAN H17 (2004)	9,600	26.21	1.25	0.79	26.5
IVECO 260	9,700	26.48	1.26	0.80	26.8

The data presented in Table 2 clearly indicate that the DAF FA 75.240, despite having the lowest payload capacity (3.78 tonnes), generated the highest annual GHG emissions (30.3 tCO₂eq), contributed over 26% of total emissions. This disproportionate environmental impact is primarily attributed to its outdated Euro II engine, poor fuel efficiency, and degraded combustion performance. In contrast, the remain-

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ing vehicles, although larger in capacity, produced lower or comparable emissions, confirming the DAF vehicle's technical and ecological inefficiency.

Similar findings have been recorded in relevant European literature. Emissions per ton of collected waste from older diesel vehicles in sparsely populated municipalities in Denmark range between 10 and 22 kg CO₂eq/t, while modern vehicles with Euro V and VI engines have an average between 5 and 9 kg CO₂eq/t [18].

Maintenance costs represent another important element of the overall operational picture. Maintenance costs were derived from the company's internal financial records and reflect actual expenditures, not estimates. The annual maintenance costs per vehicle are presented in Table 3.

Table 3. Maintenance costs per vehicle

Vehicle	Service cost (EUR/year)
DAF FA 75.240	4,600
MAN H17 (2003)	3,580
MAN H17 (2004)	3,320
IVECO 260	3,320

As shown in Table 3, the DAF FA 75.240 vehicle recorded the highest annual maintenance cost, totalling 4,600 EUR in 2023. This represents over 31% of the fleet's total maintenance expenditure, despite the vehicle having the lowest payload capacity and the oldest manufacturing year (1997). In contrast, the remaining vehicles, although larger and more intensively used incurred lower maintenance costs, ranging between 3,320 and 3,580 EUR annually..

The elevated cost associated with the DAF vehicle is attributed to its outdated mechanical systems, frequent breakdowns, and the need for specialised servicing due to its Euro II classification. These findings confirm its technical and financial inefficiency and support its prioritisation for replacement. According to international technical guidelines, such as those published by the World Bank, operational costs for modern municipal vehicles, including servicing, typically range between 0.15 and 0.25 EUR per kilometre, depending on usage intensity and local service conditions. For vehicles with an annual mileage of 10,000 to 15,000 km, this translates to expected maintenance costs between 1,500 and 3,750 EUR per year [20]. The DAF vehicle's cost exceeds this benchmark, reinforcing the need for fleet modernisation through ESCO-based investment.

2.3 Scenario development

Based on the analysis of the technical condition, operational efficiency, and costs of the existing vehicle fleet of the communal company "Progres" a.d. Doboj, three scenarios for the modernization of the municipal waste collection system have been developed. The selection of these three scenarios was based on operational feasibility, budget constraints, and fleet composition. Hybrid and electric alternatives were

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excluded due to infrastructure limitations and high upfront costs, which currently make them impractical for Doboj's city context [22]. Scenario 1: Replace two outdated vehicles (DAF FA 75.240 and MAN H17/2003) with one modern, high-capacity unit.

Scenario 2: Replace only the DAF FA 75.240, the least efficient vehicle in the fleet.

Scenario 3: Replace only the MAN H17/2003, aligned with long-term fleet renewal strategy.

Each scenario was evaluated for its impact on fuel consumption, GHG emissions, maintenance costs, and financial viability under ESCO financing conditions.

3 Results and Discussion

Based on the developed scenarios for the modernization of the vehicle fleet of the Communal company "Progres" Doboj, a detailed evaluation of the expected effects in the areas of fuel consumption, GHG emissions, maintenance costs, and total annual operational costs has been carried out. The analysis was conducted using both technical and financial indicators, including fuel savings, emission reductions, maintenance cost reductions, and investment profitability metrics such as Simple Payback Period (SPP), Net Present Value (NPV), and Internal Rate of Return (IRR).

For clarity and comparative analysis, Table 4 presents the key results of the simulations for three developed scenarios of fleet optimization.

