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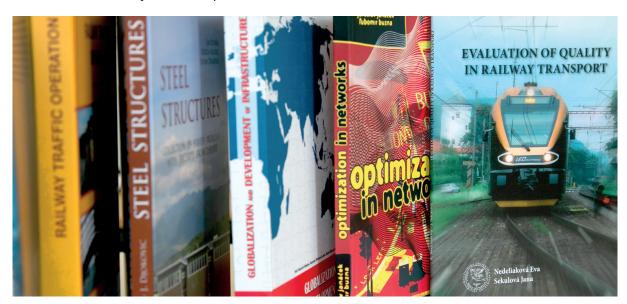


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RELATIONSHIP BETWEEN THE TRANSPORT PERFORMANCE AND FINANCIAL COVERAGE IN URBAN PUBLIC TRANSPORT IN THE CZECH REPUBLIC

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Resume

The research presented aimed to compare the transportation performance, as measured by vehicle kilometers, to the operating costs incurred by thirteen transport companies in the Czech Republic from 2010 to 2019. This period was chosen to ensure that our research is not affected by the Covid-19 pandemic. The financial coverage of operating costs includes revenues from fares and compensations from city budgets. We utilized data from the annual reports of The Association of Transport Companies of the Czech Republic. Based on the obtained data, we confirmed a positive relationship between the city's population, the extent of transportation performance, and consequently, the total operating costs.

This research examined the conflict between the passenger and urban public transport, supported by the European Union's promotion of sustainable urban mobility plans in regional cities.

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1 Introduction

A transport journey is defined as the travel from a point of origin, such as a residence, to a destination, like a workplace. In this context, the specific modes of transportation a person utilizes are not crucial. A transport journey is invariably linked with the use of someform of transportation. Individuals cover the distances between their points of departure and destinations by walking, cycling, taking the bus, trolleybus, tram, train, metro, passenger car, or motorcycle. The choice of transportation mode is influenced by various factors, including distance, age, personal preferences, economic and social status, the purpose of the journey, and travel costs. The indicator that characterizes the utilization of different transportation modes in people's journeys within the city on a typical working day is the transport division of labour, commonly known as modal split, [1].

The data presented in Table 1 highlight a significant proportion of public transport and passenger cars, dominating transport journeys exceeding two kilometers. For instance, according to Mobility and local passenger

transport [8], walking constitutes 54% of journeys covering distances up to two kilometers, while urban public transport and individual car transport are the primary modes of urban mobility for longer distances. The shares of urban public transport and individual car transport in the modal split are both 39% for distances ranging from three to five kilometers. Further, for distances spanning five to ten kilometers, urban public transport accounts for 34%, whereas individual car transport represents 54% of the modal split. The study conducted by Kubik et al. [13] confirmed a notable correlation between the choice of means of transport and journey duration.

In Brno [3], the modal split for individual car transport and public transport was 24.6% and 64.7%, respectively, in 2010. These figures changed to 31.7% and 57% in 2012, 37% and 52% in 2014, and 31% and 53% in 2019. In Zlin [11], the modal split in 2001 was 76% for individual car transport and 24% for urban public transport. By 2006, this shifted to 41% and 59%, followed by 38% and 62% in 2010, and 34% and 66% in 2015.

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Table 1 Transport division of labour (data in %)

	Year	Walking	Cycling	Public transport	Car	Other means of transport
Brno [2-3]	2017	18	1	43	38	
Ostrava [4]	2014		2	30	68	
Pilsen [5]	2014	7	3	51	39	
Olomouc [6]	2018	34	6	27	32	1
Liberec and Jablonec [7]	2017	18		32	47	3
Hradec Kralove [8]	2015	39	18	20	22	1
Pardubice [9]		31	14	22	33	
Ceske Budejovice [10]	2016	22	2	27	49	
Zlin [11]	2015	25	2	24	45	4
Jihlava [12]	2015	35	7	28	30	

According to the survey "Czechia in Motion" [14], a national study of traffic behaviour from 2017 to 2019, cities with populations between 50,000 and 100,000 inhabitants report a 17.8% share of urban public transport and a 33% share of individual car transport, with an average journey length of 8.7 kilometers. In cities with over 100,000 inhabitants, the modal split is 36% for urban public transport and 27.3% for individual car transport, with an average journey length of 8.35 kilometers.

The use of cars in passenger transport has significant adverse effects on the quality of life in cities, including air pollution with CO_2 emissions and other pollutants, noise and vibration, escalating dust levels, higher accident rates, traffic congestions, land appropriation, and land fragmentation, [15-16].

To address these challenges, the creation and implementation of sustainable urban mobility plans are crucial for improving the current state of urban passenger transport. These plans not only aim to solve internal transport issues for residents and visitors but also focus on the transportation of goods within the city and its environs. Their overarching goal is to establish conditions conducive to sustainable development and enhance the overall quality of urban life, [17-18].

The strategic objective of sustainable urban mobility plans for all cities is to progressively decrease the share of individual car transport and concurrently increase the share of urban public transport in the modal split. For instance, the City of Brno [2] has set ambitious targets, planning to achieve a 30% share of individual car transport and a 54% share of public transport by 2030. The vision for 2050 is even more ambitious, targeting a 56% share for public transport and a 20% share for individual car transport.

Similarly, the city of Ceske Budejovice [10] is directing its urban mobility strategy within the modal split, aiming for a 46% share of individual car transport in 2025, which is expected to further decrease to 41% by 2035. Simultaneously, the city anticipates a rise in the share of urban public transport to 30% by 2025 and 33% by 2035.

Inventions, such as the car, have profound implications for solving economic, political, socio-cultural, and psychological challenges. The car, deemed a pivotal technology for everyday mobility, symbolizes speed and freedom of movement [19]. As the use of urban public transport for daily journeys becomes more prevalent, understanding the motivations of individuals who opt for individual car transport becomes imperative. Simultaneously, there is a need to explore methods and tools to shift the decision-making of these individuals towards a greater reliance on eco-friendly modes of transportation.

Public transport requires public subsidies to be affordable and to exploit its full potential in congestion alleviation [20]. Our calculations suggest that increasing the share of urban public transport in the modal split by 3%, with the current number of transport journeys per person on a typical working day, would necessitate reinforcing the existing infrastructure of urban public transport (including drivers and vehicles) by 11% to 15%. This enhancement would inevitably lead to a significant rise in operating costs. Coupled with the current ticket pricing structure, time coupons, and an increasing number of fare-free passengers, there would be a heightened demand for external funding to cover the costs of urban public transport.

Urban public transport, being an emblematic example of eco-friendly transportation, excels in mass passenger transport and extensively utilizes electric vehicles, such as trolleybuses, trams, electric buses, and compressed natural gas (CNG) as fuel for city buses [21]. It serves as a viable alternative to individual car transport. Strengthening the role of urban public transport in urban mobility requires more than just increasing its performance and implementing various improvements. This intention necessitates a combination with environmentally responsible transport behaviour among urban passengers. Future expectations, regarding a greater role for urban public transport in urban mobility, must grapple with the existing capacity constraints, rising operational costs, and the escalating

Table 2 The potential and performance of transport companies

perfor City mil. c kilom		sport nance in vehicle cres per ar	in mil. of	performance person per ear		of public t vehicles		of public t drivers	Length of lines in kilometres	
	2010	2019	2010	2019	2010	2019	2011	2019	2011	2019
Prague ¹⁾	166.2	167.6	1,343.7	1,656.2	2,255	1,949	4,175	4,280		
Brno	38.3	39.4	353.6	361.7	764	791	1,398	1,396	952	1,069
Ostrava	34.1	31.8	102.6	96.1	647	630	994	1,059	1,068	1,069
Pilsen	15.0	15.5	100.9	125.0	326	359	565	576	487	593
Olomouc	6.2	6.7	57.9	57.0	136	146	240	249	302	331
Liberec and Jablonec	8.7	7.8	35.8	42.0	168	154	248	217	619	444
Usti nad Labem	7.2	6.9	51.3	39.6	145	175	255	241	487	424
Hradec Kralove	6.3	6.0	37.9	38.0	133	130	234	228	314	338
Ceske Budejovice	5.7	5.9	40.2	47.4	138	153	199	227	217	208
Pardubice	5.7	5.8	27.2	33.2	130	144	196	206	588	596
Zlin and Otrokovice	4.8	5.0	35.3	33.7	93	95	187	178	235	288
Jihlava	2.8	3.0	13.7	16.0	61	69	97	101	106	158
Karlovy Vary	2.7	2.5	14.4	15.7	62	92	125	111	286	424

1) Only tram and bus

need for compensations from city budgets to offset operating losses.

In the subsequent section of this paper is addressed the issue of capacities and performances within the urban public transport. Following this, the examination of the operating costs of transport performance from 2010 to 2019 was conducted. Instead of operating costs, the study utilizes the category of financial coverage, which encompasses revenues generated from transporting individuals and compensations (Decree 296/2010 Coll. [22]). This choice is made due to the fact that certain urban public transport operators are involved in additional business activities, and their operating costs include expenses related to these diverse endeavours. The data pertaining to financial coverage provide the most accurate insight into the costs associated with operating urban public transport in individual cities. Transport companies responsible for urban public transport operations in the Czech Republic are founded and owned by cities.

Our focus was on evaluating the level and progression of capacity and transport performance within urban public transport. This analysis serves as the foundation for assessing the current status of transport companies and the reported efficacy of their management. The analytical approach is based on data publicly disclosed by the Association of Transport Companies (Annual Reports 2010 - 2019, [23]).

The capacity analysis relies on data concerning the number of public transport vehicles, the count of drivers, and the length of routes. Information on the number of vehicles deployed during the peak hours was also taken into account. In all the instances, these are the primary data points that significantly reflect the operational foundations of individual companies. The assessment of urban public transport performance is conducted based on transport performance, specifically the vehicle kilometers travelled. Table 2 also includes the commonly used indicator of transported persons, derived by recalculating sold tickets and time coupons. The transported person is considered synonymous with one journey in a means of transport. In our methodology, transport per transfer ticket is calculated as 1.5 transported persons, representing one transport journey within the context of the transport division of labour - the transfer of a person from the place of departure to the destination. It is important to note that this indicator includes free passengers, such as children under five years and seniors aged 70+, traveling based on an identity card. Some cities may also provide free travel to other individuals. Due to discrepancies in carrier-specific data, we do not consider this information suitable for our analysis.

In 2019, transport performance, when compared to the base year 2010, increased by more than 5% only in the cities of Olomouc (8.2%) and Jihlava (7.5%). Six cities exhibit growth of up to 5%, while five cities experience a decrease in transport performance of up to 10%. An examination of the capacities of transport companies reveals that Ceske Budejovice increased

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both the number of vehicles (by 11%) and the number of drivers (by 14 %). Other cities, such as Olomouc, Pilsen, Pardubice, and Jihlava, demonstrated changes in monitored parameters ranging from 5% to 10%. Prague, Brno, Hradec Kralove, and Zlin's transport companies showed changes in both parameters from -5% to 5%. In some cases, an increase in one parameter coincided with a decrease in the other. Notable instances include Ostrava, where the number of drivers increased (7 %), while the number of vehicles decreased (-3 %), and Usti nad Labem, where the number of drivers decreased (-5%) and the number of vehicles increased (21 %). Karlovy Vary's transport company experienced a decrease in the number of drivers (-11%) and an increase in the number of vehicles (48 %). Lastly, Liberec's transport company reported decreases in both drivers (-12%) and vehicles (-8%).

Based on the provided data and more in-depth analyses, it can be concluded that both the capacity and transport performance of urban public transport remained relatively unchanged from 2010 to 2019, and these patterns appear to be enduring. Notable alterations include the replacement of vehicles, the introduction of ecological buses powered by compressed natural gas (CNG) and electric buses, and an increasing share of low-floor vehicles across all the types of transportation means.

In 2011, transport companies operated 5,491 vehicles, consisting of 2,915 buses (none with CNG), 709 trolleybuses, and 1,867 trams. Of these, 2,521 were low-floor vehicles. By 2019, the reported number of vehicles had decreased slightly to 5,310, including 2,890 buses (603 with CNG), 46 electric buses, 742 trolleybuses, and 1,678 trams. Notably, 4,229 vehicles were now low-floor.

The number of drivers employed by transport companies remained relatively stable, with 9,763 drivers in 2010 and 9,785 drivers in 2019, [23].

Despite the efforts to enhance the urban public transport, the stagnant transport performance is accompanied by a decline in its share in the modal split. Progress in urban public transport is linked to the establishment and operation of integrated transport systems in broader territories, the implementation of transport telematics, the digitization of timetables and check-in systems, the construction of public transport terminals, and the gradual transition to greener modes of urban public transport. While these changes contribute to the attractiveness of urban public transport, they seem insufficient to significantly alter the travel behaviour of the residents in individual cities.

2 The aim of this research

A consistent rise in operating costs is observed in tandem with the transport performance of urban public transport during the period from 2010 to 2019. This increase is attributed to the upward trend in personnel costs, fuel and energy expenses, as well as repair and maintenance costs. The coverage of costs for operating urban public transport relies on two main sources. The first source comprises revenues generated from fares within urban public transport. The second source involves compensations from the city budgets allocated for the operation of urban public transport. To meet escalating costs, compensations must continuously increase, particularly in response to the stagnation or decline in revenues from urban public transport.

Revenues from urban public transport in the analyzed set of cities varied from 75% to 113% during these years. In contrast, compensations within the same period exhibited an increase from $108\,\%$ to $208\,\%$. Compensations represent a significant expenditure item in the city budgets, significantly burdening them. In 2019, compensations for urban public transport activities accounted for 7.5% to 25.5% of the cities' operating expenses. It can be observed that the transport performance, denoted by the number of vehicle kilometers traveled, increases with the growth of the city's population. Consequently, both total costs and unit costs, attributed to transport performance, experience an uptick. This scenario leads to an increase in the shares of compensations required to cover the expenses associated with the transport performance.

In this paper, the level and development of a relationship between the transport performance and its financial coverage have been examined in depth. Additionally, it is possible to explore similar relationships between the transport performance and individual components of financial coverage, namely revenues from fares and compensations from city budgets.

This research has soughtto model the relationship betweenthetransport performance and its financial coverage, serving as a foundation for projecting the anticipated development of urban public transport.

Q1. To ascertain a statistically significant relationship between the distance traveled in vehicle kilometers and the overall financial coverage of transport performance from 2010 to 2019 for a group of transport companies in regional cities and Prague.

Q2. If a correlation is identified, the objective is to determine the developmental trajectory for individual transport companies during the specified period.

3 Used data and analyses

To fulfill the research objectives, we employed the method of quantitative research on the secondary data. The data was sourced from the annual reports of the Association of Transport Companies of the Czech Republic spanning the years 2010 to 2019. Our analysis encompassed thirteen cities, and a total of 130 items were at our disposal. However, one record was incomplete and consequently excluded from the analysis.

The data were summarized and scrutinized for

extreme and missing values. The following variables were employed for the data analysis:

- City
- Year
- Population
- Vehicle kilometres (veh_km)
- · Revenues from urban public transport
- Compensation
- Financial coverage.

We assessed the variables for data normality using the Shapiro-Wilk test. Considering that variables, like vehicle kilometres, revenues from urban public transport, compensations, and financial coverage, can attain high values, potentially including extreme values, a logarithmic transformation of this data was carried out. Subsequently, we explored the dependencies between the variables. The regression method, employing a mixed-effect model, was applied to verify the research hypotheses. All the statistical calculations were performed using the statistical software R 3.6.1.

3.1 Model

For the specified research objectives, we constructed a mixed-effects model:

$$\begin{split} log_{e}(costs_{i,j}) &= \beta_{0} + \beta_{1} \log_{e}(veh_km_{i,j}) + b_{1}t_{i} + \\ &+ b_{2} \log_{e}(veh_km_{i}) + u_{i,j}. \end{split} \tag{1}$$

where $log_e(costs_{i,j})$ is the logarithmic transformation of the data variable, β_o is the fixed effect intercept, β_1 $log_e(veh_km_{i,j})$ is the fixed effect slope of the tax base, b_It_i is the random-effect of the year, $b_2\ log_e(veh_km_i)$ is the random-effect slope of vehicle kilometres, $u_{i,j}$ is

the error term. Cities were also modelled based on both vehicle kilometres and time, allowing for the hypothesis that the cost per vehicle kilometre may vary across different cities. The Akaike Information Criterion (AIC) and the ANOVA were utilized to assess the model's appropriateness.

4 Results

This section outlines the outcomes of the statistical analysis. Initially, we conducted descriptive statistics to summarize the data. Subsequently, we formulated and scrutinized the statistical model.

In Table 3, one could observe the averages for individual data items, particularly in terms of revenues, compensations, and financial coverage. Additionally, the skewness and kurtosis of individual data itemscould be noted. The potential presence of extreme values in skewness and kurtosis prompted the logarithmic transformation of the variables employed.

In Figure 1, a clear linear dependence of the cost per vehicle kilometre in individual cities is evident. A logarithmic transformation of the axes was applied, considering cities like Prague, which exhibit both higher costs and more vehicle kilometres, compared to other cities. Notably, the distinct clusters, formed by individual cities are observable in this chart. Prague can be viewed as an extreme case in comparison to cities such as Brno or Ostrava.

Table 4 presents the computation of the coefficients for the examined regression model. Notably, if a city had only one vehicle kilometre, the financial coverage would average at 0.02 CZK (0.00084 EUR). Additionally, the regression model elucidates that a 1% increase in

Table 3 Descriptive statistics of analysed data

	n	mean	SD	median	min	max	skew	kurtosis	SE
year	129	2014.47	2.87	2014	2010	2019	0.01	-1.24	0.25
population	129	225727.0	316903.8	94559	4853	131531	2.7	6.09	27901.8
veh_km	129	23268.29	42902.21	6242	2431	169830	2.8	6.49	3777.33
revenues	129	571.91	1185.78	142	47	4717	2.92	6.98	104.4
compensation	129	1350.51	3238.58	216	56	14668	3.11	8.22	285.14
fincoverage	129	1922.42	4416.12	372	105	19362	3.05	7.78	388.82

Table 4 Calculation of the model coefficients

Model	AIC=310.95				
Fixed effects	Value	Std. Error	DF	t-value	p-value
(Intercept)	-3.908	0.3684	115	-10.61	0
log(veh_km)	1.097	0.0407	115	26.93	0
Random effects	Std. Dev				
t	0.0235				
log(veh_km)	0.0164				

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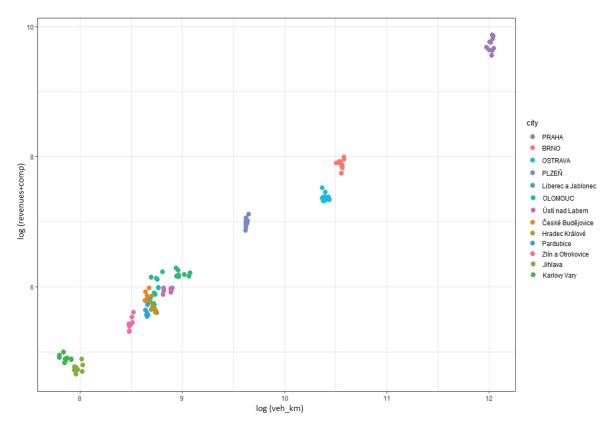


Figure 1 Dependency of financial coverage per vehicle kilometre in individual cities

Table 5 Random effect coefficients of the model

	t	log(veh_km)
Brno	0.0103	0.0153
Ceske Budejovice	0.0151	0.0193
Hradec Kralove	0.0265	-0.0138
Jihlava	0.0037	-0.0147
Karlovy Vary	0.0201	0.0092
Liberec and Jablonec	0.0318	0.0105
Olomouc	0.0437	0.0029
Ostrava	0.0182	-0.0214
Pardubice	0.0126	-0.0074
Pilsen	0.02	0.0226
Praha	0.0318	0.022
Usti nad Labem	0.0147	0.0067
Zlin and Otrokovice	0.0198	-0.0106

vehicle kilometres corresponds to an average increment of 1.1% in financial coverage.

Table 5 reveals that allthecities experienced an increase in their financial coverage over the given period. Particularly, the cities of Olomouc, Liberec, and Prague exhibit the highest growth over time. If the vehicle kilometres remained constant, this growth would average around 4% per year. Notably, the development in Brno, the second-largest city in the Czech Republic, is somewhat surprising, showing a growth of approximately 1% per year over time.

Concerning the financial coverage of vehicle kilometres for specific cities, fluctuations are evident. Some cities, such as Hradec Kralove, Pardubice, Zlin, Otrokovice, Jihlava, and Ostrava, exhibit financial coverage per vehicle kilometre that is, on average, lower than the overall average for the Czech Republic. Contrarily, Pilsen and Prague boast the highest financial coverage per vehicle kilometre, a surprising observation given the size of these two cities. Conversely, Ostrava reports the lowest financial coverage per vehicle kilometre.

5 Discussion

The urban public transport stands as an indispensable mode of mobility within the urban areas. The Transport Yearbooks of the Czech Republic from 1998 to 2013 [24] indicated a 75% share for urban public transport and a 25% share for individual car transport in the all-day transport division of labor in the early 1990s. By 1998, this share had shifted to 60% for urban public transport and 40% for individual car transport. A similar trend is evident in Poland, where the motorization index, i.e., the number of private cars per 1000 inhabitants rose by approximately 125% in 2017 compared to 2000 [25]. According to the national survey, "Czechia in Motion" [14] conducted from 2017 to 2019, cities with populations ranging from 50,000 to 100,000 inhabitants reported a 17.8% proportion of urban public transport and a 33% share of individual car transport in the transport division of labor. Cities with populations exceeding 100,000 inhabitants exhibited a 36% share for urban public transport and a 27.3% share for individual car transport. This trend, suggesting that public transport usage rises with resident population, was supported by Santos et al., [26].