Table 4. Comparative overview of fleet modernization scenarios

Scenario	Investment (EUR)	Fuel savings (L/year)	Cost savings (EUR/year)	GHG reduction (tCO ₂ eq/year)	SPP (years)
Scenario 1	127,850	7,365	18,560	20.11	6.9
Scenario 2	92,000	1,978	6,710	5.39	13.7
Scenario 3	92,000	4,343	8,700	11.86	10.6

The results confirm that Scenario 1, in which two old vehicles (MAN H17 and DAF FA 75.240) are replaced by one modern, technically more efficient vehicle with a lower load capacity, is the most rational and cost-effective option. It achieves the highest annual savings (18,560 EUR), the largest GHG reduction (20.11 tCO₂eq/year), and the shortest payback period (6.9 years), making it the only scenario with full financial and operational justification.

Scenario 2, which involves only the replacement of the DAF FA 75.240 vehicle, has the lowest effects, with an annual savings of 6,710EUR and a reduction in emissions of 5.39 tCO₂eq/year.

Scenario 3, where only the MAN H17 vehicle is replaced, achieves moderate savings (8,700 EUR/year) and emissions reduction (11.86 tCO₂eq/year), but with a longer payback period.

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Using the SPP methodology as a tool for assessing investment efficiency, the results of this study are consistent with the findings of relevant international research. In the analysis for ICCT, programs for replacing communal vehicles in urban areas showed an average return on investment between 6 and 12 years [21], which falls within the range of return dynamics recorded in scenario 1 of the analyzed system (SPP: 6.89 years). The application of the MARKAL model in the transition to zero-emission fleets in municipalities has resulted in an average reduction of operational costs and GHG emissions between 30% and 45% [18]. In this analysis, the modernization of the vehicle fleet results in a reduction of fuel consumption by more than 26%, along with an annual reduction of emissions by 13.86 tCO₂eq, which constitutes a 27% decrease compared to the initial values, falling within the same range.

Similar results were recorded in a study that analyzed the rationalization of routes in the city of Dobož [23]. The authors demonstrated that by applying optimized routes and reducing empty runs, the operational costs of the utility company can be reduced by up to 20%, while work efficiency increases through better time organization and technical specifications of the vehicles.

For a more thorough and in-depth assessment of the financial sustainability of the analyzed measures for modernizing the vehicle fleet, an evaluation of all scenarios was also conducted using the indicators of net present value (NPV) and internal rate of return (IRR) over a time horizon of 12 years, which corresponds to the typical duration of ESCO contracts in the public sector. The aim of this analysis was to examine whether the project savings achieved through the replacement of one or more vehicles can generate a real financial surplus in a relatively short period.

The results are summarized in Table 5, which displays the key investment parameters for all three variants: the amount of investment, annual expected savings, calculated net present value, and internal rate of return.

Table 5. Financial indicators

Scenario	NPV (BAM)	IRR (%)	Status
Scenario 1	27,760	9,78%	Profitable
Scenario 2	-35,720	-1,99%	Unprofitable
Scenario 3	-19,040	2,01%	Marginal

Scenario 1 aligns with international benchmarks. ICCT studies report SPPs of 6–12 years for fleet upgrades [21], while EU ESCO projects typically achieve IRRs between 8% and 14% [24]. Dobož's results fall within this range: replacing two outdated vehicles with one efficient unit yields annual savings of approx. 18,560 EUR, GHG reductions of 20.11 tCO₂eq/year, NPV of 27,760 EUR, IRR of 9.78%, and a payback period of 6.89 years. These savings fully cover the investment within a 12-year ESCO contract.

Comparable EU fleet rationalisation projects report NPV values between 40,000 and 80,000 EUR, further confirming the viability and replicability of the proposed model [24].

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To evaluate the robustness of Scenario 1 under varying economic and technical conditions, a sensitivity analysis was conducted. The aim was to test how fluctuations in key input parameters, such as fuel price, maintenance cost, discount rate, and investment cost, affect the financial viability of the proposed ESCO model. Table 6 presents the results of this analysis, demonstrating the range of outcomes for IRR, NPV, and payback period under realistic variations. This approach ensures that the recommended scenario remains resilient and applicable even in the face of market uncertainty.

Table 6. Sensitivity of NPV, IRR, and Payback Period for Scenario 1

Variable Modified	Range Tested	Annual Savings (EUR)	IRR (%)	NPV (EUR)	SPP (years)
Fuel price	1.38–1.52 EUR/lit	16,540 – 14,030	10.1 – 7.8	29,600 – 18,200	7.73 – 9.11
Maintenance cost	±20% (692 – 1,062 EUR/year)	13,757 – 12,503	9.0 – 7.4	22,800 – 16,400	8.1 – 10.2
Discount rate	4% – 8%	fixed at 13,450	—	33,400 – 14,900	—
Investment cost	±10% (115,065 – 140,635 EUR)	fixed at 13,450	10.2 – 7.6	27,300 – 12,100	8.6 – 10.5

The sensitivity analysis confirms that Scenario 1 remains financially viable across all tested variations. The most influential parameters are fuel price and investment cost, both of which significantly affect NPV and IRR. Even under adverse conditions, such as increased fuel price or higher capital cost, the investment maintains a payback period below the ESCO contract duration of 12 years and an IRR above the reference discount rate of 6%.

These results reinforce the robustness of Scenario 1 and its suitability for implementation in transitional urban contexts, where market volatility and budget constraints are common. The methodology also provides a replicable framework for evaluating ESCO-based fleet upgrades under uncertainty.

4 Conclusion

This study analysed the technical, operational, and financial characteristics of the existing vehicle fleet operated by the Communal company "Progres" Dobož, identifying key inefficiencies in fuel consumption, maintenance costs, GHG emissions, and fleet utilization. To address these challenges, three investment scenarios are proposed as a sustainable financing mechanism.

Scenario 1, which involves replacing the two outdated vehicles (MAN and DAF) with one modern, high-capacity unit, emerged as the most favourable and financially viable option. It achieves annual savings of 18,560 EUR, reduction of 20.11

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tCO₂eq/year, and a payback period of 6.89 years. Investment indicators confirm its profitability (NPV = 27,760 EUR; IRR = 9.78%).

These results are consistent with international benchmarks: ESCO projects on the Greek islands achieved ROI within 6.5 years [25], while EU fleet rationalisation initiatives report IRRs between 8% and 14% [24].

On the other hand, Scenario 2 and Scenario 3, although technically feasible, show negative NPV values and IRR below the reference discount rate (6%), rendering them financially unsustainable without external co-financing or extended contract durations.

The findings have several practical implications. First, they demonstrate that ESCO models can be successfully applied to fleet renewal in transitional economies. Second, they highlight the importance of combining technical upgrades with route optimisation to maximise savings and environmental benefits. Based on the technical, environmental, and financial evaluation, Scenario 1 is recommended for implementation through a 12-year ESCO contract.

Limitations of the study include the exclusion of hybrid and electric vehicle alternatives due to infrastructure constraints, and reliance on local cost data, which may vary across municipalities.

Beyond its local relevance, the Dobož case contributes to the broader academic discourse by illustrating how ESCO models can be adapted to fleet renewal in transitional urban contexts. The methodology developed in this study, linking operational diagnostics with investment scenarios, offers a replicable framework for other municipalities in Bosnia and Herzegovina and similar transitional economies seeking to modernise their waste collection systems through energy service contracting. By quantifying technical inefficiencies and framing them within a savings-based investment logic, the study provides a practical extension of ESCO principles into underexplored areas of municipal infrastructure.

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Web Application for Accident Prediction at Road– Railway Crossings Using a Heterogeneous Queuing System Model

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Abstract. This paper presents a web application developed based on a published theoretical model of occurrence maximum crash risk at road–rail crossings. The primary objective of the research is to provide practical software implementation of a model Heterogeneous Queuing System for estimating potential accident risk using various input parameters, as well as to perform the ranking of selected road–rail level crossings according to the risk parameter, from the lowest to the highest level of risk and vice versa. The core of the solution relies on a theoretical foundation designed to quantify the likelihood of collisions under different factors and conditions. To implement the model, based on known data, various traffic conditions, and crossing configurations, the synthetic reliability of road–rail level crossings and the corresponding risk values were calculated, enabling the validation of theoretical assumptions. The web application was developed using Java Spring Boot for the backend, PostgreSQL for data storage, and an Angular-based web interface that provides visualization, sorting, and ranking of the calculated risk values. The presented application demonstrates how established theoretical models can be implemented and analyzed through modern web technologies to support further research and decision-making in road–rail crossing safety assessment.