Sustainable urban development necessitates a gradual reduction in individual car transport and an emphasis on environmentally friendly modes of transport, such as urban public transport. The operation of urban public transport, being a public service, is linked to substantial operating costs, covered by revenues from urban public transport fares and compensations from city budgets. In 2019, compensations constituted 51% to 75% of the financial coverage of operating costs. These operating costs persistently rise, while revenues from fares continue to decline. Such a trend results in an escalated demand for compensations from city budgets.

This reality, coupled with the aim to strengthen the role of urban public transport in urban mobility, is inadequately addressed. Operating costs in all the cities reflect funds expended on fuel and energy consumption, repair and maintenance, and personnel costs. Revenues from passenger transport are disconnected from actual expenses, lacking precise market content. The pricing policies of tickets and time coupons, as well as preferential travel opportunities for specific groups, are beyond the control of service providers, falling under the jurisdiction of local councils. These councils, comprised of representatives who are also members of the control bodies of carriers, approve the compensation requirements of transport companies. In this role, driven by tight city budgets, there is a constant pressure to reduce and economize the operating costs. These circumstances underscore a fundamental contradiction between the aspiration to fortify the role of urban public transport in urban mobility and the practicality of incessantly escalating demands for compensations from the city budgets.

Our intention was to compare the intercity

transport performance and operating costs incurred in individual years from 2010 to 2019, to predict the further development of urban public transport in the Czech Republic. The acquired data demonstrate a direct correlation between the number of inhabitants of a city, the extent of transport performance, and the absolute amount of operating costs. Research by Ruiz-Montanez [27] supports this, indicating that as a city expands in the number of boroughs, the economic funds required to support the public transport must increase in a greater proportion compared to the growth of boroughs. On the other hand, regarding the cost-effectiveness, the key factor is density. Systems with high levels of usage density tend to be more cost-efficient [28], with cities boasting greater population densities generally proving more efficient than the smaller cities [29]. In addition Borjesson et al. [30] concluded that the appropriate level of subsidies for the bus services varies significantly between congested corridors in large cities and smaller cities. This variation primarily arises from the differing impacts of crowding costs, compared to waiting and schedule delays.

The financial coverage per vehicle kilometre in 2019 displays varying levels among studied cities. Prague exhibited a financial coverage of CZK 115.5 (EUR 4.67) per vehicle kilometre. Cities, such as Brno, Liberec, Jablonec, Pilsen, and Olomouc, reported values ranging from CZK 75 to 80 (EUR 3.15 to 3.35), while Ceske Budejovice reported CZK 67.5 (EUR 2.83). Other cities reported financial coverage in the range of CZK 53 to 58 (EUR 2.22 to 2.44), except for Jihlava, which reported a value of CZK 44 (EUR 1.84) per vehicle kilometre.

In the analysis of the dataset, provided by large urban transport companies for the period 2010 to 2019, focusing on stagnant transport performance, we quantified the average annual rate of change in operating costs for this entire set of cities. Subsequently, we calculated the change deviations of individual carriers from the average level.

We have confirmed a statistically significant relationship between the transport performance and its financial coverage for the examined group of carriers. The average year-on-year change in financial coverage per vehicle kilometre was found to be 1.1%. Subsequently, we calculated the average deviation of the development of their costs from the aggregate year-on-year change for individual cities.

We intentionally used the data from before the Covid-19 pandemic. Covid-19 has had a major impact on public transport systems worldwide, necessitating public financial support to maintain services amid drastically reduced ridership and the need for social distancing [31]. In a recent review by Hörcher and Tirachini [20], it is noted, that the pandemic has highlighted the critical need for efficient resource allocation and demand management in public transport. Despite the unprecedented challenges posed by Covid-19, the public transport remains essential in densely populated urban

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areas due to the spatial inefficiency of alternative modes of transportation. We believe that our results remain relevant and up to date.

6 Conclusion

This researchaimed to evaluate the relationship between the financial coverage of costs associated with the transport performance of urban public transport, focusing on a dataset that includes the capital city of Prague and twelve regional cities in the Czech Republic, with an emphasis on anticipating future developments. The research covered the period from 2010 to 2019.

A statistically significant relationship between transport performance and financial coverage for the examined carriers was confirmed. The average year-on-year change in financial coverage per vehicle kilometre was 1.1%.

Analysis of statistical data from transport companies, encompassing metrics, such as vehicle kilometres traveled, the number of drivers, the quantity of vehicles, and their utilization during therush hour traffic, revealed fluctuating and essentially stagnant transport performance of urban public transport in individual cities throughout this period.

The sustainability of such transport performance is closely linked to escalating operating costs. Those costs are partially offset by revenues from fares, constituting a share that ranged from 23.8% to 43.1% of the total financial coverage in 2019. The second significant component of financial coverage is comprised of compensations from the budgets of individual cities. The perpetual increase in operating costs results in heightened demands for financial compensations from city budgets. This trend is primarily attributed to the stagnation of fare revenues, with some cities even experiencing a steady decline. Such a development is intricately connected to the stagnation of prices for urban transport and the growing number of individuals being transported free of charge.

One of the strengths of our research is the comprehensive dataset spanning a decade, which provides a robust basis for analyzing trends in financial coverage across multiple cities. The use of regression analysis further strengthened our conclusions by identifying significant relationships between the vehicle kilometres and financial coverage.

However, our study has some limitations. The financial coverage data may be influenced by city-specific factors, such as local economic conditions, political decisions, and differing accounting practices among transport companies. Additionally, the focus on financial coverage per vehicle kilometre does not account for other important factors, like service quality and user satisfaction.

In conclusion, our study provides valuable insights into the financial dynamics of urban public transport. While the findings show some trends in financial coverage of urban public transport, they also highlight the need for ongoing efforts to improve efficiency and sustainability. Future research could benefit from a more detailed analysis of the factors influencing the financial coverage, including qualitative aspects like service quality. Addressing the identified limitations through future research and providing a holistic understanding of the demand side of urban mobility will be crucial in developing more comprehensive strategies for urban mobility.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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THE EFFECTIVENESS OF PUBLIC INTERVENTION IN THE REGIONAL AND URBAN MOBILITY BASED ON THE EXAMPLES OF POLAND AND SLOVAKIA

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Resume

Ensuring the sustainable development of urban and regional public transport systems is one of the major challenges faced by public authorities. This article examines changes over more than two decades in the two key synthetic measures for balancing transport: urban and regional public transport and individual motorization in two neighbouring EU countries, Poland, and Slovakia. The findings reveal the low effectiveness of transport sustainability policies, particularly in Poland, as evidenced by a decline in public transport usage and a significant increase in the number of private cars. Comparing the two countries Slovakia's policies proved more effective, showing lower increases in the number of private vehicles and only a slight decline in the volume of urban public transport.

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1 Introduction

The ensuring of sustainable development of cities and urban transport, mobility, availability of services, and reduction of burdens of negative effects resulting from transport and related inter alia to the use of liquid fuels, emission of harmful compounds and CO₂ are included in the objectives of the transport policies at a level of cities and countries. Because of the share of population, living and staying in cities in the total population, increasing over years, and thereby an increasing importance of cities, despite the subsidiarity rule binding in the European Union, also at the level of this group policies and other documents are adopted, which cover the issues of cities and the urban transport. The urban transport, including the urban public transport, became the object of public intervention; it is one of more important areas in the activities of cities and also one of allocations of the EU funds spent on national and regional levels. The services of urban public transport in many cities worldwide, including Poland and Slovakia, are not provided based on market rules; the public sector decides about the scope, standard, and quality

parameters of the service, prices and groups of persons entitled to discounted fares, which next results in the necessity of financing this activity from the public funds. Substantial amounts are spent on the public financing; the co-financing is provided for the current activities - the provision of urban public transport services, as well as on the investments in the form of vehicles purchase, the construction of various infrastructure types. In addition, the implementation of IT systems, for example, on the electronic tickets or other solutions generally improving the quality and attractiveness of services. The co-financing originates not only from city budgets, but from other levels and from various types of funds, as well, for example, related to the environmental protection, the support for disabled persons, which improve the accessibility and safety, and also, what is important, from the EU funds. The funds spending is directed in various ways, in particular the proportion between the investment projects, e.g., the construction of new stations, transfer car parks, tram or trolleybus lines, and actions directed towards the modernisation, improvement in the provided services, safety, and their attractiveness. The investments, in particular the

tangible ones, are more visible; it is easier to show the physical effect, they are looking well in the media and hence one can assume with certain probability that they enjoy a greater interest than those, in which the existing solutions are improved, and which, for example, consist in the organisational changes or small modernisations. Anyhow, in many statements related to the use of public funds, especially the EU funds, their absorption for any price is unfortunately emphasised, and not their effective and efficient use [1]. The support for the urban public transport comprises not only financing; it is also possible to mention numerous detailed pieces of legislation and administrative solutions, which create special conditions for this sector. The regulation, which provides a possibility of direct contracting, without a previous open competitive procedure, is an example. Other solutions, supporting the urban public transport, include the closing of city centres for the private cars traffic, the construction of transfer car parks, and paid parking zones.

As a result, the public intervention in the urban mobility consists of many actions; in this context a question arises, related to the effectiveness of the public intervention, in particular, which actions are the most effective under given conditions, how it is possible to compare the incurred expenditures to the obtained effects and benefits. The question about the effectiveness of actions is legitimate, especially in the context of the policy of limiting individual motorisation carried out in many countries for decades, at simultaneous support for the public transport. The available data show that in numerous cases this objective has not been accomplished, even a trend can be observed, not only of an increase in the number of private cars, as well as in manufacturing and sales of SUV type cars, featuring heavier weights and larger front surfaces (greater air resistance) than the classical saloons, which results in higher energy consumption, while the offered engine powers and maximum speeds, in the context of speed limits applied in cities and outside them, can be very seldom used.

In a similar way, albeit within a smaller scope, the public intervention is applied in the public transport of regional reach. In addition, in this case, its legitimacy results from premises almost similar to those in cities, in particular to ensure accessibility and to reduce the private cars traffic.

2 Materials and methods

The paper aims to present changes over a twodecade period in individual motorisation and the volume of transport in the urban, regional and national public bus transport in Poland and in Slovakia. Both member states of the European Union, in which the same regulations are in force - treaties, regulations, directives, and policies determined at the European Union level, including transport, as well as other documents. Moreover, there are similar rules of using the EU funds for the solutions in the field of creating sustainable transport. Additionally, the effectiveness of sustainable transport policies were assessed to determine the potential for higher effectiveness in promoting public transport and limiting individual motorization.

The census data were used, made available mostly by the national statistical offices of these states. In particular, there were different approaches to the regional bus transport; in Poland the financing and intervention of public authorities was substantially limited, in Slovakia this approach was more balanced. The effects of diversified approach were assessed, comparing the volumes of transport by the urban public transport, suburban bus transport, as well as an increase over years in the number of private cars, and thereby the motorisation index.

The study is based on the critical literature review and comparative analysis. A literature review as a research method allows to synthesise the research result to show evidence on a meta-level [2]. Comparative analysis using qualitative and quantitative data allows for analysing different dimensions of complex transport systems to derive policy-relevant conclusions. The research procedure contains two steps. The first one aimed at the qualitative analysis of each country's legislation on the organisation of urban and regional transport. In the second step, the analysis of quantitative data was conducted to examine changes in the modal split in the urban and regional transport. Comparative studies may be used, which become, apart from induction and deduction, a large group of research methods of universal application. They may be used in various contexts, where the basic objectives comprise the identification of best practices or action models, the learning and understanding of the influence of context factors on behaviour and results of compared units, or the drawing of conclusions in particular about general rules of action, under specified external conditions. The comparative studies also allow to reach conclusions based on the experience of others, which to some extent allows to avoid making errors, and also to compare the own effectiveness and that of other entities in the accomplishment of the adopted objectives. However, they have certain limitations; because of different conditions and not precisely identified factors of influence, the conclusions should be drawn cautiously, especially in the field of making positive or negative assessments. The external factors frequently differ in the case of making comparisons of entities from different states. Obviously, it is necessary to consider different conditions existing in cities in different countries, e.g., the decisions related to the spatial planning, urban transport management, and also the social environment linked with the style of life, habits, and the culture prevailing in the given area, or the determination to implement sustainable development solutions.

Both qualitative and quantitative methods were used in the research. In the case of quantitative methods official census data, published by the relevant national statistical offices, were used, and, therefore, they are basically beyond discussion about the methodological correctness of their collection and reliability. Collected census data allow to formulate (compared to qualitative methods) less subjective and more unambiguous conclusions. Moreover, what is important is that these are data from a longer period, which eliminates the influence of random and also short-term deviations from the long-term trend. The number of regional and urban public transport journeys, as well as the number of passenger cars and thus the motorization index, are the key measures of the modal split and modal shifts and from the point of view of the transport policy goals - they are often used in reports [3]. These measures are also important from the point of view of sustainable urban transport policy and development and quality of life in cities. Of course, long-term changes in the modal split and the number of passenger cars are not the result of individual projects or programs, but of the totality of activities in a given period, and also of societies' attitudes towards mobility and transport modes. Identification and assessment of the impact of individual factors requires a separate study using factor analysis methods, and this is not the subject of this paper.

In the conducted research, the data provided by statistical offices were sufficient to describe the phenomenon, eliminating the need for additional research or expanding the numerical data scope. This enabled broader use of qualitative methods, including data analysis, literature review, generalizations, and conclusions. While recognizing the importance and frequent dominance of quantitative methods, it is essential to note that qualitative research methods are equally valid. Furthermore, they allow focusing on explaining ongoing processes, such as social phenomena, and addressing elements of phenomena or theories, including generalizations, that are not subject to qualification or where qualification is unnecessary [4]. The primary goal of assessing the effectiveness of sustainable development policies was to draw conclusions for the future, ensuring that public authority tools, particularly the legal regulations and public financing, are properly and effectively used. While past assessments are essential, a forward-looking perspective is crucial. Comparing the two countries aimed to show that societal behaviors, often favoring car use, are not the only factors influencing the transport modes. Diverse changes in urban and regional public transport usage and individual motorization indicate the real impact of tools available to public authorities.

The term of policy, including the transport policy, or as it is increasingly often named - the mobility policy, is defined in various ways [5-9]. In a practical dimension it is possible to assume that the policy is a process [10-11], in which certain stages/phases proceed:

- research and analyses, and the formulation of a draft policy,
- social consultations and report preparation,
- adoption of the document by the competent authorities,
- policy implementation,
- policy evaluation,
- start of a new cycle, hence starting the research and policy formulation.

Obviously, these stages may be described in more detail, separating more actions, or performing the division in a different way. These stages not necessarily follow each other, they are also not separate. Certain actions overlap [12], for example, the policy implementation still continues, and within certain scopes it is already subject to evaluation. At the evaluation of the implemented policy, in a way the analysis is already conducted, and the knowledge is acquired, which will be used in the new cycle of the policy. Moreover, it is difficult to close the research once the document has been adopted; the research is a continuous process, which, for example, may be performed for the evaluation needs, but it is also possible to use it in other related objectives - with the process of solutions implementation, and the evaluation of the planned and carried out projects.

In Poland, for many years the transport plans were prepared and resolved as voluntary; only in 2011, once the Act of 16 December 2010 on the Public Collective Transport took effect, a part of municipalities and intermunicipal unions were obliged to develop and resolve the transport plans, referred to as the plans of sustainable development of the public transport. Similarly in Slovakia, the Act 56/2012 of 31 January 2012 on the Road Transport, introduced the obligation of transport service plans, later on that was transferred to the Act of 21 June 2023 on the Public Persons Transport and on the Amendment and Supplement to Selected Acts. The Sustainable Urban Transport Plans are certain equivalents, and also a broader approach; their development was ordered by the European Commission, introduced in the package on the mobility in cities (COM(2013) 913 final, from 17.12.2013). This is an element of the Commission actions aimed at reducing the pollutants emission from transport and at achieving the climate neutrality, as one of conditions to obtain co-financing of projects; at the same time the advisory support and co-financing from the UE funds at the development of plans are ensured (Commission Recommendation (EU) 2023/550 of 8 March 2023, notified under document C(2023) 1524). The preparation and updating of mobility plans is a process, if they apply to cities and urbanised areas, implemented just on those levels.

The attention should also be drawn to the necessity of applying scientific methods, including the consideration of results of studies, in the processes of formulating and later on evaluating the undertaken actions [13-17]. The

adopted goals, and consequently the undertaken projects, which involve substantial public resources, are related, for example, to the adoption and next implementation and enforcement of legal solutions, performance of various organisational changes, or also involve funds for investment projects, or direct co-financing of the provision of selected services. If, as a result, no planned effects are obtained, questions should arise about the legitimacy of the adopted solutions and spent public funds, the administrative efficiency, or determination to implement the adopted targets and related solutions, since such a situation is important for the economy and rationality of actions, and for the funds spending, including the public funds.

Numerous instruments have been developed to support the process of forecasting, including those intended to study the transport behaviour of residents and to forecast the demand in transport [18-20]; there are also numerous studies which are aimed at further development of such instruments [21]. They are widely used, for example during the decisions on the construction or modernisation of roads or other infrastructural facilities, spatial planning, implementation of new services or solutions, or the transport management. In addition, the support with IT tools for the data acquisition processes is now significant, as well as the modelling and forecasting. They can be and should be used already at the stages of policy formulation, for the assessment of various considered scenarios.

The effectiveness is the term, or a measure applicable to many human actions or projects, and thereby to the policy, as well. It is important to evaluate various policies and measures and measure the effectiveness of transport policy, including in cities [22-27]. The effectiveness is a degree of intended objectives accomplishment; the evaluation applies to the extent of intended goals achievement, to what degree, without the assessments of the amounts of expenditures assigned for this objective. The term of efficiency is used in the case of expenditures consideration [28]. However, it is necessary to emphasise that the accomplishment of objectives is a process; these are often gradual and small changes, not necessarily the best among those possible, but what is very important, heading towards a defined target. Hence the assessment of effectiveness should be carried out in various time frames, shorter - to acquire faster the information about the course of processes and introduce specified corrections, if the outcome is not consistent with expectations, and longer - when the effects should already be visible. Obviously, considering the projects, which may be completed within a short time, this assessment should be made appropriately faster.

The limited volume, as well as the need to maintain an appropriate structure of the paper, provide an opportunity only to make a rather general reference to the methodology of the research methods of policy evaluation. The complexity of the methodology and the use of diverse methods is a result not only of the broader dimension of theories and paradigms of social research and their evolution but also of the fact that the transport policy is not a policy in its own right, it is part of and a tool for the implementation of general goals in the city of the region, the country or on the scale of the European Union. The purpose of assessment and, more broadly, evaluation, is primarily to improve the quality, effectiveness and efficiency of public interventions, including transport, and therefore, in addition to the diagnosis and evaluation of the effectiveness of a given policy program, the key are recommendations and conclusions results from past policies and interventions. Therefore, bearing in mind the purpose of public intervention evaluation research, a certain methodological eclecticism is allowed, since, as a rule, it is not about verifications as in classical research of general theories, but specific explanations relating to a given practical situation, concerning, for example, the existence or not of a given causeeffect relationship between the intervention and the achievement of the assumed states. When the low effectiveness of interventions are found, there should be a reflection on the policy measures used, but also to what extent they coincide with social expectations.

The research and thus the methodology for evaluating the effectiveness of public interventions have a history, a specific methodology, as well as conditions and principles of implementation [29-30]. The source of evaluation stems from the needs of business practice - it developed with the increasing number and scale of public interventions and the need for assessment of undertaken actions. It is assumed that the origins of evaluation are in the 1900s in the USA, while the significant development of methods and the spread of their practical use in Europe in the 1950s and 1960s [29]. The expansion of the European Union, to include the new member states and the channelling of significant resources through various programs, has expanded the need for evaluation procedures.

The methodologies of project evaluations are well known, both in the framework of financial evaluation made from the point of view of a specific entity, and economic evaluations extended by external costs and benefits and therefore from a broader - social - point of view. Comparisons are made within the accepted time distance and dimension (financial or economic evaluation) of the results obtained to the expenses incurred. At the level of specific units, this is necessary, and evaluations are unambiguous. However, in the case of the public policies evaluation, a more general approach is used, it is due to the multidirectional impact and the considerable period of the effects of the interventions undertaken. The crucial becomes the evaluation of the degree of achievement of the adopted goals. To a large extent, this evaluation is intended to cause a discussion of measures used during the intervention, the legitimacy of the resources directed, which is important for ongoing monitoring, as well as the formulation of future public interventions. It should be noted that often for different programs, different evaluation approaches can and do occur [31].

The reality of adopted objectives and solutions is the base of the effectiveness. The adoption of objectives and tasks, which implementation already at the stage of their formulation is unrealistic, results in the weakening of motivation, and their implementation will feature low effectiveness. In addition, the effectiveness is also affected by the choice of instruments [32-33], by having appropriate resources available, not only financial, but also in the field of legal solutions preparation, and later on, by their supervision and enforcement. The effectiveness also depends on the social acceptance of the adopted solutions, as well as the pursuit and determination to implement and realise them.

The evaluation of effectiveness is a process aimed at studying to what extent a specific strategy, programme or project have accomplished the intended objectives. Various methods of proceeding may be used in this case; this depends on such factors as the very specific of intervention, the available resources, including time, or possibly the imposed external requirements. Combinations of methods can also be used. In the performed studies the indicator-based evaluation was applied, two basic and crucial indicators from the field of the method of movements were adopted. Obviously, the studies may be expanded on further indicators, for example, showing a unit emission from vehicles.

However, it is relative, whether a given project is realistic or not. For example, this may be referred to the changes in the use of individual and public transport in cities. Obviously, there are numerous factors, which affect it, however, broader conclusions are obtainable only as a result of comparisons of various cities, and the course of related processes in them.

It is possible to show examples in the field of transport, in which the objectives adopted within the transport policy have not been achieved, or the degree of their accomplishment was not satisfactory. An increase in the number of private cars is visible in the urban areas in some European states, and a still significant share of this mode in the urban traffic.

3 Polish solutions in urban and regional transport

The Act on Municipal Local Government (at that time territorial government), adopted in Poland in 1990, stipulated that units of the municipal local government are responsible for the ensuring of urban public transport. At the same time, the cities received the assets used for this task implementation, the national (state-owned) assets used to perform the tasks of ensuring the urban public transport became the property of municipalities through municipalisation. The Act on Public Procurement adopted in 1994 (now the

Public Procurement Law) stipulated, that the spending of public funds must (with certain exceptions) be preceded by an open competitive bidding procedure, hence the conclusion of contracts with transport contractors was preceded by such procedures. Only from the 1st of May 2004, hence the moment of Poland's accession to the European Union (EU), and when the EU legislation became part of the Poland's legal system as a member state, it became possible to award contracts directly. The regulations adopted in the Regulation of the Council and of the European Parliament No 1370/2007 took effect in 2009, which clearly defined situations, in which it is possible to conclude contracts directly.

The organisation of urban public transport in Poland is diversified; to a large extent it results from the diversification of cities in terms of the area, spatial development, population, and many other features, which affect the volume and the nature of transport needs. With a growing size of the city, the local transport needs are satisfied by a specialised system of municipal management, which is the urban public transport. In the smallest settlement centres, including towns, the local transport needs are satisfied by entities providing transport services of regional reach. However, a significant number of cities use the services of specialised urban transport entities. A part of smaller towns have their own urban transport systems, certain use the systems serving the neighbouring cities or the conurbation urban transport systems. With an increasing city size the service by an urban transport system becomes universal. As it results from the study, which was carried out in 2021 in 582 cities in Poland (out of 954 cities in 2021), the urban public transport was functioning in 54.45% of small towns, 95.6% of medium-size cities (population from 20 to 100 thousand), and in all the big cities, population of over 100 thousand [34].

Under the existing regulations, cities are free to decide about the transport organisation. The bus transport is the urban public transport in the smallest towns, and the activities connected with the organisation and the very provision of transport services are performed, for example, by own organisational units or the services are outsourced. The formulae of net costs prevail then, in which the carrier provides the sales of services, while the town finances the public transport by a subsidy, e.g., for a unit of operational work, i.e., a vehicle-kilometre, or paying a compensation for the provision of public services. Hence the risks of the town and of the carrier can be distributed differently, depending on the adopted solution; the risk of obtaining revenues in the case of subsidy to the volume of operational work (revenues on tickets plus subsidy) is incurred by the carrier, but in the situation of an adopted formula, where the compensation is calculated as the cost of transport minus the tickets income plus a reasonable profit, then the risk related to the amount of income is incurred by the town. In Poland, in the

past there was no exclusive law used in the passenger transport, which resulted in a high risk of the demand size, hence the attitude of small towns to starting new lines was pretty ambivalent.

In medium-size cities the principles are similar to small towns, however, they are supplemented with solutions, in which the organisers of urban transport are established. The organisers of the urban transport universally exist in big cities; in this case the transport integration is an important factor, in the situation where it is performed by many entities providing services by the bus and tram transport, and in conurbations the railway transport, as well. In the case of railway transport it is possible to mention the Warsaw Commuter Railay, PKP Rapid Urban Railway in the Tri-City, and the Rapid Urban Rail which serves the city of Warsaw and neighbouring municipalities. Gross costs contracts exist here, in which the risk of demand, and thereby the obtaining of ticket revenues is on the side of the public transport organiser, and ultimately on the city.

Table 1 presents the number of transported passengers in the urban public transport in the selected years from the 1990 - 2022 period; because of the Covid-19 pandemic and its significant impact on the volume of transport, the figures for the last years were provided. A decrease in the volume of transport is visible; in 2022 this volume went down to a level of 61% of the 2000 figure, and to a level of 78.4% of the 2010 value. Of course, the volume of transport in 2022 and the following year was influenced by the Covid 19 pandemic, in particular the solutions adopted at that time in the field of remote learning and work, as well as restrictions to human mobility [35-36]. As a result, initially forced by the pandemic, after its end, the use of remote communication, using telecommunication and information technologies, has become a part of many activities in places and to the extent that is possible and beneficial. Therefore, in the coming years, the use of communication and other solutions and activities based on remote communication will be one of the factors limiting the volume or slowing down the increase of mobility/volume of movement in cities.

For the bus transport of regional reach, as a rule, the district governments and the voivodeship (province) governments are not willing to take the risk and to conclude contracts, in which the transport services would be a public task and a compensation would be paid up to the amount of costs connected with the provision of this service. The entities performing the transport services usually were obtaining from the State Budget (via voivodeship governments) the reimbursement of lost income due to the application of statutory discounts. As a result, such transport services are usually provided based on commercial rules, and hence, the revenues on tickets sales plus funds received due to the application of statutory discounts cover then the related costs. Such a solution resulted in a significant decline in the transport offer in the regional bus transport, in the reduction of both lines' number, vehicle-kilometres, and carriers. The situation is to be changed by the establishment on a national level, in mid-2019, of the Fund for Bus Transport Development, under which the municipal governments can obtain funds to restore the non-operating bus connections. In addition, the ownership structure of entities has changed over years; in the bus transport the enterprises belonging to the public sector transported 34.9% of the total passengers in 2021, and those belonging to the private sector -65.1% [41].

Table 2 presents the number of passengers carried by the bus transport in Poland in the years 1990 - 2022. The table also includes the data on the bus international transport, however, in terms of the passengers' number they are small as compared to the domestic ones, for example, in 2021 this transport carried 1.3 million passengers, hence less than 1%.

A significant decrease in the volume of transport is visible in the years 2000 - 2022, and 2010 -

Table 1 The number of passengers transported by the urban public transport in selected years, 1990 - 2022, based on [37-41]

Years Specification	1990	1995	2000	2005	2010	2015	2019	2020	2021	2022
Number of transported passengers/passenger rides (millions)	7,264.1	5,909.9	5,011.7	3,989.3	3,904	3,672.2	3,865	2,270.8	2,500.9	3,059.8
Year of $2000 = 100\%$			100	79.6	77.9	73.3	77.1	45.3	49.9	61
Year of $2010 = 100\%$					100	94.1	99	58.1	64	78.4

Table 2 The number of transported passengers in the years 1990 - 2022 by the bus transport (enterprises with a number of employees above 5 persons, till 1995, later on - above 9 persons, without the urban public transport), based on [41-43]

Years Specification	1990	1995	2000	2005	2010	2015	2019	2020	2021	2022
Number of transport-ted passengers/passenger rides (millions)	2,085	1,215	954	782	570	417	328	160	169	214
Year of $2000 = 100\%$			100	82	59.7	43.7	34.4	16.8	17.7	22.4
Year of 2010 = 100%	_				100	73.1	57.5	28.1	29.6	37.5

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Years Specification	1990	2000	2005	2010	2015	2019	2020	2021	2022
Population of Poland	38.073	38.254	38.157	38.530	38.437	38.383	38.089	37.908	37.766
Year of 2000 = 100%		100	99.7	100.7	100.5	100.3	99.6	99.1	98.7
Urban population	23.546	23.670	23.424	23.429	23.166	23.033	22.777	22.624	22.490
Year of $2000 = 100\%$		100	99	99	97.9	97.3	96.2	95.6	95
Population living outside cities	14.527	14.584	14.733	15.101	15.271	15.350	15.311	15.284	15.276
Year of 2000 = 100%		100	101	103.5	104.7	105.2	105	104.8	104.7

Table 3 The population, including the urban and living outside cities in Poland, in selected years from the 1990 - 2020 period, in million persons, as of the 31st of December of the given year, based on [45]

2022 likewise, which results from various reasons; a significant increase in the number of private cars and the universal motorisation of the public are frequently sought causes. Obviously, the number of private cars in Poland increased a few times; their number in 1990 was 5,261,000, in 2000 - 9,921,260, in 2010 - 17,239,800, and in 2022 - 26,457,659 [44]. Attention should be drawn to the fact that the CEPiK (Central Register of Vehicles and Drivers) system comprises vehicles, which were not cancelled from the register in the past; relevant adjustments are predicted, it is possible to assume now (not to use the figures, which are known to be overvalued) that the number of reported vehicles, which have current technical tests permitting to participate in the traffic, should be reduced by 20%; hence for 2022 it is a level of 21.170 million (for 2010 is the level 13.791 million cars), which gives the calculated index of motorisation of around 560 private cars per 1000 inhabitants in the 2022. The increase in the number of cars applies both to cities and areas outside cities, thereby it affects both the urban and regional transport, although in cities the solutions, which reduce the use of private cars, may be applied to a larger extent.

Table 3 presents the population, including the urban and living outside cities in Poland, in selected years from the 1990 - 2020 period, in million persons. Changes in the population living in cities and outside them, between 2000 and 2022, are not higher than 5%, where these figures are also affected by the suburbanisation, that is living in areas outside cities, and commuting to them. The decline in the bus transport in Poland, in the extra-urban transport, is much higher than, in a similar period, the decrease in the volume of urban public transport, where it does not result from the changes in the population. Hence, it is possible to assume that the limited public financing of the extra-urban transport and the transferring of the costs and revenues risks on the carriers was one of factors contributing to the decline in the volume of transport.

The voivodeship governments are the organisers of the regional railway transport. In Poland, twelve railway carriers are operating now, fulfilling the function of an operator of the public transport. Considering their ownership structure, one can notice that a definite majority of them was established by voivodeship governments, as internal entities, intended to perform services for a given voivodeship. In addition, a small share in the voivodeship transport market is held by the Arriva RP, which provides services of public nature in the area of the Kuyavian-Pomeranian Voivodeship [46]. Because of the services provision, the railway carriers receive the compensation, which is calculated, most generally, in accordance with the provisions of the Regulation of the European Parliament and of the Council No 1370/2007.

4 Solutions in Slovakia in urban and regional transport

In Slovakia, the contracts on the provision of services by the urban or regional public transport until 2009 were concluded without a previous public bidding procedure, in the form of direct contract awarding to a specific contractor, most frequently in the form of gross costs contracts, in which a part of cost risks was transferred to the employer. The form of such contracts is close to a management contract, in which the employer reduces the contractor's risks related to the provision of transport services [47-48]. The Regulation of the European Parliament and of the Council No 1370/2007, repealing the Council Regulations (EEC) Nos 1191/69 and 1107/70, took effect in 2009. It indicates the necessity of performing procurement leading to contracts awarding through an open, fair, and consistent with transparency and non-discrimination rules procedure, except for the procurement below a defined threshold of the number of kilometres or values, the situations of disturbances in the provision of services, or a direct risk of such a situation, and also in the case of internal entities. The Regulation specifies crucial elements of contracts; they apply primarily to the scope of obligations, which must be met by the service provider, and the remuneration/compensation, so that it would be carried out transparently, objectively, and would not result in an excessive level of the compensation, but on the other hand it would ensure an appropriate profit on the equity. It also specifies the period of contracts validity; the maximum periods of their validity are provided, however, longer periods are allowed, if that

is justified by the depreciation or investments in the infrastructure. The issues of risk sharing, the type of contract, the formula of gross or net costs, or certain modifications from the point of view of risk sharing are left for the parties to the contract. Therefore, considering the necessity of thrifty and effective spending of public funds allocated to the public transport, as well as taking local conditions into account, and the experience of the service provider, it is advisable to prepare and conclude such contracts, in which it will be interested in the implementation of solutions increasing the quality and attractiveness of the public transport as well as the number of carried passengers and, due to that, also the income on sales of services.

Table 4 presents the number of passengers transported by the public bus transport and by the urban public transport in the years 2003 - 2022. A decrease in the number of transported passengers is visible; this decrease is higher for the extra-urban bus transport, in 2022 the number of transported passengers was 33.8% of the 2003 figure and 53.3% of 2010. The decline in the volume of transport in the urban public transport may be referred to as insignificant; in 2022 the number of transported passengers was 94.6% of the 2003 figure and 96.8% of 2010. The decline in passenger number in years 2020-2021 was caused mainly due to preventive

measures taken by the government of Slovakia against the spread of the Covid-19 epidemic. These include, first of all, the transition to online teaching in all schools in Slovakia, as well as the transition of some employees to remote work. A diversified decrease does not result from a change in the population living in cities and outside them; in 2022 the population living in cities was lower than in 2003, and the population outside cities was higher by 8% as against 2003 (Table 5).

This change is probably related to the effect of suburbanisation. The number of private cars in Slovakia obviously rose over years; in 1990 their number was 875,550, in 2003 already 1,356,185, in 2010 - 1,669,065, and in 2022 -2,555,491 [50], which for 2022 gives a motorisation index of 470 cars per 1000 inhabitants; it is lower than the motorisation index in Poland. In Slovakia, the number of cars in the years 1990 - 2022 increased almost three times, in Poland - approximately four times (assumption 21.170 million cars in 2022). It is therefore necessary to expand activities supporting public transport in cities, e.g., using the experience economy [51], transport integration [52] and pricing approaches [53].

At the comparison of Poland and Slovakia it is necessary to state that, being a few decades ago at

Table 4 The number of passengers transported by the public bus transport and by the urban public transport in the years 2003 - 2022, based on [49]

Years Specification	2003	2005	2010	2015	2019	2020	2021	2022
Public bus transport - number of passengers/ passenger rides (in '000)	493,706	449,456	312,717	252,175	238,886	156,333	149,826	166,689
Year of $2003 = 100\%$	100.0	91.0	63.3	51.1	48.4	31.7	30.3	33.8
Year of $2010 = 100\%$			100.0	80.6	76.4	50.0	47.9	53.3
Urban public transport- number of passengers/ passenger rides (in '000)	394,465	395,064	385,594	379,468	382,662	283,913	259,459	373,186
Year of $2003 = 100\%$	100.0	100.2	97.8	96.2	97.0	72.0	65.8	94.6
Year of $2010 = 100\%$			100.0	98.4	99.2	73.6	67.3	96.8

Table 5 The urban population and population living outside cities in Slovakia in the years 1993 - 2022, based on [54]

Years	1993	2003	2005	2010	2015	2019	2020	2021	2022
Specification									
Population of Slovakia	5,338,816	5,379,161	5,384,822	5,424,925	5,421,349	5,450,421	5,457,873	5,449,268	5,434,712
Year of 2003 = 100%		100	100.1	100.8	100.8	101.3	101.5	101.3	101
Urban population	2,811,807	3,009,219	2,995,570	2,976,808	2,921,600	2,912,062	2,912,493	2,898,472	2,875,614
Year of 2003 = 100%		100	99.5	98.9	97.1	96.8	96.8	96.3	95.6
Population living outside cities	2,527,009	2,369,942	2,389,252	2,448,117	2,499,749	2,538,359	2,545,380	2,550,796	2,559,098
Year of 2003 = 100%		100	100.8	103.3	105.5	107.1	107.4	107.6	108

a similar stating point - of socialist economy (still within Czechoslovakia), with the state-owned means of production and being at that time on the eve of intensive individual motorisation, and from the 1st of May 2004, as European Union Member States under identical regulatory frameworks established on the EU level, Slovakia has been implementing a much more effective policy of sustainable development of the transport system. Such reduction in the extra-urban public bus transport, as in Poland, did not happen. Additionally, the increments in the number of private cars are lower than in Poland, and as a result, the motorisation index is also lower, such significant declines as in Poland did not occur in the transport by the urban public transport.

5 Results and discussion

The changes over years in the volume of transport by the urban public transport, regional and national bus transport and in the number of cars were considered to evaluate the effectiveness. These are the basic synthetic measures indicating the methods of travelling and thereby the obtained effects and effectiveness of the transport policy performance as well as making the transport systems sustainable. Obviously, the regulatory and public financing of the urban public transport leads to the improvement in the financial and material standing of the entities in the public transport system, enables them to purchase and implement modern and low-emission vehicles, as well as to implement numerous innovative solutions, including the IT systems. However, the basic objective should consist in the obtaining of the effect in the form of maintaining or increasing the volume of the public transport and reducing the individual mobility by cars, and the material changes should lead to this objective.

The number of rides and the motorisation index for individual cars may also be used for many analyses, assessments and forecasts, and in addition, in the case of forecasts, only for a short time based on rules of the hitherto trend continuation. When making forecasts for many years, for longer periods, like in the case of forecasts made at the assessment of the demand for infrastructure, 25 years and more, it is necessary to consider such factors as changes in the population, economic growth, mobility, income, and various qualitative changes, which will affect them. Over years, very sophisticated instruments have been developed for the traffic forecasts, and hence for the demand for infrastructure and transport services, supported by IT tools. In those methods the explained variables include the volume of personal traffic, the volume of freight transport, the volume of traffic on a given section or individual sections of the transport network, while the explanatory variables include the division of residents and working persons for the adopted regions, the volume of production, imports, and exports, the mobility, and the income. The making of forecasts became significant primarily for the projection of the demand for transport and transport systems development, and during the performance of feasibility studies for the transport investments.

In both countries the challenge consists in a sustainable development of urban and regional transport systems, in the situation of certain caroriented mobility culture, manifesting in a large increase in the number of private cars. Both Poland and Slovakia have been, for years, using the EU funds, which support the projects in the field of sustainable transport development. A certain difference in Poland, despite a similar to Slovakia initial strategy, consisting in the division of one big enterprise of bus transport, which was carrying out the transport of regional and national reach (SAD in Slovakia, PKS in Poland), is the reduction over years of the public financing of regional and national bus services, which resulted in a significant decrease in the volume of transport and thereby a reduction of the offer, and implying from that also the ceasing of services provision by a part of entities from this sector. In addition, the interest of private capital is similar; in Poland the business is also run by companies with a share of private capital, including the foreign capital.

Poland and Slovakia are neighbouring countries, close in terms of culture, in a large part facing similar challenges, both economic and social. In terms of the area and the population, Slovakia is a country smaller than Poland. The total area of Poland in 2023 was 311,928 km², while that of Slovakia 49,035 km². In terms of population Poland ranks fifth after the Federal Republic of Germany, France, Italy, and Spain, while Slovakia ranks 18th among the 27 EU states, among such countries as Bulgaria, Denmark, Finland and Ireland [55].

The larger population of Poland is also related to a higher number of cities, including the big ones. Table 6 presents the comparison. The share of cities with a population below 20 thousand is similar; in Poland it is 78.46% while in Slovakia 73.76%. However, Poland has a substantially higher share of cities with the population above 100 thousand; in Poland there are 37 such cities, a share of 3.78%, and in Slovakia 2 cities, a share of 1.42%. The external costs of transport, including the unit costs, referred to a specific vehicle on a section of 1km, are substantially higher in the urbanised areas due to a much larger number of persons being within the reach of impact than in smaller cities and areas of a lower population density. In this context, in Poland there should be a much higher pressure on making the transport systems sustainable and reducing the negative external effects.

Table 7 presents the comparison of selected measures, which characterise Poland and Slovakia. In Poland and Slovakia, the motorisation was intensified together with the acceleration of the economic development and GDP growth, and for many years a car was a good which was

not commonly accessible, and if so, then the choice was practically from the makes manufactured in the states of the former socialist block. It is assessed that this factor, a possibility of purchasing a good which for a few decades was not accessible, still affects decisions of the people in those countries. In Poland, in many circles the possession of a car is considered a symbol of social status. This social factor is considered a major reason for the more than 400% increase in the number of cars over three decades in Poland, compared to just over 190% in Slovakia. However, the difference in motorization rates between the two countries is not as pronounced, at about 20%, with the data for Poland being estimated and currently undergoing updates. Additionally, the development of infrastructure as well as the growth of GDP and of people income favour that, which allows purchases, but which is also one of the growth factors for the people mobility.

A significant increment in the number of cars over recent years was accompanied by a decrease in the volume of urban public transport. In Poland, the decline from 2002 to 2005 was over 23%, while in Slovakia

it was just over 5.5%. When comparing Poland and Slovakia, the level of urban public transport rides per resident per year is quite similar, with Poland having slightly over 136 rides and Slovakia nearly 130 rides, resulting in a difference of less than 5%.

Over the years, both in Poland and Slovakia, there has been no substantial change in the proportion of people living in cities versus outside (Tables 4 and 6). There is a balance between the increasing importance and attractiveness of cities, their role in accumulating various functions, leading to migration to urban areas, and the effect of suburbanization, which involves the development of areas outside cities but in their proximity. Over two decades, there has been a noticeable increase in the population outside cities: approximately 4.7% in Poland (from 2000 to 2022) and about 8% in Slovakia (from 2003 to 2023). Suburbanization is generally associated with the growing importance of and reliance on private cars. In addition, changes in the population are not significant, hence this is not a factor substantially affecting the volume of passenger transport, both in cities and outside them.