Keywords: Web application, Java, Angular, PostgreSQL, safety, road-rail crossings.

1 Introduction

Research aimed at improving traffic safety is always useful and welcome, while conflicting traffic flows always represent a potential for the occurrence of accidents and crashes. The absence of the principle of priority distribution in conflicting flows leads to accidents and crashes, and the disregard of this principle leads to chaos. The foundation of this web application is a model based on a heterogeneous concept of conflict between two types of transportation systems. It focuses on the study of traffic safety at road–railway crossings through a mathematical model designed to calculate the maximum risk and determine the reliability of level crossings. The term “risk” refers

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to the frequency rate of accidents and incidents with harmful outcomes (arising from hazardous situations) and the degree of severity of the resulting damage.

In the model, stochastic engineering boundaries of the abstract number of accidents and incidents are defined. The primary method used is queueing theory, specifically the application of the theory of mass service systems. The service system in this case is a road–railway level crossing, where the arrival flow of road and rail vehicles follows a Poisson distribution, while the service time that is, the time required for the system of a single level crossing to serve users follows an exponential distribution, and the queue capacity is infinite (M/M/1 model).

The model [1] is based on a theoretical analysis of the continuous movement of road and rail vehicles within the level crossing service system. Each transportation subsystem possesses a specific safety level, calculated from statistical historical analysis (data on accidents and incidents). The model, as well as the accompanying web application, enables the calculation of the risk level for each level crossing individually.

Within the defined engineering framework, the proportion for estimating and comparing the risk of accidents and incidents at level crossings is located from deterministic to stochastic event boundaries. The computation of this proportion is based on real cases.

The model [1] on which the application is built defines a theoretical minimum risk, representing the first engineering boundary. The maximum theoretical number of accidents or incidents may occur in the absence of priority allocation, i.e., under the theory of chaos. In this way, the second engineering boundary is determined. The real risk lies between the maximum and minimum risk boundaries.

As in all other applications where it is necessary to process a very large amount of data with various parameters within a short period of time, this application also serves as a tool providing a fundamental basis for the implementation of the mentioned model, without the inclusion of additional analytics that could introduce potential errors.

The application enables the ranking of road–railway crossings from the most hazardous to the most reliable, for various levels of crossing protection, across different railway lines and road categories, as well as the systematization of data on theoretical risks for a large number of level crossings. The data obtained through the web application, together with other methods and procedures for researching traffic safety at road–railway crossings (such as surveys on: average sensory and motor abilities of drivers, reliability of signal and safety devices, pavement quality at level crossings, and the severity of recorded accidents/incidents in terms of the number of injured or deceased persons, etc.), provide support to the competent ministry, public railway infrastructure managers, and road authorities in identifying which level crossings with the lowest calculated reliability or highest risk require additional financial investment to improve traffic safety at these locations. An illustrative example of an application that evaluates collision probability based on calculated risk is NASA's Near-Earth Object (NEO) monitoring system. This system determines the probability of Earth's impact with nearby celestial bodies by analyzing orbital parameters, measurement uncertainties, and risk indices. Similar to the presented web application, it relies on

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the quantification of risk as a probabilistic measure of potential collision events, thereby demonstrating the practical applicability of risk-based modeling in complex dynamic systems.

2 Methodology

A level crossing can be conceptualized as a queueing system that serves vehicles from two interacting traffic subsystems: the railway and the roadway. For the purpose of implementation, an existing published model [2] is adopted, and the statistical parameters defined within that model are utilized as input data for the development of the web application. The application incorporates the geometric characteristics of the crossing, kinematic (velocity-related) factors of both road and rail traffic, and the probabilistic properties of a heterogeneous queueing system [3].

2.1 Input parameters

The application utilizes the statistical parameters [2] listed in Table 1. The geometric characteristics of the road–rail crossing are illustrated in Fig. 1.

Table 1. Statistical parameters used in the application.