Table 6 Comparison of the number and structure in terms of the population of cities in Poland and in Slovakia, based on [54, 56-57]

Population ranges	Poland		Slovakia	
	Number of cities	% share	Number of cities	% share
To 5 thousand	405	41.36	26	18.44
Above 5 thousand to 20 thousand	363	37.1	78	55.32
Above 20 thousand to 50 thousand	127	12.96	28	19.86
Above 50 thousand to 100 thousand	47	4.8	7	4.96
Above 100 thousand to 500 thousand	32	3.27	2	1.42
Above 500 thousand	5	0.51	0	0
Total	979	100	141	100

Table 7 Comparison of selected measures, which characterise Poland and Slovakia (2022), based on [44, 50, 55] and data from Tables 1, 3, 4, 5

Specification	Poland	Slovakia
Population (in '000)	37,766	5,434.7
Population living in cities (urban population) (in '000)	22,490	2,875.6
The share of population living in cities in the total population	59.55%	52.91%
Population living outside cities (in '000)	15,276	2,559.1
The share of population living outside cities in the total population	40.45%	47.09%
Area - km²	311,928	49,035
Population density - person/km ²	121.07	110.81
Number of cars (2022) (in '000)	21,170 (estimated data)	2,555.5
Motorisation index (cars per '000 habitants in 2022)	560 (estimated data)	470
Change in the number of cars 2022/1990	302.4% (estimated data)	191.9%
Change in the number of cars 2022/2010	53.5% (estimated data)	53.1%
Urban public transport - number of passengers/passenger rides (in '000)	3,059,800	373,186
Change in the number of passengers urban public transport 2022/2005	-23.31%	-5.53%
Change in the number of passengers urban public transport 2022/2010	-21.62%	-3.22%
Urban public transport - number of passengers/per city resident/per year	136.05	129.77

Unfortunately, Poland and Slovakia have experienced a significant decline in intercity bus transport, which cannot be viewed positively. A potential solution could be the broader implementation of demand-responsive transport services.

6 Summary

There are many similarities in the processes of urban and regional public transport transformation and in the principles of the transport policy performance, as well as in using the administrative or financial instruments in Poland and Slovakia. This is natural, because these countries started the economic transformation, including transport, from a similar initial state and almost at the same time. They belonged to a block of states, in which after World War II the state ownership of the means of production was introduced and the management was centralised. At the beginning of the 1990s the reforms were implemented towards the market economy, and later on, at the same moment (1st of May 2004), they entered the European Union structures and thereby adopted the legal order of this group. As a result, referring in particular to the urban and regional public transport, the principles of contracts conclusion for the public transport services are the same, because they result from the Regulation of the Council and of the European Parliament No 1370/2007. The presented data on the number of rides by public transport and the number of cars indicate a low effectiveness of the pursued transport policy, with the effectiveness being even lower in Poland. Obviously, the transport systems experienced numerous positive changes related to the modernisation of the means of transport and infrastructure, and improvement in the services quality. However, considering that the effects achievement should be crucial, it shows the necessity of adapting the influence instruments available to the public authorities. The results of studies allow to refer not only to the effectiveness of the transport policy instruments and the city development policies, but to draw attention to the increase in the number of cars both in Poland and Slovakia, as well, and thereby a mass nature of individual motorisation, and hence a long-term nature of the process of replacing cars with low-emission vehicles, e.g., hybrid or electric ones. In addition, the universality of cars indicates the fact that the implementation of sustainable development and reduction policies will be a major challenge of social dimension, resulting in a change of transport behaviour developed over years, as well as in expenditures on lowemission vehicles.

The analysis of synthetic data on the number of private cars and the number of journeys by the public transport shows a greater effectiveness of actions under the policy of sustainable development of transport pursued in Slovakia. Substantially smaller than in Poland are the declines in the number of passengers transported by the regional and national public bus transport, and the declines in the volume of transport in the urban public transport may be considered insignificant. Additionally, an increment in the number of private cars, and hence the motorisation index, is substantially smaller in Slovakia than in Poland.

In the context of results of preliminary studies, it is considered necessary to carry out more detailed studies on the effectiveness of the transport policy instruments and of various actions and implemented solutions, in particular the benefits obtained on the incurred expenditures and their consistency with the assumptions and expectations. The comparisons were made using the examples of Poland and Slovakia. At the same time, making of a comparison is a suggestion of expanding the studies for some selected groups of states, e.g., by their size, by the so-called old EU states and those that joined in 2004 and later, or all EU states, by the GDP per capita, by identification of differences, and later on, in factorial studies, to capture those factors and their influence on the diversification. The conclusions can lead to the necessity of certain differentiation of policy instruments, to effectively achieve the intended objectives. To draw particular attention inter alia to the expectations, opinions, material diversification and hence various possibilities of societies, which affect their opinions.

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Conflicts of interest

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FACTORS NEGATIVELY AFFECTING THE QUALITY OF WORK OF PTI TECHNICIANS - THE CASE OF THE SLOVAK REPUBLIC

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Resume

The authors examine the negative impact of objective and subjective factors on the quality of work of periodical technical inspection stations (PTI) technicians. In this context, the authors conducted a survey among the PTI technicians and vehicle operators. From the results formulated in the article, it emerged that the quality of PTI technicians' work, and thus the entire PTI, is negatively affected mainly by the high degree of subjectivity entrusted to PTI technicians, when evaluating the technical condition of vehicles (94.12%) and the resulting scope for incorrect judgments and influencing the result of PTI (corruption, acquaintances), and the approach of PTI owners (influencing technical inspections results due to fear of losing customers, pressure on quantity over quality, method of rewarding the PTI technicians, etc.). The authors also propose some measures to improve the quality of PTI activities.

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1 Introduction

To increase the road traffic safety, every civilized country has minimum technical requirements that must be met by vehicles in the road traffic. The introduction of regular inspections of the technical condition of vehicles and regular measurement of emissions is also related to this [1].

The periodical technical inspection station (PTI) is a workplace specialized in carrying out technical control. From the point of view of safety, these workplaces are very important. Through them, errors on the vehicle, its parts, systems, components, or separate technical units, are identified to eliminate the possibility of traffic accidents [2]. The technical suitability of these vehicles for operation in the road traffic is assessed based on the detected faults on the vehicles.

Technical inspections are carried out in approved premises using approved devices. Technical inspections are directly carried out by the PTI technicians, who must have the necessary education, experience and qualifying examination.

Given that the basic element of PTI is the PTI technician, who is a human being with all the human qualities that underwrite his work, PTI technicians are also the weakest link in the process of performing technical inspection and need to be given special attention. They carry out technical inspections independently and under their own name, as a part of which they have the task of identifying all the defects on the vehicles and categorizing them correctly. The PTI technicians are individually responsible for their activities. Given that the work of PTI technicians has a direct impact on the road safety, it is very important how they perform it.

Various objective and subjective factors can negatively affect the quality of work of the PTI technicians. They objectively create prerequisites for the activity of PTI technicians, the subjective ones directly affect their activity, and respectively they can also complement or condition each other. In this context, it is also necessary to distinguish between the intentional and unintentional actions, degree of culpability, etc. In the article, the authors focused on investigation of

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the objective and subjective factors that can negatively influence the activities of the PTI technicians in the case of the Slovak Republic.

1.1 Literature review

Technical inspections have a significant impact on road safety, and the technician plays an important role in it. A study by Schulz and Franck analyzed the benefits of introducting a new system of technical controls in Pakistan in 2016. The results show a measurable impact of technical controls on reducing the traffic accidents [3].

The importance of technical inspections is described in the article by Klemenc et al. They analyzed the results of technical inspections of selected EU countries - Slovenia, Germany and Finland. According to the results of technical inspections in Slovenia, the lighting and braking systems are among the most significant defects. These systems check within the framework of technical inspection can be considered as objective diagnostic methods [4].

Checking the brake system is the most important diagnostic activity during the technical inspection from the point of view of vehicle safety. Although commonly available objective methods for diagnosing the brake systems in the form of roller brake testers are currently used, these methods are also constantly evolving. This is mainly due to the possible influence of the brake performance result by the the technician (e.g., manipulation of the tire pressure). This problem is analyzed by Ajami et al. [5].

Obs, Glowinski and Kurpisz analyzed the technical condition of vehicles in western Poland. On a representative sample of vehicles, they described the most significant defects detected during technical inspections in Poland. The value of vehicle ineligibility in this country is significantly low - 3% [6].

To objectify the performance of technical inspections and eliminate the influence of the technician, it is possible to expect the implementation of several diagnostic systems in the future, which would enable the detection of the defects of various vehicle parts. Since the road vehicles are increasingly equipped with electronic systems, it will be necessary to diagnose these systems during the technical inspections. Authors of [7] analyzed the possibilities of checking adaptive systems in road vehicles.

In some EU countries, the technical condition of the vehicle's suspension is now objectively checked. One of these countries is Poland, where suspension testers are used for checking the technical condition of this vehicle system. Szczypinski-Sala, Kot and Hankus dealt with the possibilities of testing the spring system [8].

In addition, during the inspection of the vehicle's exhaust system, it is possible to expect the

introduction of new measuring devices to identify the concentration of pollutants, such as NOx, or particle numbers. Franzetti et al. pointed out the importance of measuring the volume of nitrogen oxides during the checking of the vehicle's emission system [9].

Todić, petkovic and Vranjes also analyzed the composition of gasoline and diesel engines exhaust gases and the possibilities of checking them during the technical inspections [10].

2 Material and methods

The basic documents and sources for application of investigation methods are data from the Automated National Information System of Technical Inspections (CIS TK), which stores data on the results of technical inspections from all the PTIs in the Slovak Republic and methodological instructions for carrying out technical inspections, issued by the Ministry of Transport of the Slovak Republic (MOT). Additional data on PTI, PTI technicians, PTI technician competence training and qualifying examinations, were obtained from the Technical Service of Technical Inspections TESTEK, as, as well as from the first author's own work at the MOT.

All the obtained data were further processed by the authors of the work, and statistical methods and tools, as well as graphic interpretation, were used for their processing [11]. The results of a survey, conducted by the authors for this purpose among PTI technicians and vehicle operators, form the basis for elaboration of this article.

A questionnaire was created to find out the opinions of the PTI technicians on the setting of their competence training, which they must undergo by law, as well as to find out other factors that can negatively affect their activity, consisting in not evaluating defects on vehicles. The survey was conducted through an electronic questionnaire developed in the Google Forms application, through which the PTI technicians were asked eight questions. This survey was carried out between February 10, 2023 and February 28, 2023, and PTI technicians were informed about it through CIS TK. The survey questions were divided into two groups. The first group consisted of questions related exclusively to the educational system of PTI technicians, and the second group consisted of questions related to other factors potentially influencing the activity of a PTI technician.

At the same time, an orientation survey was conducted among vehicle operators on factors negatively influencing the results of technical inspections. The survey was conducted among random vehicle operators throughout Slovakia, who were asked two questions and their answers were recorded in a paper questionnaire.

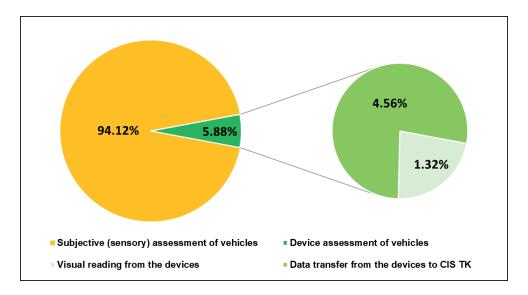


Figure 1 Sensory and device assessment of vehicles

3 Investigation of factors negatively affecting the quality of work of the PTI technicians

Within this section, selected factors negatively influencing the activity of PTI technicians, are examined. For this purpose, however, it is necessary to first examine the conditions creating space for the action of factors that negatively affect the activity of the PTI technician. In the case of PTI technicians, the degree of subjective decision-making when assessing the technical condition of vehicles, which was legislatively entrusted to them by the state, can naturally be considered as such a basic condition. The greater the scope for subjective judgments PTI technicians have in their work, the greater the scope for influence of factors negatively affecting the quality of their work.

3.1 Investigating the degree of subjectivity and technology in the work of the PTI technicians

The PTI technicians assess the technical condition of a vehicle, its parts, components and separate technical units, through devices and senses (sight, hearing, smell and touch) as part of the technical inspection, based on their knowledge acquired through formal education, competence training and their experience. Intuitively, it can be assumed that wherever a PTI technician evaluates the result of some control item by means of a device or technological equipment, the probability of a wrong judgment during its evaluation naturally decreases, and vice versa. The more control items the technician evaluates only visually or by senses, the greater the space opens up for the subjective perception of the state of the checked items of the vehicle, and thus also for the emergence of a wrong judgment. PTI's technological

equipment intended for carrying out technical inspection thus creates prerequisites for an objective assessment of the technical condition of vehicles. To identify the relationships between the subjective and technological evaluation of vehicles, and thus the margin of error of the PTI technicians in performing the technical inspection, an analysis was carried out of the control items for which the assessment requires the PTI technological equipment (devices), and an analysis of the control items for which the PTI technicians use only their senses [12]. The result of the analysis is recorded in Figure 1.

From Figure 1 one can see that out of all the vehicle items inspected (986), up to 94.12% are evaluated by subjective assessment, i.e., based on the senses (especially visually) and only 5.88% by the PTI devices. However, in the background of the control items that are evaluated through devices, there is another determinant that causes their dichotomy. Namely, 1.32% of control items are evaluated based on the visual reading of the value from the device (pressure gauge, thermometer, tread depth gauge, etc.) and 4.56% are evaluated based on the data transferred to CIS TK (braking tester, mobile application for braking test measurement and error codes from the On-board diagnostics (OBD) control unit of vehicles), [13]. However, the difference between them is significant. In the case of measured data, which are then visually read directly from the device, without being transferred to CIS TK, they may be misinterpreted by the PTI technicians and there is no proof of their relevance for the supervision bodies. When data (defects) are transferred directly from the devices to CIS TK, the possibility of their incorrect interpretation is eliminated and, at the same time, they serve as proof of the correctness or incorrectness of the assessment of related control items by PTI technicians. This causes the highest objectivity of the technical assessment condition of vehicles.

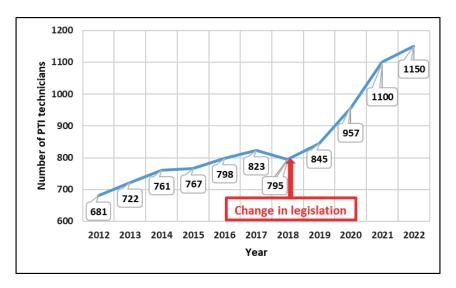


Figure 2 Development of the number of the PTI technicians in the period 2012 - 2022

The above points out the three basic ways of nonrelational (technical) work of the PTI technician. The first way refers to parts of the technical inspection where judgments are based solely on a subjective basis. The second method points to the reality of a continuous combination of subjective judgments with the help of the use of available devices means, i.e., their parallel and simultaneous referentiality. In the third method, devices are considered the only frame of reference for the PTI technician's decision-making about vehicle faults, in which the subjective judgments are not a relevant basis for the decision-making. At the same time, all the three mentioned methods of non-relational work of the PTI technician are significantly permeated by the education and mechanical experience of the PTI technicians.

Devices (objective) assessment of defects on vehicles represents for the PTI technicians not only a prescribed. but an internalized reference point for decision-making, as well, and therefore the simplest and most objective way of performing the technical inspection. This is the strongest point of technical inspection of vehicles. However, the subjective (sensory) assessment of the vehicle's technical condition is the most decisive in the process of technical inspection, and for the PTI technician it is the most used and most important tool for identifying the vehicle defects. It also represents the most demanding part of non-relational work, where there is a very high risk of incorrect judgment by the PTI technician, caused by unintentional or even intentional actions. This is the weakest point of technical inspection [14].

Based on the aforementioned finding, it is possible to examine the impact of specific factors (from objective to subjective) that can negatively influence the activity of the PTI technicians through their subjective (sensory) assessment of the technical condition of a vehicle.

3.2 Investigating the impact of the PTI technicians' education on selected negative indicators

If we do not take into account other factors, the basic prerequisite for the activity of the PTI technician is his knowledge and skills. He acquires them formally through official education at school in a certain curriculum, covered by an educational institution, and he acquires them informally during his work, as a part of compulsory training for technicians and through practice. However, both of these types of education can play an important role in terms of the quality of work performed by the PTI technicians. To assess the formal and informal education of the PTI technicians for their work, a survey will be conducted within this section.

Compared to the previous legislation, in the Slovak Republic Act No. 106/2018 Coll. among other things, they simplified the conditions regarding the education and experience of persons wishing to become the PTI technicians. The required technical education in defined fields and relevant experience can be replaced by an exam to verify knowledge about vehicles, the so-called pre-education. The exam may be voluntarily preceded by professional training. The aim of this was to make the work of the PTI technician available to a larger number of people, since at the time of creation of the relevant legislation, there was a decrease in the number of PTI technicians, as well as interest in this work. Similarly, with the new legal arrangement, compared to the previous one [15], the PTI network was also released, which means that conditions were established for creation of other PTIs [16], and the related need for new technicians.

This became apparent immediately, when after the Act No. 106/2018 Coll. the number of the PTI technicians began to rise sharply, which is shown in Figure 2.

Given that the replacement of formal technical

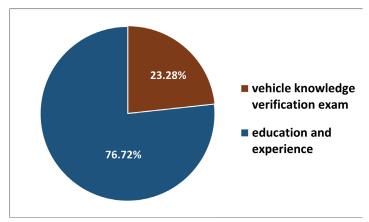


Figure 3 Percentage share of education of participants in the basic competence training of the PTI technicians in the period 2020-2022

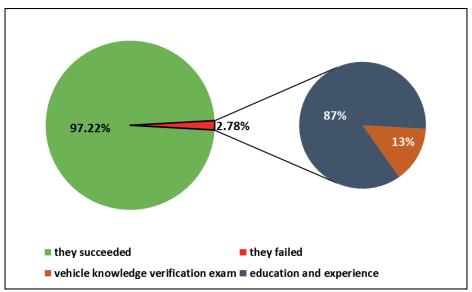


Figure 4 The overall success rate of the exams in the period 2020-2022 and the relationship to the education of the PTI technicians

education and related experience with an exam to verify knowledge about vehicles, the so-called pre-education can be considered as a factor that could theoretically negatively affect the work of a technician, from the point of view of insufficient knowledge and experience resulting from the absence of relevant formal education, the above will be subjected to investigation, from the point of view of selected critical indicators, which are success in the technician's professional qualifying exam, and violation of regulations consisting in failure to identify serious and dangerous defects on vehicles by the PTI technicians.

For the purposes of that research, the basic benchmark was the ratio of the number of the PTI technicians who were replaced by the fulfilment of proper educational conditions in the relevant technical fields, and the practice by vehicle knowledge verification exam, to the number of technicians who fulfilled those conditions properly. The subjects of the research were persons who participated in the basic competence training of the PTI technicians in 2020, 2021 and 2022.

From the mentioned persons, those who successfully completed the vehicle knowledge verification exam, before the basic competence training, and those who fulfilled the proper requirements for education and experience, were identified. By comparing them to each other, the percentages were calculated, which are shown in Figure 3.

From Figure 3 can be seen that in the monitored period, almost a quarter of the graduates of the basic competence training of the PTI technicians did not have a formal education, but replaced it with an exam to verify their knowledge of vehicles. In the following section, these basic preferential shares of groups of technicians are compared to selected critical indicators and their influence is investigated.

As a result of replacing the formal education of the PTI technicians with an exam to verify their knowledge about vehicles, the success of the technical inspection technicians' professional competence exams that followed the basic training in the years 2020, 2021 and 2022 is presented in Figure 4.

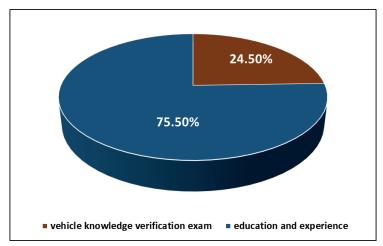


Figure 5 Percentage share of education of the PTI technicians who were found to be in violation of regulations in the period 2020-2022

In Figure 4 is shown that in the observed period, after the basic competence training of the technicians, a total of 97.22% of the graduates of the basic competence training were successful in the qualifying examinations for the professional competence of technical inspection technicians, and 2.78% of the graduates of the basic competence training were unsuccessful (after all three exam dates). Of the unsuccessful graduates of basic training in the qualifying exams, 87% met the proper requirements for education and experience of a PTI technician, and 13% of them replaced it by an exam to verify the knowledge of vehicles. Based on the mentioned criterion, it is therefore not possible to conclude that the replacement of proper education and experience with a vehicle knowledge verification exam for participants in the basic competence training of the PTI technicians, in the period 2020 - 2022 have resulted in their failure in the PTI technician qualifying exam. The share of people with the so-called pre-education, among those who failed the PTI technicians' professional competence exams (13) %), is lower than their overall share among graduates of basic competence training (23 %).

The impact of replacing the formal education of the PTI technicians with a vehicle knowledge verification exam on the activity of the technical inspections technician was investigated in such a way that for the period of 2020 - 2022 all the PTI technicians were identified for whom the professional supervision authorities found violations of related regulations, which consisted in not recording serious and dangerous defects on vehicles. Subsequently, it was investigated to what extent those PTI technicians fulfilled the conditions for proper education and experience according to Act No. 106/2018 Coll., and to what extent they replaced this education and experience with the vehicle knowledge exam. The result of this comparison is shown in Figure 5.

From Figure 5, it is clear that of the PTI technicians, who were found by the supervisory authorities to have violated regulations in the period 2020 - 2022 by not

detecting serious and dangerous defects on vehicles, 75.50% met the conditions for proper education and experience according to Act No. 106/2018 Coll., and 24.50% replaced this education and experience with a vehicle knowledge verification exam. The mutual ratio of fulfillment of the conditions for the education of the PTI technicians among the technicians who violated the regulations was almost identical to the mutual ratio of the fulfillment of the conditions for the education among the graduates of the basic competence training (Figure 3). Based on the mentioned criterion, it is therefore not possible to conclude that the replacement of proper education and experience with a vehicle knowledge verification exam for the PTI technicians in the period 2020 - 2022 would result in a higher rate of violation of regulations by such the PTI technicians, as a result of their lower level knowledge and experience in the field.

Thus, the mentioned survey did not prove the influence of individual alternatives of the required education of the PTI technicians on the selected critical indicators. The replacement of proper technical education and experience with a vehicle knowledge verification exam had no effect on this category of people's success in PTI technicians' qualifying competence exam, nor on their rate of violation of regulations in connection with the failure to identify serious and dangerous defects on vehicles. In other words, in connection with the research on the impact of the the PTI technicians education on the selected critical indicators, no negative phenomenon was identified, which could be interpreted as a consequence of the lower level of knowledge and experience of the PTI technicians, resulting from the replacement of their formal education and experience with the vehicle knowledge verification exam, and, therefore, negatively affecting the quality of work of the PTI technicians.

Within this, however, only the requirements for the technician in terms of formal education were examined. What is more essential for the work of the PTI technician is the system of their mandatory competence trainings, which are already precisely focused on performance

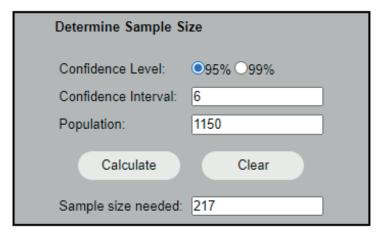


Figure 6 Determining the sample size using the Sample Size Calculator service [18]

of the PTI technician's work. However, whether this informal education (competence training) of the PTI technicians is suitable for their activity was investigated by a questionnaire survey, which is evaluated in the following section of the article.

3.3 Survey about the competence training conducted among the PTI technicians

In connection with the search for answers to some research questions, a survey was conducted among the PTI technicians in the Slovak Republic, which was methodically described in section 2. Part of the questions of this survey were related to the competence training of the PTI technicians, to which the technicians are required by law to undergo (basic competence training and refresher training). The subject of this part of the survey was the assessment of the sufficient setting of the competence training for the technician's work (content, scope, frequency), from the point of view of the PTI technicians.

In this context, the PTI technicians were asked the following four questions:

- In your opinion, is the current system of competence training and refresher training for technicians sufficient for quality technician work? (Answer option "YES" or "NO").
- 2. In your opinion, is the knowledge acquired at the mandatory competence training of PTI technicians (basic training/refresher training) sufficient for the job of a technician? If not, state what and how you would change the training. (Answer option "YES" or "NO"; when answering "NO" a free text field was displayed).
- 3. In addition to the current PTI technician refresher training, would you welcome more frequent training without a qualifying exam? (Answer option "YES" or "NO"; when answering "YES", the following answer options were displayed: "EVERY YEAR", "EVERY TWO YEARS", "OTHER INTERVAL" with the

- option of entering the free text).
- 4. Would you change the competence training and examination system for technicians in any other way? (Answer option "YES" or "NO"; when answering "YES" a free text marking field was displayed).

To determine the minimum sample of the PTI technicians, data on the number of the PTI technicians at the start date of the survey was used, i.e., 10/02/2023. According to the CIS TK, 1150 PTI technicians were registered on that date, [17]. The Sample Size Calculator was used to calculate the sample [10], with the following parameters:

- The confidence level (Confidence Level), 95% is the most often used, therefore this standard value was used.
- A confidence interval is a type of interval estimate of an unknown parameter in statistics; in this case the number 6 was chosen.
- In this case, the total number of statistical units of the basic file (Population) is 1150.

The result is the minimum sample calculation shown in Figure 6, which, in this case, is 217.

As a part of the evaluation of the questionnaire survey, it was found that 255 PTI technicians participated in the survey, which sufficiently fulfilled the calculated minimum sample, or was significantly exceeded. It follows from the above that the results of the survey can be fully used and considered representative within the set criteria. The answers to each survey question were processed and then presented in graphs. Answer to question No. 1 is shown in Figure 7.

From the results of the answers to questionnaire question No. 1, it is shown that more than two-thirds of PTI technicians who participated in the survey are satisfied with the system of basic competence training and further refresher training of technicians (70.40%). Less than a third were dissatisfied (29.60%). In this context, however, it is necessary to mention that question No. 1 was formulated in general terms, i.e., whether the technicians are generally satisfied with the system of their competence training, i.e., they must

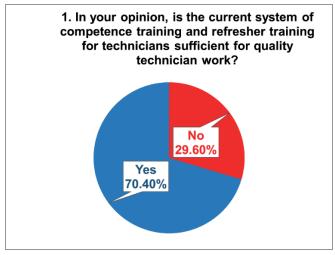


Figure 7 Answer to question No. 1 survey

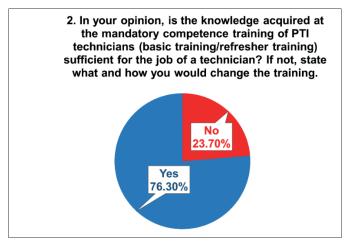


Figure 8 Answer to question No. 2 survey

first undergo the basic competence technician training and then, at regular intervals, a refresher trainings. Question No. 1 was not concerned with satisfaction of the PTI technicians with the training content. Only question No. 2, the answers to which are shown in Figure 8, covered that aspect.

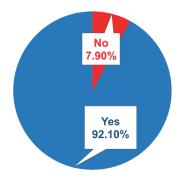
The answers to question No. 2 showed that more than three-quarters of PTI technicians are satisfied with the knowledge they acquired at mandatory technician competence training (76.30 %), or they consider this knowledge sufficient for their work. Less than a quarter do not consider this knowledge sufficient (23.70 %). Of the disaffected the PTI technicians, 53 took the opportunity to state how they would change the training by entering free text. According to their answers, the vast majority of them would make change, in particular, for refresher training to be more frequent, either based on the shorter periodicity, or changes in methodological instructions or legislation. The current 5-year period of refresher training is perceived as significantly insufficient for the PTI technicians. In addition, many PTI technicians would do away with the exams that are mandatory at the end of each refresher training. Furthermore, in training, the technicians would welcome more practical demonstrations and examples, as well as more hours of practice.

A separate question is No. 3, the answer to which is shown in Figure 9.

According to the answers to question No. 3, up to 92.10% of PTI technicians would welcome, in addition to the current refresher training courses for technicians (every 5 years with a qualifying exam), more frequent training without a qualifying exam. Only 7.90% of the PTI technicians polled would be opposed. The PTI technicians who would like more frequent refresher training, to the sub-question asking to choose a specific shorter training interval, 51.30% of them answered that they would like to have training every year, 38.90% would like to train every two years and 9.80% would choose a different PTI technician training interval. Of the PTI technicians who chose a different training interval in the survey, 22 used the opportunity to indicate which one (by entering the free text). The majority of their answers showed that they would like the PTI technician refresher training to take place as needed, especially in connection with new changes in methodological instructions or legal regulations.

Proposals for further changes to the competence

3. In addition to the current PTI technician refresher training, would you welcome more frequent training without a qualifying exam?



Another interval 9.80% Every two years 38.90% Every two years 51.30%

Figure 9 Answer to question No. 3 survey

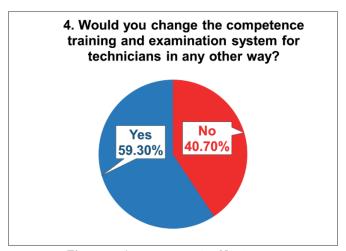


Figure 10 Answer to question No. 4 survey

training of PTI technicians (except those that were the subject of questions No. 1-3) were the topic of question No. 4, the answers to which are shown in Figure 10.

To question No. 4 PTI technicians who took part in the survey answered that 59.30% would change the competence training and qualifying examination of technicians in some other way, and 40.70% would not change it in any other way. Of the PTI technicians who chose the "Yes" option in the survey, 136 used the option to enter the free text. Again, the overwhelming majority of their responses indicated that they would like more frequent refresher training for PTI technicians, preferably on a yearly basis and without qualifying exams to stress them out. Qualifying exam would be recommended by PTI technicians only for those technicians who were found to be in violation of the regulations by the supervisory authorities.

The results of the presented questionnaire survey showed that more than 70% of PTI technicians, who participated in the survey considered, found the setting of the competence training to be sufficient, as well as more than 76% of the technicians consider the knowledge they acquired at these trainings to be sufficient, as well. However, as regards the frequency of

refresher training, the situation was clear. More than 90% of PTI technicians, who participated in the survey, expressed an opinion that, in addition to the current refresher training conducted in 5-year periods, they would welcome even more frequent training conducted mainly at annual intervals. Such an opinion was often repeated in the answers of PTI technicians in the form of inserting the free text. At the same time, there were repeated requests to put more emphasis on the practical part of the training and to explain the current changes in the legislation. Regarding the open questions, many PTI technicians also demanded the cancellation of the qualifying exam, which currently ends the five-year competence training in the Slovak Republic.

3.4 Survey conducted among the PTI technicians on the technical inspections results influenced by the PTI owners

In the previous part of the article, objective factors that could negatively affect the quality of work of PTI technicians were investigated by authors. In addition to these, there are also the subjective factors that can A98

play an even more important role in the evaluation of vehicles. The risk of negatively influencing the result of the technical inspection by PTI owners, as well as the PTI technicians, is the greatest. In connection with the investigation of the existence, manifestations and reasons for influencing the results of technical controls by the PTI owners, a questionnaire survey was conducted among the PTI technicians, which is evaluated in this part of the article.

The survey was already methodically described in section 2. Part of the survey questions was related to performance of the work of PTI technicians, and the subject was the search for factors that could negatively affect the quality of work of PTI technicians by directly or indirectly influencing the result of technical inspections by the owner of PTI.

In this context, the PTI technicians were asked the following four questions:

- Does the PTI owner interfere with the way inspections are carried out (e.g., require you to overlook certain faults on preferred vehicles)? If so, describe how. (Answer option "YES" or "NO"; when answering "YES" a free text marking field was displayed).
- Are you also rewarded based on the number of inspections performed? (Answer option "YES" or "NO").
- 3. What is your average monthly salary (gross)? (The following answer options were displayed here: "from $500 \in \text{to } 1000 \in$ ", "from $1001 \in \text{to } 1500 \in$ ", "from $1501 \in \text{to } 2000 \in$ ", from " $2001 \in \text{to } 2500 \in$ " and "from $2501 \in$ and more").
- Are you satisfied with the quality of the working environment? If not, give reasons. (Possibility of answering "YES" or "NO"; when answering "NO" a free text field was displayed).

Since the mentioned questions were asked by the PTI technician as a part of the survey, which was already described in subsection 3.3, the same parameters apply to it, and the answers to the questions can be considered representative within the set criteria. The answers to each survey question were processed and then graphically presented. Answer to question No. 1 is

1. Does the PTI owner interfere with the way inspections are carried out (e.g. require you to overlook certain faults on preferred vehicles)? If so, describe how.

Yes
20.20%

Figure 11 Answer to question No. 1 survey

shown in the graph in Figure 11.

From the results of the answers to question No. 1 it was shown that for almost a fifth of the PTI technicians (20.20%) who participated in the survey, the PTI owner intervenes in the way the technical inspection is carried out, i.e., demands that certain defects on the preferred vehicles be overlooked. Almost four fifths of the PTI technicians (79.80%) are not interfered with by the owner in the performance of their work. Of the PTI technicians whose PTI owner interferes with their activities, 38 used the opportunity to indicate in what way (by entering the free text). To a lesser extent, the PTI technicians reported being pressured by the PTI owners to inspect the vehicles of their acquaintances for faults. However, the overwhelming majority of their responses revealed that the PTI owners pressure the PTI technicians in particular to overlook defects on vehicles due to the fear of losing customers and moving them to competitors. In this context, they are putting pressure on the PTI technicians to look for defects on vehicles that are not visible on the cameras. They are mainly focused on performance (carrying out technical checks on as many vehicles as possible in the shortest possible time) at the expense of quality. Quantity brings the PTI sales, quality leads to customer outflows. The above can be considered one of the essential factors that negatively affects the quality of work of the PTI technicians and at the same time undermines the purpose for which the PTI was created. In particular, the impact of quantity on the work of technicians is expressed in the answers to question No. 2, shown in Figure 12.

From the answers to question No. 2 it is shown that more than a half of the PTI technicians who participated in the survey are also rewarded based on the number of technical inspections performed (55.70%). The complementary part of the PTI technicians stated that they are not rewarded based on the number of technical inspections performed (44.30%). In relation to the confidence interval of the survey, the answers to this question can be considered balanced. Remuneration of the PTI technicians for the number of technical inspections performed is intended to motivate the higher work productivity (performance of more technical

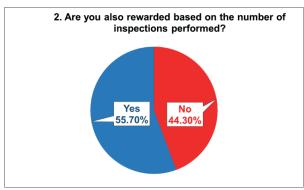


Figure 12 Answer to question No. 2 survey

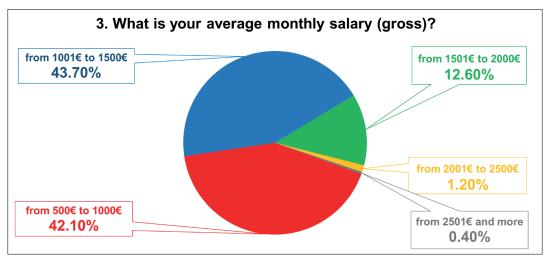


Figure 13 Answer to question No. 3 survey

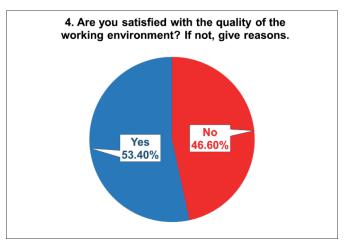


Figure 14 Answer to question No. 4 survey

inspections per unit of time), which also brings the PTI owners higher sales. However, the above can also be considered as one of the factors that negatively affects the quality of work of the PTI technicians, as it indirectly forces them to perform the technician's work inconsistently. The following question 3 deals specifically with the remuneration of the PTI technicians, answers to which are shown in Figure 13.

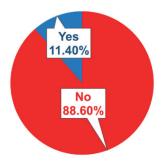
Of all the PTI technicians who took part in the survey, the largest part has a monthly salary between 1,001 € and 1,500 € (43.70 %). The PTI technicians, whose monthly salary ranges from 500 € to 1,000 € (42.10 %), closely followed and in third place are technicians whose monthly salary ranges from 1,501 € to 2,000 € (12.60 %). Technicians whose monthly salary is between 2,001 € and 2,500 € and 2,501 € and more made up a negligible part of the sample (1.20% and 0.40%, respectively,). Given that at the end of 2022, the average nominal monthly salary of an employee in the Slovak economy reached 1,304 €, according to the survey, at least 42.10% of the PTI technicians do not reach it. In relation to the answers to question No. 2, however, it is possible to assume that the gross salary data do not indicate the actual monthly income of the PTI technicians, as they do not include an additional (variable) salary component that depends on the number of technical inspections performed. At the same time, the relevance of the data on the monthly salary of the PTI technicians is distorted by the fact that, due to the preservation of anonymity, it is not known from which region the technicians who participated in the survey came from. However, for the purposes of a rough idea of the salaries of the PTI technicians to exclude extremes that would naturally result in the emergence of other negative phenomena, the collected data is sufficient.

Last but not the least, the quality of the PTI technicians' performance can be influenced by the quality of the work environment in which the PTI technicians work. This is addressed in the following question No. 4, answers to which are shown in Figure 14.

From the answers to question No. 4 it is shown that slightly more than a half of the PTI technicians who participated in the survey are satisfied with the quality of the working environment (53.40 %). Slightly less than half are not satisfied (46.60 %). In relation to the confidence interval of the survey, the answers to this question can be considered balanced. Of the PTI technicians who are not satisfied with the quality of the

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1. Have you encountered corruption among PTI employees?



2. Are you also looking for a PTI where you have acquaintances (a well-known technician, intermediary, etc.)?

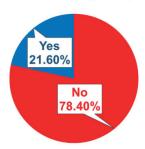


Figure 15 Answer to survey questions

working environment, 90 used the opportunity to state the reasons for their dissatisfaction (by entering free text). From the majority of their answers, it emerged that they most negatively perceive factors harmful to health at the workplace, such as exhaust gases, noise, dust, cold and drafts. Furthermore, the PTI technicians pointed to inadequate working conditions (equipment of premises for employees), insufficient evaluation, the fact that they are pushed to high performance by the owners of PTI, and at the same time are constantly monitored and controlled by professional supervision authorities and sanctioned. The PTI technicians consider the mentioned to be very stressful and mentally exhausting. In the case of disgruntled the PTI technicians, however, their answers can be considered predictable in a way, since the negatives, they state, result from the very nature of their activity. It is also not excluded that employees of other related industries (e.g., car repair shops, tire repair shops, etc.) would respond in the same way, and therefore it is not certain whether the negative phenomena declared by the PTI technicians could be influenced or improved by regulatory measures. Nevertheless, the dissatisfaction of the PTI technicians with the quality of the working environment can be considered as one of the factors that negatively affect the quality of their work.

The results of the presented questionnaire showed that the quality of work of the PTI technicians is negatively influenced by PTI owners, either through the direct interventions (exerting pressure to overlook faults on vehicles and to perform a large number of inspections), or indirectly through their evaluation system and the quality of the work environment.

Just as the PTI owners directly or indirectly negatively affect the quality of work of the PTI technicians, so the technicians themselves consciously influence the results of technical inspections, i.e., they deliberately do not evaluate all the serious and dangerous defects on vehicles. The existence and reasons for such actions of the PTI technicians is described by authors in the following part of the article.

3.5 Survey of influencing the results of technical inspections by the PTI technicians conducted among vehicle operators

The fact that the PTI technicians intentionally influence the results of technical controls follows from the results of professional supervision performed on the PTI by supervisory authorities [19-22]. Publicized and non-publicized criminal prosecutions of the PTI technicians for crimes of corruption, in turn, help to complete the idea of the PTI technicians' motivation for such actions. Intentional influencing of the results of technical inspections by the PTI technicians can also be indirectly demonstrated through research.

As the above is a very sensitive topic, it was not practical to conduct a relevant survey directly among the PTI technicians as they would probably not admit it. Therefore, a survey conducted on the subject among vehicle drivers, who subject their vehicles to regular technical inspections at the PTI, could provide more information. Due to the high number of vehicle drivers, as well as the fact that the mentioned topic is not the main goal of this article, the survey was only indicative, on a random sample. The subject of the survey was the confirmation or refutation of the existence of intuitive factors that have the effect of consciously influencing the results of technical inspections by the PTI technicians, i.e., corruption and acquaintances at the PTI. The basis for this is the answers of vehicle drivers who submit vehicles to regular technical inspections at the PTI.

In this context, randomly selected vehicle drivers were asked the following two survey questions:

- Have you encountered corruption among the PTI employees? (Answer option "YES" or "NO")
- Are you also looking for a PTI where you have acquaintances (a well-known technician, intermediary, etc.)? (Answer option "YES" or "NO")

Total of 88 people participated in the survey and the results of their answers were processed and then graphically depicted in Figure 15.

The answers to questions showed that more

than a tenth of the vehicle drivers interviewed had encountered corruption among the PTI employees. At the same time, more than a fifth of drivers also look for the PTI for a technical vehicle inspection where they have some acquaintances (technician, intermediary, etc.). Given that this is an indicative survey, the declared values may not be exact. That was not even the goal of the survey. The goal of the survey was only to confirm or refute the existence of negative factors that distort the PTI system, which was confirmed. The essence of the corrupt behavior of the PTI technicians is to intentionally assess a vehicle with serious and dangerous defects as fit for operation in the road traffic, and to ignore these defects for a bribe. The same applies to the so-called acquaintances on the PTI, which are sought by drivers of vehicles with the same intention.

Thus, the mentioned survey indirectly showed that the PTI technicians themselves deliberately influence the result of technical inspections, thereby reducing the quality of their work, as well as its value, and this also with the help of corrupt behavior and loss of impartiality, which can be considered a significant deforming element of technical inspections and an ethical problem. At the same time, the above can be considered as one of the essential factors that negatively affects the quality of work of the PTI technicians, thus undermining the purpose for which the PTI were established.

4 Conclusions and discussion

In this article, objective and subjective factors, negatively affecting the quality of work of the PTI technicians, were investigated by authors in the case of the Slovak Republic. At the beginning, the weakest link of technical inspections was defined, which is the PTI technician and his wide scope for subjective assessment of defects on vehicles, which creates the danger of wrong judgments and fraud. Of all the vehicle items checked, up to 94.12% are assessed by subjective assessment, i.e., based on the senses (especially visually) and only 5.88% by the PTI devices. This can be eliminated by deploying technical means monitoring the activity of the PTI technicians (e.g., monitoring and recording devices) with the possibility of archiving them. Likewise, technical means preventively eliminating the risk of incorrect (intentional, unintentional) evaluation of the results of technical inspections (devices with a connection to CIS TK, e.g., braking tester or mobile device [23]) play an extremely positive role. From the aforementioned, as well as related studies [24], it can be deduced that by deploying technical means, progress can be achieved in the quality of the PTI activities with a positive impact on the road traffic safety.

Furthermore, by examining the influence of specific (objective) factors that can negatively influence the activity of the PTI technicians, through their subjective (sensory) assessment of the technical condition of a vehicle, it was found that the effect of formal education of the PTI technicians on selected critical indicators (success in qualifying exams after the basic training of the PTI technicians and violation of regulations during the performance of technical controls) did not manifest itself. No such negative phenomenon was identified, which could be interpreted as a consequence of the lower level of knowledge and experience of the PTI technicians, resulting from the replacement of their formal education and experience with a vehicle knowledge verification exam, thus negatively affecting the quality of work of the PTI technicians.