Symbol	Descriptions
l_c	Critical length of the roadway associated with the level crossing (m)
l_t	Average length of a train (m)
L_c	Critical distance for road vehicles, equal to the average frontal length of the train or the effective width of the crossing danger zone (m)
L_t	Critical distance for railway vehicles, equal to the average frontal width (or blocking length) of the crossing occupied by a train (m)
λ_c	Average daily arrival rate of road vehicles at the level crossing (vehicles per day)
λ_t	Average arrival rate of trains at the level crossing (trains per day)
v_c	Average velocity of road vehicles approaching and passing the level crossing (m/s)
v_t	Average velocity of trains passing the level crossing (m/s)
T	The number of years considered in the accident analysis
n_{real}	Total number of real accidents recorded during the observation period T

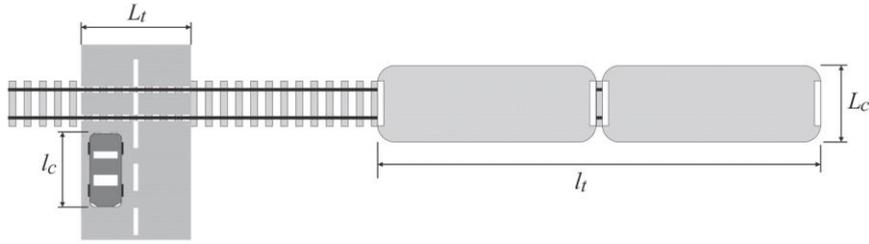


Fig 1. The key geometric parameters.

The number of recorded accidents and incidents can be normalized to the number of road vehicles statistically observed at the level crossing n_{real} during observation period T . This normalization enables calculation of the accident or incident intensity per vehicle, i.e., the probability that a randomly selected vehicle will be involved in an event.

2.2 Traffic Flow Parameter

The real probability of an accident p_{real} (1) is calculated based on the total number of vehicles recorded, n_{real} , during the observation period T . It represents the normalized number of vehicles passing the level crossing per day and per unit length of the critical roadway section. The parameter is defined as follows:

$$p_{real} = \frac{n_{real}}{T \cdot 365 \cdot \lambda_c} \quad (1)$$

This parameter is used in subsequent calculations to determine risk exposure and the probability of accident occurrence per vehicle.

The theoretical probability of an accident p_{theory} (2) is determined based on the number of simulated vehicles n_{theory} obtained from the adopted model [2]:

$$p_{theory} = \frac{n_{theory}}{T \cdot 365 \cdot \lambda_c} \quad (2)$$

The synthetic reliability of operation R (3) expresses the relative deviation between the theoretical and the probability of accident and is defined as the relation:

$$R = \frac{p_{theory} - p_{real}}{p_{theory}} \quad (3)$$

A higher value of R (3) indicates better agreement between the theoretical model and the real system, and consequently greater synthetic reliability of the level crossing. The complementary value of synthetic reliability represents the risk of the level crossing and is given by:

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$$r = R - 1 \quad (4)$$

where:

r – risk of the level crossing,

R – synthetic reliability.

After all parameters are entered, the application computes the synthetic reliability of operation R (3) and the maximum theoretical risk r (4), which serve as key indicators for assessing the safety performance of the level crossing. Based on the calculated levels of synthetic reliability and safety R (3) and risk r (4), a comparison of accident and incident risk was performed between arbitrarily selected level crossings, making it possible to identify the least safe crossing.

3 Development of Web application

Based on the previously described model of the heterogeneous queuing system [3], a web application was developed for the implementation of the proposed methodology for ranking road-railway crossings based on risk.

The application was designed with a focus on modularity, scalability, and ease of use, ensuring efficient calculation and clear visualization of the computed safety indicators.

For the development of the application, it is necessary to create a database where the calculated data will be stored. It is essential to create a backend service that performs the input of parameters for road-railway crossings and, based on the entered data, calculates the risk and reliability. Additionally, it is necessary to provide a user interface where users can enter statistical, probabilistic and geometrical data through forms, as well as ensure a visual representation of the calculated risks and reliability, along with the basic information about the road-railway crossing.

To design the web application, it is necessary to create an information model of the road-railway crossing. The level crossing is represented in the information model as a single entity, designed to support the input of both geometric and probabilistic specifications of the crossing. The entity contains the following attributes: a unique identifier (id), the name of the level crossing, the name of the railway line intersecting at the crossing, and the name of the road crossing the railway. Additional parameters include the protection level (type of safety equipment).