The authors of article also examined whether the informal education of the PTI technicians (the system of their mandatory competence trainings, which are already precisely focused on the performance of the PTI technician's work) is satisfactory for their activity. This was done through a questionnaire survey among the PTI technicians. The results of this survey mainly showed that up to 92% of the PTI technicians would like to have more frequent technician refresher training, mostly every year (51%), without a qualifying exam, with an emphasis on changing technical inspection regulations and practical demonstrations.

As for the cancellation of qualifying exams after the refresher training, the opinions of the PTI technicians can be justified by efforts to make conditions easier and eliminate stressful situations, rather than professionally justified requirements. In addition, the complete abolition of qualifying exams could ultimately lead to a reduction in the quality of the PTI, as then the PTI technicians would not be motivated to approach mandatory competence training responsibly and any increase in their frequency could be ineffective (passive completion). However, the current qualifying exam, which the PTI technicians currently have to pass every five years after the refresher training, could be simplified by consisting of a shortened written test with practical part.

As for the requirements of the PTI technicians that their refresher training take place mainly at 1-year intervals, it would be very appropriate to respond by complying to this request, i.e. the frequency of refresher training for the PTI technicians would be shorter, e.g., every 18 months, while after the completing the third refresher training, the PTI technicians would have to pass a qualifying examination. In addition, a comparison of the competence training of selected EU states that published information on the method of providing training for the PTI technicians (Croatia, Czech Republic, Finland, Hungary, and Lithuania) showed that the frequency of refresher training in these states varies from 1 year to 3 years, [25]. With such a large dynamics of changes in regulations in the field of technical inspections, the 5-year intervals of further refresher training for the PTI technicians in the Slovak Republic are really insufficient, with a possible negative impact on the quality of work of the PTI

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technicians.

In addition to the objective factors affecting the work of the PTI technicians, authors in the article are also examined the subjective factors that can play an even more important role in the evaluation of vehicles. The risk of negatively influencing the result of the technical inspection by the PTI owners as well as the PTI technicians, is the greatest. In connection with investigation of the existence, manifestations and reasons for influencing the results of technical controls by the PTI owners, a questionnaire survey was conducted among the PTI technicians. The result of this survey was that the PTI owners influence the PTI technicians to overlook defects on vehicles (especially those not visible on cameras) due to fear of losing customers and moving them to competitors. They are mainly focused on performance (carrying out a technical inspection on as many vehicles as possible in the shortest possible time) at the expense of quality. Even according to the quantity criterion, the PTI technicians are mostly evaluated. Given that the PTI technicians are employees of the PTI owners, they must respect the will of their employer.

The current setting of sanctions for violation of related regulations in the Slovak Republic is mainly aimed at the PTI technicians. Sanctions are graded according to the severity of the PTI technician violations and are applied separately for each violation. They range from 30 to 1,200, in combination with the obligation to complete special refresher training with a qualifying exam (the so-called penalty). In the case of the most serious violations, it is possible to withdraw the PTI technician's certificate, with the provision that the technician will not be able to perform his work for 10 years. On the other hand, it is possible for the PTI owner to be fined from 2,000 € to 5,000 € (usually only 2,000 €) under certain circumstances (failure to detect defects on the vehicles by several PTI technicians) and, in the case of the most serious violations, to withdraw the license to operate a the PTI (the so-called objective responsibility of the PTI owner) [26]. In relation to the common violation of regulations by the PTI technicians, the occasional sanction imposed by the PTI owner does not motivate then at all to influence the PTI technicians to perform technical inspections of a higher quality. The revenue that the PTI owners receive from the amount of technical inspections performed is far higher and more motivating than the occasional fine for not detecting defects on vehicles by the PTI technicians (the poor quality of their work). For the above reason, it would be appropriate to introduce one more sanctioning measure into the legal system of the Slovak Republic, in addition to the financial sanction, which would be aimed directly at the main motivation of the PTI owners. This would institute a temporary suspension of the PTI. If, at a given the PTI, it was determined by the professional supervision authorities, in one inspection, that the PTI technicians did not detect or record a certain number of serious or dangerous defects on vehicles, the administrative authority would decide to suspend the activity of the given the PTI for a certain period of time (for example, from a few days to a few weeks), depending on the number of undetected defects by technicians.

The mentioned measure would provide that the PTI owners would be more motivated to supervise the PTI technicians and influence them to detect all the serious and dangerous defects on vehicles, and therefore to perform their work with higher quality, and not the other way around, as it emerged from the conducted survey. The threat of a sudden decrease in sales, resulting from the temporary impossibility of performing the technical inspections, as a result of poor quality work of the PTI technicians, could eliminate the negative influence of the results of technical inspections on the part of the PTI owners and improve the quality of the PTI's work.

Furthermore, a survey, reported in this article, was carried out by authors on the influence of the results of technical inspections by the PTI technicians, carried out among the vehicle operators. From the aforementioned survey (as well as from the results of expert supervision carried out over the PTI [27]), it emerged that the PTI technicians themselves deliberately influence the result of technical inspections, including with the help of corrupt behavior and the so-called acquaintances, which can be considered a significant deforming element of technical inspections. At the same time, the above can be considered as one of the essential factors that negatively affects the quality of work of the PTI technicians, thus undermining the purpose for which the PTI were established. However, it is very difficult to apply any measures to improve the quality of the PTI activity to this phenomenon. This is a cross-sectional phenomenon, and its effective elimination is not easy. On the one hand, the Slovak Republic is fighting against corruption at the PTI so that in Act No. 106/2018 Coll. defined certification according to STN ISO 37001 Management systems against corruption, as one of the conditions for obtaining authorization to operate the PTI [28], however on the other hand, no ISO standard will prevent the PTI technician from corruption. Likewise, the occasional crackdown on corruption among the PTI technicians by law enforcement agencies has a preventive effect only in the short term. This is a significant ethical problem and the attempt to eliminate corruption at the PTI is a huge challenge for the future.

Authors of this article, objective and subjective factors negatively affecting the quality of work of the PTI technicians in the Slovak Republic environment, were investigated. However, the question remains whether the results of this article would not have been predictable, even without any research being carried out in this area. The basic element of technical inspections is the PTI technician, who is a human being with all the human qualities that underlie his work. Taking this fact into account, then one could intuitively assume that the

work of every person (not excluding the PTI technician) is positively affected by the degree of use of technical means that prevent fraud and enable better control, as well as the fact that the greater the scope for subjective judgments, the more room there is for mistakes and fraud, that no one does a full-quality job, that the one who has been entrusted with the authority to decide on something is also prone to corrupt behavior (especially if he has a low salary), that the essence of business is creation of profit and retaining customers, and that the more measures are taken aimed at eliminating phenomena, caused by the human factor, the more the quality of the resulting product or service would increase. On the other hand, without research, it would not be possible to adopt these general assumptions automatically for the PTI environment in the Slovak Republic, but in particular, it would not be possible to determine the extent and importance of individual factors that influence the quality of the PTI activity. Moreover, a fully harmonized system of technical controls is in place within the EU member states, however, no comparable average vehicle evaluation results [29]. At the same time, in each state, a person with the same human characteristics and according to the same rules performs the technical control. From the above, it follows that in each EU country there are certain specificities that more or less influence the quality of the PTI activities, and therefore it certainly made sense to get to know them in detail, and examine them in the Slovak Republic environment. Because this is the only way to effectively target them when creating measures to improve the quality of the PTI activities.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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ORIGINAL RESEARCH ARTICLE

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SUBSTANTIATION OF PARAMETERS OF CARGO MOVEMENT BY CAR ROPE SYSTEMS

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Resume

The automobile cable systems for loading and unloading operations between the vehicle-support and vehicle-vehicle points are presented in this paper. The scheme of the automobile mobile cable system is based on a two-cable cableway. Based on this scheme, the parameters of the movement of goods by automobile cable systems are substantiated at variable parameters: mass m artificial loads together with the mass of the frame structure: $35 \le m \le 95$ (kg); the angle of inclination α pairs of parallel ropes to the horizon: $10 \le \alpha \le 15$ (°); tension force ropes $2400 \le T_D \le 5000$ (N). It has been established that the dominant effect on the minimum time T has angle α , then mass m and tension forces T_D ropes. At the same time, it is worth noting that the range of discrepancy of the quantities T values, when the above factors change, is insignificant and is close to 5,7% for (m/α) and 6,6% for (T_D/α) .

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1 Introduction

The study of the development of transport and logistics technologies in the system of freight transportation using the rope systems, which has become widely used in various fields, is outlined in this article. The research analysis of the processes of loading artificial cargo into warehouses by various types of transport and technological machines has been provided in [1-2]. However, traditional types of transport mechanisms are structurally complex and material-intensive, and their use is economically feasible during the transportation of goods over long distances [3]. The well-known cable transport mechanisms for moving various artificial loads, which can be prototyped in

the development of new transport and technological machines, are presented in [4-6].

The use of rope transport mechanisms on the self-propelled wheeled mobile transport and handling complexes allows for the autonomous delivery of the necessary technological equipment to the workplace and its quick deployment for transport and handling operations [7-8]. In articles [9-10] the mobile lifting and rope mechanisms of transport equipment for the sustainable development of heavy transport are formed by autonomous self-propelled units, connected by a single rope system based on the wheeled chassis of a high load capacity. Regularities of change of optimal parameters of intermediate supports and load-carrying and traction ropes at the change of design capacity

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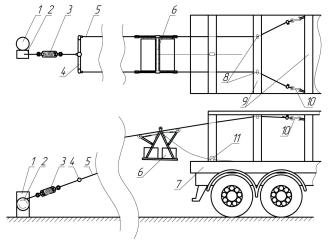


Figure 1 The schematics of a car mobile rope system for loading and unloading between the points of the car support: 1 - support; 2 - winch; 3 - spring; 4 - rocker arm; 5 - two-cable cable car; 6 - suspended cargo platform for moving cargo; 7 - car; 8 - limiters; 9 - hanging frame: 10 - hooks; 11- tow-line

of a cableway were revealed based on an analysis of performed calculations [11].

The developed experimental devices and research methods, together with the results of preliminary studies of the proposed rope transport and technological mechanism, are given in the articles [12-13].

It is important to use those devices in automobile construction to facilitate the movement of people and goods through small rivers, various obstacles, in the mountains, transportation of injured or wounded, ammunition, timber, etc. This type of modern multipurpose cable transport mechanism is perspective and effective.

The high novelty of this transport technology and the impossibility of fully using the existing design and calculation methods, which were developed for stationary cargo mobile transport and transshipment complexes, require the creation of scientifically based theoretical foundation for design, calculation, and modelling of work processes at all stages of the life cycle.

Improving the performance of rope systems for transport and handling operations, which will ensure the creation of a promising design of a multi-purpose rope transport system with the best characteristics, maximum functionality and high-quality indicators, is a key step in solving this technical problem.

2 Materials and methods

Nowadays, the usage of the rope systems has become widely used in various fields. To this end, two structural diagrams of car mobile rope systems for loading and unloading between the points of car-support (Figure 1), and car-car (Figure 2), have been developed [14].

In the first scheme, the car rope system, which consists of a rope (two-rope cableway) 5 and a suspended load platform for moving loads 6, is fastened by hooks 10 through the limiters 8 to the hinged frame 9 of the

car 7, and on the other hand through the rocker arm 4 spring 3 and ratchet mechanism (winch) 2 to the support (a screw quick-mounting support can be used) 1. The tension of the rope system is carried out by the ratchet mechanism 2, and the compensation of dynamic loads is carried out by the lanyard spring 3. The speed of the suspended load platform 6 is regulated by the line 11. Such a car rope system can be widely used for loading and unloading, moving people and goods, setting up crossings over small rivers and various obstacles, etc.

Figure 2 shows a car mobile rope system, which provides loading and unloading operations between two cars, consisting of a rope (two-cable car) 1 and a suspended cargo platform for moving goods 2. The rope 1 through limiters 3 is attached by a hook 9 and through the winch 5 to the frame 4 of the car 6, and on the other hand through the tension rollers 8 to the frame of the car 7.

The tension of the rope system is carried out by the ratchet mechanism 5, and the speed of the suspended loading platform 6 is regulated by line 10. This system can be widely used for transshipment of goods in the implementation of road freight transport.

Substantiating the parameters of cargo movement by the car rope systems, it has been stated that the loading processes of two cable cars are identical (by adjusting their equal tension through the rocker arm 4 (Figure 1) or tension rollers 8 (Figure 2). Therefore, a flat problem with conditional movement of a load of half mass $(m=m_{\Sigma}/2)$ on only one rope has been considered where m_{Σ} is the total weight of frame construction and cargo.

It has been assumed that the length of the route (projection of the length of the ropes on the horizontal plane) is equal L, the height of the rope suspension in the loading area (point A) - H, and the unloading area (point B) - h. Then the difference in height of the rope suspension ΔH at the points of loading and unloading will be $\Delta H = H - h$, Figure 3 [15]. Since the rope has

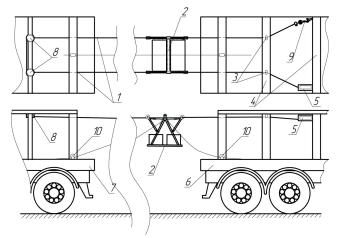


Figure 2 The schematics of a car mobile rope system for loading and unloading between the points of car-car: 1 - two-cable cableway; 2 - suspended cargo platform for moving cargo; 3 - limiters; 4 - frame; 5 - winch; 6 - car; 7 - car frame; 8 - tension rollers; 9 - hook; 10 - tow-line

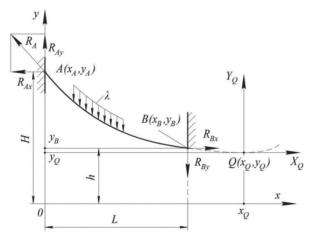


Figure 3 Calculation scheme of placement and fastening of the ropeway

its own weight, which is evenly distributed along the route, the unloaded rope (without a suspended platform with a load) is modeled with a flexible inextensible heavy thread with a uniform linear distribution λ of the entire mass of the rope m_k in length l_k [16-19]:

$$\lambda = m_k/l_k = \rho_k S_k, \qquad (1)$$

where ρ_{k} - specific weight of the rope; S_{k} - rope cross-sectional area.

The sagging of an unloaded rope by mass m_k has been considered. According to the model of sagging heavy thread, it is stretched under the action of weight $G_k = m_k g$, and in the rope there are tension forces T = T(x), the axial component of which is constant $T_x = T_0 = const$ and numerically equal to the horizontal component of the reaction force of the supports R_{Ax} and R_{Bx} respectively at the points of suspension A and B. Place the beginning of the coordinate system xQy at the beginning of the loading zone, where the axis Ox is directed along the movement of the weight horizontally at the floor level of the warehouse. The coordinates of the points of the rope suspension in the loading area are

A(0;H), in the unloading area B(L;h).

The equation of the chain line in the coordinate system *xOy* will be [16, 19]:

$$y = a_k \left[ch \left(\frac{x - x_Q}{a_k} \right) - 1 \right] + y_Q, \tag{2}$$

where a_k - chain line parameter, $a_k = T_0/(\lambda g)$; x_Q and y_Q coordinates of the vertex of the parabola Q in the coordinate system xOy, that is, the points of the global minimum of the deflection line passing through the suspension points $A(x_A; y_A)$ and $B(x_B; y_B)$.

For roads with previous working mounting tension $T_{\scriptscriptstyle 0}$, which provides a small deflection, the equation of the sag line will be:

$$y_M = \frac{(x - x_Q)^2}{2a_k} + y_Q. {3}$$

Accordingly, in the system xOy (Figure 3) Equation, which determines the running length of the cable as the load passes, has the form:

$$l_{kM} = x + \frac{x_Q^3 - (x_Q - x)^3}{6a_k^2} \tag{4}$$

Equations (3)-(4) are obtained after expanding the

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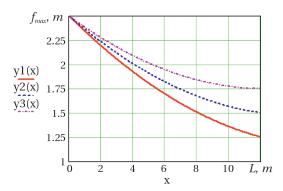


Figure 4 The shape of the sagging ropes line on the route length $L=12\,m$ with the same mounting tension depending on the difference in the levels of attachment of the rope: $y1(x) - \Delta H = 1.25\,m; y2(x) - \Delta H = 1.0\,m; y3(x) - \Delta H = 0.75\,m$

rope deflection Equation (2), and the similar rope length equation, into the Maclaurin series with discarding insignificant components. Thus, for the track length $L\!=20\,\mathrm{m}$ with deflection $1\,\mathrm{m}$ ($a_{\scriptscriptstyle k}\!=\!50~\mathrm{m}^{\text{-1}}$), the difference in deflections, calculated according to dependencies Equations (2) and (3) will be only 3 mm, and the difference in the calculated lengths will be less than $0.02\,\mathrm{mm}$, which is significantly less than the measurement errors of these values.

For a ropeway designed to move cargo under the action of gravity, the height of the suspension in the loading area H (point A) is greater than the height of the suspension in the unloading area h (point B). The equation of a straight line passing through the points of suspension point A and point B, in the xOy system is:

$$y_s = y_A - x \operatorname{tg} \beta = H - x \operatorname{tg} \beta, \tag{5}$$

where β - the angle of the straight line connecting the suspension points (the angle of the straight line), $tg\beta=(H-h)/L=\Delta H/L$.

Running sagging ropes will be [15-17, 19-20]:

$$f(x) = y_s - y_M \tag{6}$$

Taking into account the values of the suspension points A(0;H) and B(L;h) coordinates in the system xOy:

$$x_Q = \frac{L}{2} + \frac{a_k(H - h)}{L} = 0.5L + a_k \text{tg}\beta,$$
 (7)

$$y_Q = H - \frac{x_Q^2}{2a_F}. (8)$$

It follows from Equations (3) and (7) that for a ropeway of length L with a height difference $\Delta H = H - h$ at the initial installation value $a_k = 0.5 L/{\rm tg}\beta$, the zone of maximum sagging coincides with the zone of unloading $(x_Q = x_B)$; at $a_k < 0.5 L/{\rm tg}\beta$ is located on the route between the loading and unloading area $(0 < x_Q < x_B)$; at $a_k > 0.5 L/{\rm tg}\beta$ - off the track $(x_Q > x_B)$; or according to Equation (4) on the approximate dependence:

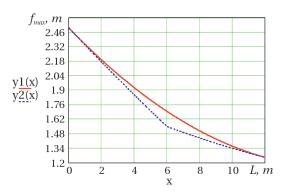


Figure 5 The shape of the sagging ropes line without cargo and with suspended cargo, located in the middle of the route

$$l_{AK} = s = x + \frac{3x_Q x(x_Q - x) + x^3}{6a_b^2},$$
 (9)

where s - the linear path parameter corresponding to the running length of the rope.

The length of the rope, suspended between the supports $A(x_A; y_A)$ and $B(x_B; y_B)$ with tension T_0 ; will be $l_{ADB} = l_k = L(1+ \mathrm{tg}^2\beta) + L^3/(64a_k^2)$. The initial length of the rope, without taking into account the increase in tension, will be $l_0 = l_k/(1+\varepsilon_0)$, where $\varepsilon_0 = T_0/(E_kS_k) = a_k\rho_kg/E_k$ - relative elongation of the rope from the mounting tension.

With the same mounting tension (a = const), depending on the height of the suspension h in the unloading zone, the route will have a different curvature (Figure 4).

Horizontal reactions of the supports (suspension points), stretching the rope without load are [19, 21-24]:

$$R_{Bx} = -R_{Ax} = T_0.$$
 (10)

Taking into account Equation (3), the vertical reactions of the supports are:

$$R_{Ay} = \dot{y}_x(0) \cdot T_0 = x_Q T_0 / a_k,$$
 (11)

$$R_{By} = \dot{y}_x(L) \cdot T_0 = (x_B - x_Q) \cdot T_0/a_k.$$
 (12)

The case of loading the rope at point D, the suspended frame structure has been considered, with a load whose total weight G=mg significantly exceeds the weight of the ropes (an order of magnitude or more). It is obvious that under the action of the load the rope will be stretched, and the tensile forces will significantly exceed their mounting tension and, accordingly, the curvature of the branches of the route will be negligible.

Figure 5 shows the chain lines of sagging of the rope with the parameter $a_{\rm k}$ = 100 m without load (solid line) and with suspended load (dashed line) with load parameter f $a_{\rm k}$ = 350 m.

As follows from Figure 5, the branches of the loaded

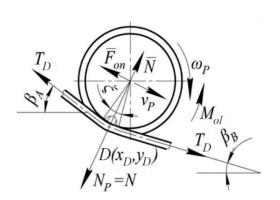


Figure 6 Calculation scheme of interaction of the rope with the suspension roller

ropeway are practically straightened. In the load zone (point D) the rope covers the suspension roller, and in the contact zone between the rope and the roller there is a normal force N, Figure 6.

Let the angle of coverage of the roller rope is ξ , and the axial tensile strength of the rope in the area of the roller is T_D . If the forces of sliding friction were neglected [25], the tension of the rope point D on both sides of the supports would be equal $T_{DA} = T_{DB} = T_D$.