The entity includes the average daily numbers of road vehicles and trains, as well as key geometric and kinematic parameters such as average lengths, critical distances, and speeds of vehicles and trains. It also stores the observation period used for accident analysis and the total number of recorded accidents.

The service-oriented backend represents the core of the solution. It implements the logic of the previously described model and, based on the entered parameters and algorithmic procedures, calculates the values of synthetic risk and the reliability of the given road-railway crossing. Communication between the three main components is achieved through various standardized communication protocols. The web client

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communicates with the application layer using HTTP, while the backend services interact with the database through JDBC-based SQL connections, ensuring interoperability, reliability, and scalability of the overall system.

Finally, it is necessary to enable users to enter parameters through an interactive form, where the entered data are validated and checked before being processed and stored in the database.

4 Testing and results

The architecture of the system is simple yet robust, consisting of three primary components. The PostgreSQL [4] database serves as the data storage layer, responsible for managing all statistical, geometric, and simulation parameters. The server-side application implemented using the Java [5] Spring Boot [6] framework, handles model computation, risk evaluation, and data processing logic. The user interface (Client), developed with the Angular framework [7], provides an intuitive and interactive environment that allows users to input parameters, visualize results, and interpret calculated indicators such as reliability and risk levels.

Communication between the client and server is achieved through RESTful APIs [8], ensuring flexibility and potential integration with external analytical or data-collection systems. The simplified proposed system architecture is illustrated in Fig. 2.

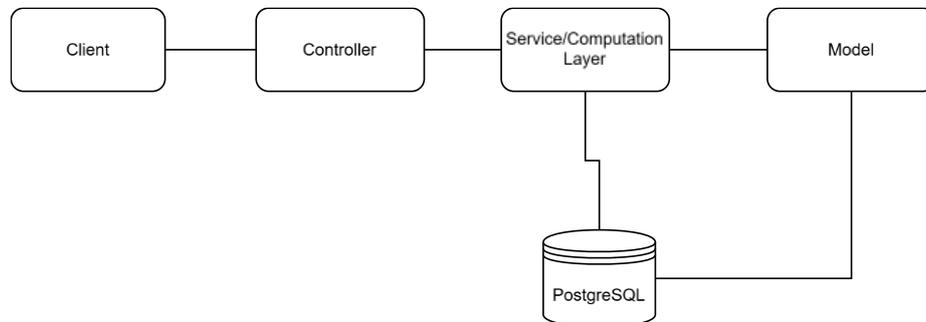


Fig. 2. Proposed simplified architecture of the web application.

A dedicated input form has been developed to facilitate the entry of general information related to each road-railway crossing within the system. The form is designed to ensure structured data collection and consistency of recorded parameters.

Two input forms were developed to enable users to enter the necessary parameters of the road–railway level crossing. After the data are entered, the application performs calculations of the synthetic risk and reliability for the selected road-rail crossing and stores all input parameters in the database. The user interface also allows modification of incorrectly entered parameters, upon which the application recalculates the updated risk and reliability values for the modified crossing.

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In Figures 3 and 4, a simplified version of the input forms developed for the purposes of this study is presented. These forms are used for entering general information about the road-railway crossing, as well as statistical data related to its operation.

Form for Road-Rail Level Crossing

I. General Information

Name of Road-Rail Crossing

Buđanovci

Railway Name and Kilometer Position

Railway no 211. 3+285km

Road Name at Crossing

Local Road L-1

Level Crossing Safety Classification(per Official Gazette RS No. 89/2016)

The level crossing is classified as passive and is equipped with road and rail traffic signs, along with an established sight triangle to ensure adequate visibility

Fig. 3. Input form for general information of a road–railway crossing.