Then, the normal reaction force of the rope acting on the roller will be [12, 14]:

$$N = 2T_D \sin(\xi/2). \tag{13}$$

For this case, with a small length of the transport route, the weight of the suspended frame structure with the load is significantly greater (an order of magnitude or more) than the weight of the rope (ropes), and, therefore, it is assumed that the rope branches from the supports to the load area are straight, (Figure 3, 7). Let's assume that the angle of inclination of the line is positive when the point of suspension of the rope is above the point of suspension of the load (the angle of inclination of the line towards the loading point A) and negative when the point of suspension of the rope is below the point of suspension of the load (angle β_B , according to Figures 6, 7). In this case, the points of suspension of the rope (point A and point B) with the point of action of the load suspension (point D) form a triangle in which the side AB is placed at an angle β with respect to the axis Ox, the side AD at an angle β_A , and the side BD - at an angle β_B , Figure 7. Accordingly, the angles of the triangle will be equal: $\angle A = \beta_A - \beta; \angle B = \beta + \beta_B;$ $\angle D = \beta_D = 180 -\xi_{p}=180-eta_{A}-eta_{B}$, where the angle of the suspension roller coverage ξ_p is:

$$\xi_{p} = \beta_{A} + \beta_{B}. \tag{14}$$

The reaction force vector N divides the angle $\angle D$ in half and is directed at an angle

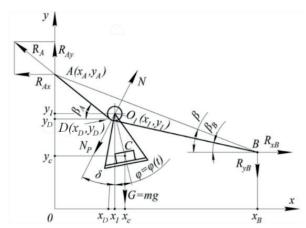


Figure 7 Calculation scheme of the suspension of the frame system with the load on the ropeway

 $\beta_D/2 = 90^{\circ} - (\beta_A + \beta_B)/2$ with respect to the sides AD and BD. Therefore, the vector N is placed at an angle concerning the vector of the force of gravity G (or to the axis Oy).

It is assumed that the forces of inertia are insignificant. Then, the normal reaction of the rope, when interacting with the roller, will be:

$$N = G\cos\delta = G\cos\left(\frac{\beta_A - \beta_B}{2}\right). \tag{15}$$

The tension of the ropes due to the action of the load in the area of its suspension:

$$T_D = \frac{G\cos[(\beta_A - \beta_B)/2]}{2\sin[(\beta_A + \beta_B)/2]}.$$
 (16)

Accordingly, the horizontal and vertical reactions at the points of suspension:

$$R_{Ax} = -T_D \cos \beta_A; \quad R_{Ay} = T_D \sin \beta_A, \tag{17}$$

$$R_{Bx} = T_D \cos \beta_B; \qquad R_{By} = T_D \sin \beta_B. \tag{18}$$

Taking into account Equations (15)-(18), the angles of inclination of the branches β_A and β_B interconnected functionally, resulting from the equality of the projections of all the forces on the axis. From the analysis of dependences Equation (16)-(18) it follows that the projection of tension forces on the axis Ox of the rope, from the side of the highest suspension point (point A), is smaller than the tension force from the lower suspension point (point B) by magnitude:

$$T_{Bx} - T_{Ax} = N\sin\delta = G\sin\delta\cos\delta =$$

$$= \frac{G\sin(\beta_A - \beta_B)}{2}.$$
(19)

Since the suspension platform moves on the rope under the action of gravity, the reaction force of the rope on the roller is directed along the axis of the roller and has no tangential component, so the tension force of the rope T_n , in the case where the weight of the rope,

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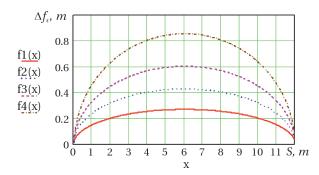


Figure 8 Dependence of deflection Δf_s route on the road s, passed by a roller on a rope at $\mathcal{E}_{\Sigma}: 1 - \mathcal{E}_{\Sigma} = 0.001$; $2 - \mathcal{E}_{\Sigma} = 0.0025$; $3 - \mathcal{E}_{\Sigma} = 0.005$; $4 - \mathcal{E}_{\Sigma} = 0.01$

compared to the weight of the load is insignificant and can be neglected, are virtually unchanged throughout the area between the points of suspension of the rope and point D. This is confirmed by the fact that the curvature of the loaded rope is insignificant, and its route is almost rectilinear, which is the basis for the assumption. Let the distance AB, Figure 7, between the rope suspensions (point A and point B) be marked as $l_{AB}=2c$. With constant rope length l_k , $l_k>l_{AB}$, when moving the load on the rope, the point of its suspension D will move along a trajectory that corresponds to an ellipse with foci located at the points of suspension of the rope $A(x_A; y_A)$ and $B(x_B; y_B)$, and the center of which is located in the middle of the segment AB.

The graph of change of a deflection of a route s, on the way passed by a roller on a rope for various loading which is accepted invariable, that is for various values ε_{Σ} is shown in Figure 8.

Resistance to movement is determined by the running path s that the roller passes along the length of the rope. The length of the rope l_k exceeds the distance l_{AB} between the points of suspension point A and point B, $l_k = l_{AB}(1+\varepsilon_\Sigma)$. Here ε_Σ is the relative excess length of the rope distance between the points of suspension of the rope in a straight line $l_{AB}=2c=L/\cos\beta$, taking into account its elongation from the pre-tension and the tension from the load [26].

For determination of the running deflection $\Delta f_s = \Delta f_s(s)$ at the point of suspension depending on the path of movement of the suspension roller on the rope s determines the energy parameters of transportation, so it is taken as an independent parameter in the model of transportation of goods by cable car. It is denoted as $s/l_b = k_s$. Then:

$$\Delta f_s = \frac{L}{2\cos^2\beta} \sqrt{\frac{(2\varepsilon_{\Sigma} + \varepsilon_{\Sigma}^2) \cdot }{\cdot [1 + (1 - 2k_s)^2 (1 + \varepsilon_{\Sigma})^2]}}.$$
 (20)

The graph (Figure 9) shows the running height difference $\Delta h(x) = -(x_s \operatorname{tg} \beta - \Delta f_s)$ for different mounting tension of the cables, providing a given excess ε_{Σ} of the length of the stretched cable over the distance

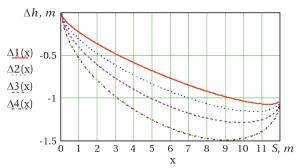


Figure 9 Dependence of the running height difference Δh suspension system with cargo on the road s, passed by a roller on a rope at: $1 - \mathcal{E}_{\Sigma} = 0.001; 2 - \mathcal{E}_{\Sigma} = 0.0025;$ $3 - \mathcal{E}_{\Sigma} = 0.005; 4 - \mathcal{E}_{\Sigma} = 0.01$

between the points of suspension of the rope.

The angles of inclination of the branches β_A and β_B (Figure 10) are determined from the triangle ΔABD :

$$\beta_A(s) = \arccos\left(\frac{a}{s}\right) + \beta,$$
 (21)

$$\beta_B(s) = ar\cos\left(\frac{l_{AB} - a}{l_k - s}\right) - \beta. \tag{22}$$

where a - projection of a stretched branch AD (running route s, which passes the roller suspension on the rope) per segment AB (distance between the points of suspension of the rope):

$$a = a(s) = s(1 + \varepsilon_{\Sigma}) - l_{AB}(\varepsilon_{\Sigma} + 0.5\varepsilon_{\Sigma}^{2}). \tag{23}$$

The changing of the angles β_A and β_B in terms of s, for different mounting tension of the rope and according to the parameter ε_{Σ} , is shown in Figure 10.

For gravitational transport of goods, the direction of reaction from the ropes is set by the angle δ , determined by the directions of the branches of the ropes, that is the angles β_A and β_B , $\delta=(\beta_A+\beta_B)/2$. Changing the running value of the angle δ for different values ε_Σ , in terms of the route s, passed by the roller suspension is shown in Figure 11.

Given the known placement of the load at the current time and, accordingly, the known laws of change of angles β_A , β_B and δ at a given tension, which determines the required excess length of the cable ε_{Σ} , it can be stated that the axial tension of the cable mechanism and the reaction determined by Equation (16)-(18).

Figure 12 shows the change in axial tension force T_D loaded rope at different parameters ε_{Σ} the calculated lengths of the rope are set, and Figure 13 shows the dependence of the reactions of the rope suspension when moving the load along the route, on the parameter s.

These dependencies confirm that the main load due to the action of the suspended system for routes with the recommended working sagging of ropes, falls on the horizontal components of the reactions of the supports, $R_{\rm Ax}$ and $R_{\rm Bx}$, at the point of suspension, which,

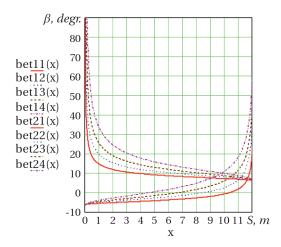


Figure 10 Changing the angles of the rope branches β_A (1) and β_B (2) in terms of s, for: $1 - \varepsilon_{\Sigma} = 0.001$; $2 - \varepsilon_{\Sigma} = 0.0025$; $3 - \varepsilon_{\Sigma} = 0.005$; $4 - \varepsilon_{\Sigma} = 0.01$

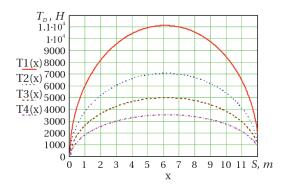


Figure 12 Changing the force of axial tension T_D , H rope in terms of the parameter of the running length of the rope s to the load point D for: $1 - \mathcal{E}_{\Sigma} = 0.001; 2 - \mathcal{E}_{\Sigma} = 0.0025;$ $3 - \mathcal{E}_{\Sigma} = 0.005; 4 - \mathcal{E}_{\Sigma} = 0.01$

in practice, can take the forces of axial tension ${\cal T}_{\scriptscriptstyle D}$ of the rope.

Figures 7-13 show the change of system parameters depending on the path s traversed by the roller on the rope. In the coordinate system xOy the projection of the load on the axis Ox will be $x = s\cos\beta_A(s)$. At insignificant slopes of the loaded route values x and s practically coincide.

In this case, it is possible to assume that the load moves on the ropes without hesitation. The potential energy of the cargo at the loading and unloading points will be $W_{Plow} = mgh_3$ and $W_{Punl} = mgh_p$, respectively. The potential energy difference will be [16-17]:

$$\Delta W_{Pdow} = mg(y_{dow} - y_{unl}) = mg(x_{unl} - x_{dow}) \times tg\beta + \Delta f(x_{dow}) - \Delta f(x_{unl}).$$
(24)

The increase in kinetic energy is:

$$\Delta W_{Punl} = m(v_{Cdow}^2 - v_{Cunl}^2)/2,$$
 (25)

where v_{Cdow} and v_{Cunt} - the initial speed that can be obtained by the system in the loading area and the

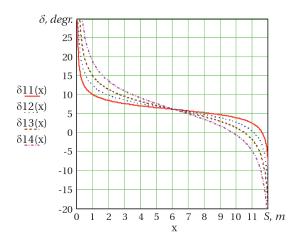


Figure 11 Changing the angle of the rope N on the roller suspension of cargo in terms of s for: $1 - \mathcal{E}_{\Sigma} = 0.001$; $2 - \mathcal{E}_{\Sigma} = 0.0025$; $3 - \mathcal{E}_{\Sigma} = 0.005$; $4 - \mathcal{E}_{\Sigma} = 0.01$

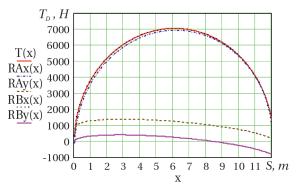


Figure 13 Dependences of changes in the force of axial tension T_D and reactions, R_{Ax} , R_{Ay} and R_{Bx} , R_{By} on the parameter of the running length of the rope s at $\mathcal{E}_{\Sigma} = 0.0025$

suspension speed in the unloading area, respectively.

Loss of resistance to displacement due to the rolling friction forces $F_{\mu}=\delta_{N}N/r_{p}=\lambda_{N}N$ is:

$$\Delta A_{Punl} = \lambda_N N l_{kx} = \lambda_N l_{kx} mg \cdot \cos(\delta + \varphi). \tag{26}$$

Substituting Equation (24)-(26) in the law of conservation of energy Δ $W_{Pdow} = \Delta$ $W_{Punl} - \Delta$ A_{λ} one obtains:

$$m(v_C^2 - v_{C0}^2)/2 = mg(x_{unl} - x_{dow}) \operatorname{tg} \beta + \Delta f(x_{dow}) - \Delta f(x_{unl}) - \lambda_N l_{kx} mg \cdot \cos(\delta + \varphi),$$
(27)

where the speed of a cargo in the unloading area is determined as:

$$v_{Cunl} = \sqrt{\frac{2g(x_{unl} - x_{dow}) \operatorname{tg} \boldsymbol{\beta} + 2\Delta f(x_{dow}) - \left(-2\Delta f(x_{unl}) - 2\lambda_N l_{kx} mg \cdot \left(-2\Delta f(x_{unl}) + v_{Cdow}^2\right)\right)}.$$
(28)

As a rule, such a speed at sharp stop of cargo and, accordingly, containers, will cause a shock that can lead to injury of a cargo. Springing of a suspended frame

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design by a clamping roller allows for a gradually reduce the speed completely, or to an acceptable value for a condition of not causing damage to the freight.

When the system is forcibly stopped in the suspension zone, its kinetic energy of gradual motion $\Delta W_{Plow} = m v_{Cunl}^2/2$ will be converted into the kinetic energy of oscillating motion $\Delta W_{Plow}^I = I_D \dot{\phi}_D^2/2$:

$$mv_{Cunl}^2 = I_D \dot{\boldsymbol{\varphi}}_D^2. \tag{29}$$

The moment of inertia $I_{\scriptscriptstyle D}$ of the oscillating suspension platform with the load can be determined both theoretically and experimentally. Since the loads of different weights and configurations can be transported, the moment of inertia of the system is easiest to determine experimentally by period $T_{\scriptscriptstyle \omega}$ (frequency $\omega_{\scriptscriptstyle I}$) of oscillations of the suspension system as a physical pendulum.

It is known that the period of oscillation as a physical pendulum [18] is:

$$T_{\omega} = \frac{2\pi}{\omega_I} = 2\pi \sqrt{\frac{I_D}{d_C m g}}, \qquad (30)$$

where m - the total weight of the frame and load; $d_{\rm C}$ - the distance from the point of suspension to the center of mass.

Hence, the moment of inertia of the suspension system is $I_D=\frac{d_c mg\,T_\omega^2}{4\pi^2}$. Taking into account Equation (29), the initial angular velocity of the system, at its stop at the point of suspension will be:

$$\dot{\boldsymbol{\varphi}}_{D_3} = \sqrt{\frac{mv_{C_{unl}}^2}{I_D}} \,. \tag{31}$$

The equation of circular motion at a stop will be:

$$I_D \frac{d\dot{\varphi}}{dt} = T_I \,, \tag{32}$$

where T_{i} - moment creating springs and rope.

Since the spring system is pre-loaded, the average value of the torque, as the calculated value $T_{\rm IC}$, has been taken. Then, the time before stopping the rotation of the system with the load, from the solution of the differential Equation (32) will be:

$$t_{\Delta} = I_{D} \frac{\dot{\boldsymbol{\varphi}}_{D_{3}}}{T_{IC}} = \frac{\sqrt{I_{D} m v_{Cp}^{2}}}{T_{IC}}.$$
 (33)

The analysis of the obtained results allowed to establish that the increase in speed and, accordingly, the decrease in transport time occurs with a decrease in the rolling resistance, which is achieved by increasing the mounting tension, which leads to a decrease in the angle of the roller rope coverage ξ and, accordingly, reducing the coefficient of friction λ_N . In addition, transporting the heavier loads leads to an increase in sag difference $\Delta f(x_{dow}) - \Delta f(x_{unl})$, which also reduces transportation time. Structurally, the rotation of the system is limited by locking devices in the unloading

zone, which dampen the excess speed in cases where it is not damped by the spring-loaded rollers. The residual speed has been observed for heavy loads (more than $50\,\mathrm{kg}$) and was not more than $10\,\%$ (less than $0.2~\mathrm{m}$ /s) of the suspension speed at the end of the route.

Theoretical studies have shown that the spring rollers significantly reduce the oscillation amplitude of the system and clamping the rope also act as a damper, as the oscillating process leads to bending of the rope and internal friction between its threads, which leads to sharp damping of oscillations that can occur when starting and stopping the frame construction with cargo.

3 Results and discussion

confirm the theoretical developments. experimental studies have been conducted. They were based on the developed method, which is presented in [24]. An experimental setup has been developed to adjust and determine the tension of ropes, the magnitude of their deflection in the vertical direction from the value of the discrete load in different zones, the angle of the pair of ropes to the horizon, and the time of movement on the frame structure of a piece cargo from the loading zone to the unloading zone. The scheme of functioning of the automobile mobile rope system based on a two-cable cable car, on which the suspended cargo platform moves on rollers has been outlined. This platform is made in the form of a rigid frame structure, which is suspended on load-bearing rollers and its movement is limited by the action of spring-loaded pressure rollers [15] Figure 14. At measurement of forces at loading of levers with pressure the rollers of rope system the dynamometer electronic brand DE 5-0.5 was applied [14].

When determining the dependence of the transportation time T of the piece goods in containers by rope mechanism in the warehouse, the range of changes in the values of the factors was as follows: mass m of artificial loads together with the constant mass of the frame structure for their location: $35 \le m \le 95$ (kg); the angle of inclination α of a pair of ropes parallel to the horizon: $10 \le \alpha \le 15$ (°); tension force T_D of ropes $2400 \le T_D \le 5000$ (N).

Based on the carried-out statistical processing of the received results of research on multifactor experiment the regression equation of dependence is constructed $T = f(m; \alpha; T_p)$ [2]:

$$T = 11.915 - 0.2 \cdot 10^{-3} T_D - 0.543\alpha - 0.0153m + + 0.71 \cdot 10^{-8} T_D^2 + 0.35 \cdot 10^{-5} T_D\alpha + 0.0121\alpha^2 + + 0.12 \cdot 10^{-3} \alpha m + 0.51 \cdot 10^{-4} m^2.$$
 (34)

The analysis of the regression Equation (34) showed that the average values of the factors from the specified ranges of the transportation time t of the piece goods in the warehouse is approximately $T \approx 5.92$ s. The dominant effect on the minimum transportation time t of the piece

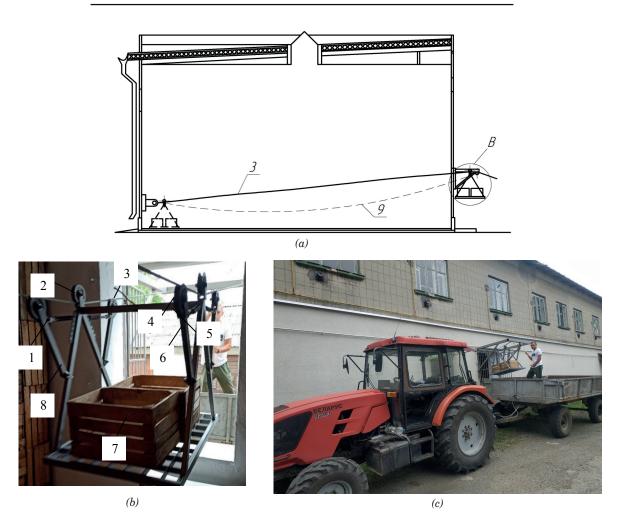


Figure 14 General view of experimental installation of the rope system: a) structural diagram; b), c) general view of the artificial cargo loading area: 1 - hinged levers; 2 - rollers; 3 - two-cable cable car; 4 - pressure rollers; 5 - tension springs; 6 - frame structure; 7 - artificial loads; 8 - brackets; 9 - helper rope

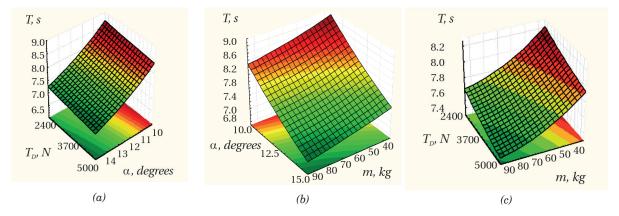


Figure 15 The Response surface transportation of piece goods in the warehouse due of time change in terms of the force of tension, the angle of their inclination to the horizon and the mass artificial cargo: $a - T = f(T_p, \alpha)$; $b - T = f(\alpha, m)$; $c) - T = f(T_p, m)$

goods in the warehouse has the angle of inclination α of a pair of parallel ropes to the horizon ($T\approx5.47$ s), then the mass m of artificial loads together with the constant mass of the frame structure for their location ($T\approx5.78$ s) and the tension force T of ropes ($T\approx5.83$ s). It should be noted that the range of differences in values

 T_D when changing the above factors is negligible and is close to 5.7% for (m/α) and 6.6% for (T_D/α) .

Based on the performed calculations, which were carried out with the help of a package of statistical applications for processing and analysis of the obtained results of experimental research for PC, the threeB234 ROHATYNSKIY et al

dimensional spatial dependences of time response surfaces T of transportation of the piece goods in the warehouse and their two-dimensional cross-sections for a visual representation of laboratory tests have been constructed

The conducted multifactor experiment had the following limits of variable parameters: mass m artificial cargo together with the mass of the frame structure: $35 \le m \le 95$ (kg); the angle of inclination α pairs of parallel ropes to the horizon: $10 \le \alpha \le 15$ (°); the force of tension T_D of ropes $2400 \le T_D \le 5000$ (N) (Figure 15).

In the study of the influence of two variable parameters on the value of the transportation time T of the piece goods to the third party was given a fixed average value with the appropriate values: m=65 (kg); $\alpha=15$ (°); $T_D=5000$ (N). It is established that the dominant influence on the minimum time T has angle α , then mass m and the force of tension T_D of ropes. However, it should be noted that the range of differences in the values t when changing the above factors is insignificant and is close to 5.7% for (m/α) and 6.6% for (T_D/α) .