II. Statistical Parameters

<p>Daily Road Vehicle Flow (λ_r) [vehicles/day]</p> <div style="border: 1px solid black; padding: 2px; width: 100%;">807</div>	<p>Daily Train Flow (λ_t) [trains/day]</p> <div style="border: 1px solid black; padding: 2px; width: 100%;">23</div>
<p>Mean Road Vehicle Length (l_r) [m]</p> <div style="border: 1px solid black; padding: 2px; width: 100%;">6.8</div>	<p>Critical Distance (Road) (L_r) [m]</p> <div style="border: 1px solid black; padding: 2px; width: 100%;">2.8</div>
<p>Mean Road Vehicle Speed (v_r) [km/h]</p> <div style="border: 1px solid black; padding: 2px; width: 100%;">32</div>	<p>Mean Train Length (l_t) [m]</p> <div style="border: 1px solid black; padding: 2px; width: 100%;">350</div>
<p>Critical Distance (Train) (L_t) [m]</p> <div style="border: 1px solid black; padding: 2px; width: 100%;">5</div>	<p>Mean Train Speed (v_t) [km/h]</p> <div style="border: 1px solid black; padding: 2px; width: 100%;">70</div>
<p>Observation Period (T) [years]</p> <div style="border: 1px solid black; padding: 2px; width: 100%;">11</div>	<p>Total Accidents/Incidents (n_{real})</p> <div style="border: 1px solid black; padding: 2px; width: 100%;">6</div>

Fig. 4. Input form for statistical parameters of a road–railway crossing.

The user interface (UI) of the web application was developed using the AngularJS framework and incorporates a Material Design based graphical interface [9]. The application also supports pagination, enabling efficient management and visualization of a large number of recorded level crossings. Users can enter and view data for multiple level crossings, with sorting options available according to the calculated syn-

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thetic reliability and risk. However, the most significant parameters for analysis are the risk and synthetic reliability, which serve as the primary indicators for evaluating theoretical safety of each crossing.

The graphical interface of the developed web application, along with the representative results obtained from testing on selected level crossings in Serbia Railway Infrastructure, is shown in Fig. 5.

<i>Name of the Railway-Road Crossing</i>	<i>Security Level</i>	<i>Reliability</i> ↓	<i>Risk</i> ↑
Buđanovci	The level crossing is classified as passive and is equipped with road and rail traffic signs, along with an established sight triangle to ensure adequate visibility.	0.999617130414	0.000382869586
Brasina	The level crossing is passive and is secured by traffic signs on both the road and railway, along with a designated visibility zone (sight triangle)	0.999839082554	0.000160917446
Kraljevci	The level crossing is active and secured with automatic half-barriers, light traffic signals, and road traffic signs.	0.999908403544	0.000091596456
Štitar	The level crossing is active and secured with barriers and traffic signs on the road. The level crossing is mechanical and equipped with wiring.	0.999942933756	0.000057066244
Platičevo	The level crossing is active and protected by half-barriers, as well as visual and audible warning signals. The operation of the level crossing is controlled via the station.	0.999986629355	0.000013370645

Fig. 5. User interface of the web application and example of evaluated crossings in Serbia.

Based on the obtained results shown in Fig. 5, the road-railway crossings were ranked from the least safe, with the highest level of risk, to the safest, with the lowest level of risk.

The web application has been fully implemented following the proposed architecture. For the purpose of transparency and reproducibility, the complete source code and deployment instructions are available in a public GitHub [10] repository.

The repository provides access to the application’s backend Spring Boot [6], frontend Angular [7], and database configuration PostgreSQL [4], allowing other researchers to reproduce or extend the presented results

5 Conclusion and Future Work

All results presented through the user interface were validated against an already published model, confirming their correctness. The developed web application, therefore, represents an implementation of the proposed heterogeneous queueing system model. Furthermore, the application allows the input of data not only for Serbian road–railway crossings, but also for any crossing worldwide, enabling the calculation of corresponding synthetic reliability and risk indicators.

The web application can also be applied in road traffic analysis for a larger number of unsignalized intersections, serving as a tool to assist in determining which of the less reliable or high-risk intersections should be prioritized for financial investment in traffic signalization, and similar measures.

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Considering the always limited financial resources and the unlimited desire to improve the level of traffic safety, this represents a significant contribution.

This work represents the implementation of an existing model, with the primary objective of enhancing safety at road–railway crossings and reducing accidents.

Further improvements may be achieved through the integration of AI and Tensor-Flow-based predictive models [11], as well as OCR-based image [12] analysis, to support intelligent risk detection and proactive safety enhancement.

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