4 Conclusion

The developed automobile cable systems for loading and unloading operations between the vehicle-support and vehicle-vehicle points are presented in this paper. In the developed cable system, the rotation of the system is limited by locking devices in the unloading area, which eliminates the excess speed in cases where it is not eliminated by spring-loaded rollers. It has been established that the residual speed was observed for heavy loads (more than 50kg) and was no more than 10% (less than 0.2 m/s) of the suspension speed at the end of the track. The analysis of the obtained theoretical results made it possible to establish that an increase in speed and, accordingly, a decrease in transportation time, occurs with a decrease in the rolling resistance, which is achieved by an increase in mounting tension, which leads to a reduction in the roller coverage angle ξ with a rope and, accordingly, reducing the coefficient of friction λ_N . In addition, transporting a load with a greater weight leads to an increase in the difference in sags $\Delta f(x_{dow}) - \Delta f(x_{unl})$, which also reduces the transportation time. It has been established that for a change of time T in terms of the force T_p within the limits $2400 \le T_p \le 5000$ (N), and angle α within the limits $10 \le \alpha \le 15$ (°) at mass: m = 65 (kg), the dominant factor is the influence of the angle α . Thus, for $T_D = 2400$ (N) the increase of angle α from 10° to 15° leads to a decrease in value T from 6.69 to 5.58 s. For $T_D = 5000$ (N) the increase of angle α from 10° to 15° leads to a decrease in value T from 6.46 to 5.39 s. Accordingly, the shorter the transportation time T, the higher the performance of the transportation system. It was established that the change in time T due to the angle of inclination α within the limits $10 \le \alpha \le 15$ (°) and mass $35 \le m \le 95$ (kg); with a stable tension force T_D ropes $T_D = 3700$ (N), the dominant factor is the influence of the angle α . Thus, for $T_D = 2400$ (N) the increase of angle α from 10° to 15° leads to a decrease in value T from 6.69 to 5.58 s. For $T_D = 5000$ (N) the increase of angle α from 10° to 15° leads to a decrease in value t from 6.46 to 5.39 s. It has been established that for the change of time T in terms of the tension force $T_{\scriptscriptstyle D}$ of ropes within the limits $2400 \le T_D \le 5000$ (N), and mass m within the limits $35 \le m \le 95$ (kg), at a stable angle of inclination α to the horizon $\alpha = 12.5$ (°) the dominant factor influencing the change in T value is the influence of the mass of artificial loads m. Thus, for $T_D = 2400$ (N) an increase in mass m from 35 to 95 kg leads to a decrease in the value T from 6.32 to 5.89 s. For $T_D = 5000$ (N) an increase in mass m from 35 to 95 kg leads to a decrease in the value T from 6,11 to 5.68 s.

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Conflicts of interest

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EXPERIMENTAL STUDY OF THE SYSTEM "SOURCE OF EXHAUST GAS - STORAGE CAPACITY"

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Resume

The article presents the results of testing the validity of the hypothesis about the possibility of isolating the exhaust gases of the internal combustion engine (exhaust gas source). The objective was to conduct an experimental study of the "exhaust gas source - storage tank" system. In the experimental study, the following was performed: establishment of influencing factors and output parameters; selecting the number of experiments; methods and means of measurement; conducting an experiment at the stand.

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1 Introduction

The main measures to improve the environmental safety of vehicles can be divided into two groups cleaning and isolation of exhaust gases (EG). Currently, a huge number of measures for exhaust gas purification are known and studied, and methods for isolating exhaust gases have not been sufficiently studied and covered in the literature. The review and analysis show that basically all the methods for reducing harmful emissions from diesel exhaust gases today are based on cleaning methods, and methods for isolating exhaust gases are not currently being considered. Thus, it is necessary to further search for the new design solutions to reduce harmful emissions from diesel locomotives by insulating them.

The main goal of the experimental study of the "exhaust gas source - storage tank" system is to test the validity of the hypothesis about the possibility of isolating the exhaust gases of the internal combustion engine (exhaust gas source) by determining the time of filling the storage tank (experimental stand) with gases depending on the engine rotation speed.

The experimental study included the following stages [1]:

- 1. Establishment of influencing factors and output parameters. As an influencing factor, we take the load mode of the internal combustion engine, characterized by the rotation speed (n, rpm). As an output parameter we take the time of filling the storage tank (t, min) of the experimental stand with exhaust gases from the internal combustion engine.
- Selecting the number of experiments. The object of experimental research is the "Exhaust gas source - storage tank" system reproduced on an experimental stand, which is designed to solve the stated purpose of the experiment. This object can be represented as a "Black box" of an one-factor experiment, where the influencing factor enters rotation speed (n, rpm), and the output parameter comes out - time to fill the storage tank (t, sec). Thus, registration of the output parameter in an one-factor experiment is carried out by considering the influence of one factor and determining one value of the output parameter. Based on the above conditions, and in accordance with the Methodology of rational planning of experiments [2], to conduct the experiment it is necessary to first carry out $N=1^{1}=1$ parallel experiments for each loading mode of the internal combustion engine, according to the

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dial of the measuring device (tachometer) of the experimental stand:

- □ experiment No. 1 1st mode 900 rpm;
- □ experiment No. 2 2nd mode 1000 rpm;
- □ experiment No. 3 3rd mode 1100 rpm;
- □ experiment No. 4 4th mode 1200 rpm.
- 3. Methods and means of measurement. Measurement methods: to measure the time of filling the storage tank, a method is used that is based on measuring time intervals (with a stopwatch) of filling the tank with exhaust gases under different operating modes of the internal combustion engine; to maintain the safe operation of the experimental stand, it is necessary to monitor the pressure and temperature in the system; when measuring pressure, a method based on mechanical pressure measurement (manometer) is used: a thermometer is used to measure temperature. When conducting experiments, the following measuring instruments are used: stopwatch, manometer, and thermometer. The measuring instruments used during the experiment must be verified in accordance with the requirements of the metrology rules. When carrying out measurements, the possibility of exhaust gas leakage must be excluded.
- 4. Conducting an experiment at the stand. All the experiments were carried out on an original experimental stand to study the system "exhaust gas source storage tank" (Figure 1, a), according to the developed Experimental Work Program [1]. The operating diagram of the experimental stand is shown in Figure 1, b.

Technical characteristics of the experimental stand (Figure 1):

- ICE 1.9-liter diesel from a Volkswagen car;
- compressor from a ZIL-130 car;

- connecting transmission belt;
- storage tank consists of 3 oxygen cylinders with a total volume of 0.12 cubic meters;
- cooling container 0.04 cubic meters;
- tachometer from a Volkswagen Golf III;
- thermometers No. 1 from 0 to 350 $^{\circ}$ C, No. 2 from 0 to 120 $^{\circ}$ C;
- manometers No. 1 from 0 to 1.6 MPa, No. 2 from 0 to 1.0 MPa;
- bypass valves No. 1 up to 0.3 MPa, No. 2 up to 0.8 MPa.

2 Materials and methods

An experimental study of the "exhaust gas source-storage tank" system was carried out on an experimental stand for studying diesel engine exhaust gases (Figure 1). The experimental stand was developed and installed in the laboratory of the Department of Industrial Transport of the Abylkas Saginov Karaganda Technical University.

Conducting experiment No. 1 (1st mode - 900 rpm) on the experimental stand was carried out in the following order:

- the protection of working personnel was checked for compliance with regulatory requirements and safety rules;
- 2) the laboratory premises were checked for compliance with regulatory requirements and safety rules;
- 3) the equipment of the experimental stand was checked for compliance with regulatory requirements and safety rules;
- 4) the signal to start experiment No. 1 was sent;

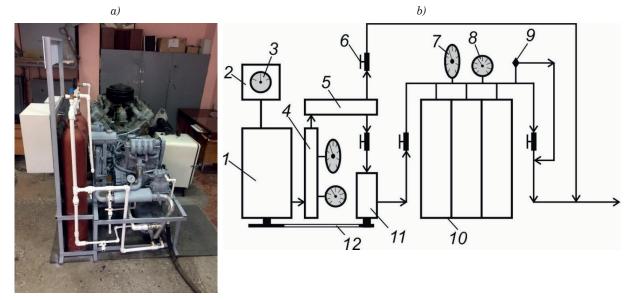


Figure 1 Experimental stand for studying the system "source of exhaust gases - storage tank": 1 - ICE; 2 - ICE launcher remote control; 3 - tachometer; 4 - exhaust system; 5 - exhaust gas cooling tank; 6 - valve; 7 - thermometer; 8 - manometer; 9 - bypass valve; 10 - storage tank (consisting of 3 tanks); 11 - compressor; 12 - connecting gear

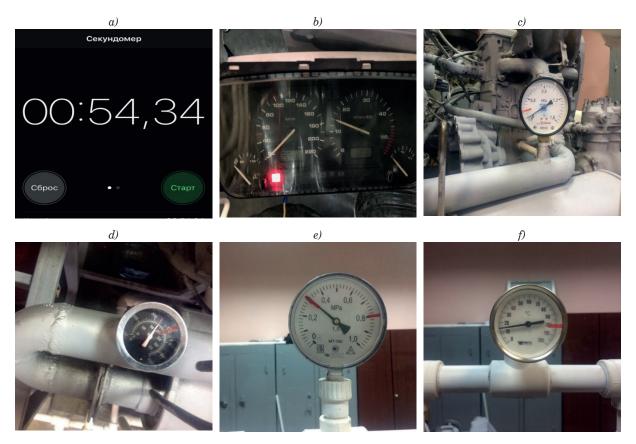


Figure 2 Registration of the experiment No. 1 results: a - storage tank filling time; b - rotation frequency; c - exhaust pressure from the internal combustion engine; d - temperature at the outlet from the internal combustion engine; e - pressure in storage tank; f - temperature in the storage tank

- 5) the internal combustion engine stand was launched;
- 6) the filling of the storage tank of the stand was registered and the results of experiment No. 1 were recorded:
 - \Box time to fill the storage tank (Figure 2, *a*);
 - \square rotation frequency (Figure 2, *b*);
 - □ exhaust pressure from the internal combustion engine (Figure 2, c);
 - \Box temperature at the outlet from the internal combustion engine (Figure 2, d);
 - \square pressure in the storage tank (Figure 2, e);
 - \Box temperature in the storage tank (Figure 2, f);
- 7) the signal about the completion of experiment No. 1 was sent:
- 8) the internal combustion engine of the stand was stopped;
- 9) exhaust gas was discharged from the storage tank of the stand.

All the remaining experiments were carried out according to the above order for the selected loading modes of the internal combustion engine of the experimental stand:

- experiment No. 2 2nd mode 1000 rpm;
- experiment No. 3 3rd mode 1100 rpm;
- experiment No. 4 4th mode 1200 rpm.

B Results and discussion

The obtained results of an experimental study of the "exhaust gas source - storage tank" system based on 4 parallel experiments performed on an experimental stand (Figure 1) are presented in Figure 3.

Based on the analysis of the experimental curve of the average indicators for parallel experiments of the experiment (Figure 4 - *blue*), we select an empirical formula, after determining which one, we obtain its final form:

$$y_{Ti} = a \cdot e^{bx_i} = 490.4559 \cdot e^{-0.0024x_i},$$
 (1)

where x_i - rotation speed (influencing factor), n, m^{-1} ; y_i - time to fill the storage tank of the experimental stand (output parameter), t, sec.

Substituting the average indicators for parallel experiments of the experiment (Figure 3), we obtained theoretical indicators, which are presented graphically in Figure 4 - *violet*:

$$y_{T1} = 490.4559 \cdot e^{-0.0024 \cdot 55.7} = 56.3 \text{ sec},$$

 $y_{T2} = 490.4559 \cdot e^{-0.0024 \cdot 45.0} = 44.3 \text{ sec},$
 $y_{T3} = 490.4559 \cdot e^{-0.0024 \cdot 33.5} = 34.8 \text{ sec},$
 $y_{T4} = 490.4559 \cdot e^{-0.0024 \cdot 28.5} = 27.4 \text{ sec}.$ (2)

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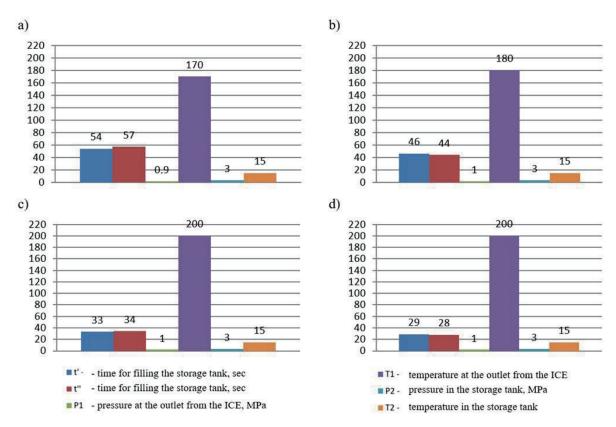


Figure 3 Results of an experimental study of the "exhaust gas source - storage tank" system based on 4 parallel experiments: a - results of parallel experiment No. 1 at an internal combustion engine speed of 900 rpm (1st mode); b - results of parallel experiment No. 2 at an internal combustion engine speed of 1000 rpm (2st mode); c - results of parallel experiment No. 3 at an internal combustion engine speed of 1100 rpm (3st mode); d - results of parallel experiment No. 4 at an internal combustion engine speed of 1200 rpm (4th mode)

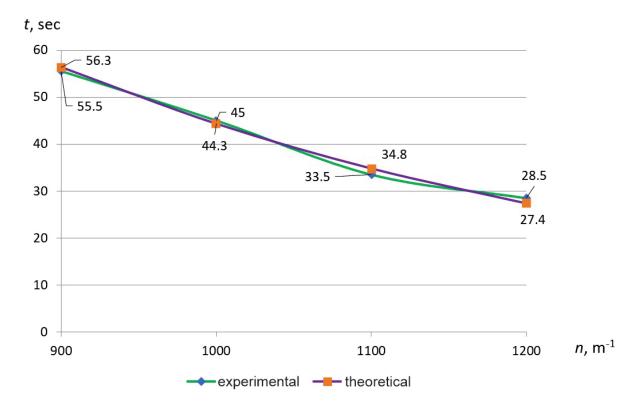


Figure 4 Convergence of experimental and theoretical indicators

To determine the percentage of scatter (variability) of the required function y_{T_i} (Equation (1)) relative to its average value, determined by the variability of factor x, the coefficient of determination was calculated [2]:

$$k_{D} = \left(\frac{N \cdot \sum x_{i} \cdot y_{i} - \sum x_{i} \cdot \sum y_{i}}{\sqrt{\left[N \cdot \sum x_{i}^{2} - \left(\sum x_{i}\right)^{2}\right] \times \left[V \cdot \sum y_{i}^{2} - \left(\sum y_{i}\right)^{2}\right]}}\right)^{2}$$

$$k_{D} = \left(\frac{4 \cdot 166000 - 4200 \cdot 162.5}{\sqrt{\left[4 \cdot 4460000 - 4200^{2}\right] \times \left[V \cdot \left[4 \cdot 7039.8 - 162.5^{2}\right]\right]}}\right)^{2} = -0.99^{2}$$

$$= 0.98.$$
(3)

The result obtained means that 98% of the spread is determined by the variability of x, and 2% by other reasons, i.e., the variability of function y (Equation (1)) is almost completely characterized by the spread of the factor x.

The suitability of the research hypothesis was assessed, as well as theoretical data for adequacy, i.e. correspondence of the theoretical curve (Figure 4 - *violet*) to experimental data (Figure 3). The essence of such

a test is to determine the error of approximation of experimental data using the Fisher criterion, in which it is necessary to calculate the experimental value of the $k_{\scriptscriptstyle FE}$ criterion and compare it with the theoretical ones - $k_{\scriptscriptstyle FT}$

The experimental Fisher criterion is calculated using the well-known formula [2]:

$$k_{fe} = rac{D_a}{D_{cr}} = rac{\left(\sum_1^N (y_{iT} - \bar{y}_{ie})\right)^2 / (N - d)}{\left(\sum_1^m \sum_1^N (y_{iT} - y_{ie})^2) / (mN)},$$
 (4)

where D_a - adequacy dispersion;

 D_{av} - average dispersion of the entire experiment;

 y_{iT} - theoretical value of the function;

 y_{iE} - experimental value;

 \bar{y}_{iE} - average experimental value from m measurements; d - the number of coefficients in the theoretical regression equation; since in the theoretical expression there is one significant term x, then d = 1.

Substituting the data into Equation (4), we obtain the experimental Fisher criterion:

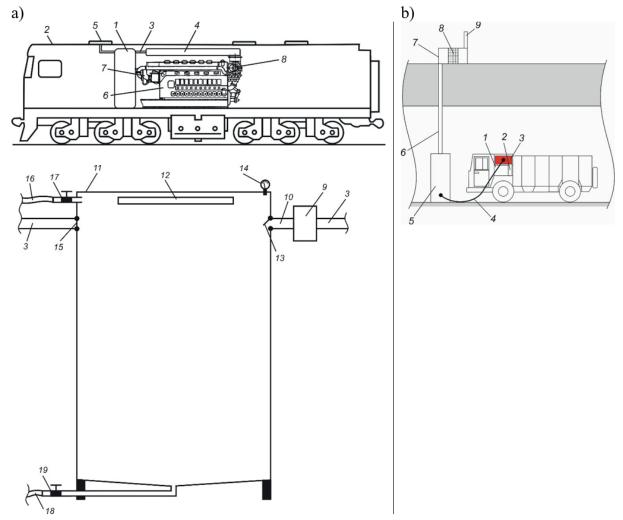


Figure 5 Suggested practical application options: a) quarry diesel locomotive with proposed exhaust insulation device for diesel engine; b) underground self-propelled engine exhaust gas insulation device

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$$k_{fe} = \frac{0.8^{2} + (-0.7)^{2} + 1.3^{2} + 1.1^{2}/4 - 1}{(23^{2} + (-0.7)^{2}) + ((-1.7)^{2} + (-0.7)^{2}) + + (1.8^{2} + 0.8^{2}) + ((-1.6)^{2} + (-0.6)^{2})/2 \cdot 4}$$

$$k_{fe} = \frac{1.3}{1.95} = 0.7$$
(5)

The theoretical value of the Fisher criterion k_{FT} for a confidence probability of 0.95 and the number of degrees of freedom $q_1 = N \cdot d = 4 \cdot 1 = 3$, $q_2 = N \cdot (m \cdot 1) = 4 \cdot (2 \cdot 1) = 4$ is taken equal to $k_{FT} = 9.1$ [2]. Due to the fact that $(k_{FE} = 0.7) < (k_{FT} = 9.1)$ - the model is adequate, i.e., the resulting mathematical model with a confidence probability of 95% describes well the process under study.

4 Conclusions

The problems of protecting the earth's atmosphere from the harmful effects of various types of transport are becoming increasingly urgent every year, their solution must be comprehensive and not a single source of exhaust gases that negatively affects the earth's atmosphere should be ignored [3-7].

An experimental study of the "exhaust gas source - storage tank" system, on an experimental stand developed for these purposes, confirmed the validity of the hypothesis about the possibility of isolating the exhaust gases from an internal combustion engine (exhaust gas source), by determining the time of filling the storage tank (experimental stand) with gases depending on the frequency engine rotation.

Based on the results of the research, the following were developed:

• a device for insulating the exhaust gases of a diesel locomotive engine (Figure 5, a), which contains the following equipment: proposed

device 1, quarry diesel locomotive 2, connecting pipe 3, silencer 4, exhaust pipe 5; diesel engine 6, centrifugal supercharger 7, turbocharger 8, compressor 9, pipe 10, storage capacity 11, refrigerator 12, non-return valve 13, pressure gauge 14, bypass valve 15, discharge hose 16, valve nozzle 17, discharge hose 18, drain pipe with valve 19 [8-9];

• device for insulating the engine exhaust gases of an underground self-propelled machine (Figure 5, b), which contains the following equipment: engine of an underground self-propelled machine 1, compressor 2, storage capacity 3, exhaust hose 4, receiving tank 5, pipeline 6, purification tank 7, filter 8, exhaust system 9 [10].

However, the proposed method of isolating the exhaust gases of an internal combustion engine (source of exhaust gases), by filling the storage tank with gases using the forces of the exhaust gas source itself, is also applicable for other types of transport, and has promising applications.

The presented results of experimental studies, in our opinion, have serious applied significance, which will undoubtedly be of interest to engineers and scientists involved in research in the field of improving the environmental safety of vehicles.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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RESEARCH AND DEVELOPMENT OF A SPECIAL AIR CUSHION CONVEYOR DESIGN FOR THE TRANSPORTATION OF BULK CARGOES

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Resume

The scientific task of the nozzle scheme uses for formation of an air cushion by using the energy of a jet of air supplied under pressure, simultaneously to form an air cushion, as well as to create the driving force of a load-bearing web, was formulated and the main idea of the work was defined. The optimal option to significantly increase the productivity and length of special types of conveyors is to use the energy of a jet of air supplied under pressure simultaneously as an air cushion and as the driving force of the load-carrying body, which makes it possible to sharply reduce the coefficient of resistance to movement of the load-carrying body and improve its operating conditions. Supporting the load-carrying body with an air cushion allows to increase the speed of movement to 8 to 9 m/s and more, increase the reliability and safety of conveyor operation, and protect the environment.

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Nomenclature

- 1. AC air cushion
- 2. ACCB air cushion conveyor belt
- 3. LIWT Leningrad Institute of Water Transport
- 4. KarSTU Karaganda State Technical University
- 5. AB air bag
- 6. HCHC hovercraft carrier
- 7. KRU-350 conveyor drives
- 8. CIS-Commonwealth of Independent States

1 Introduction

It is known from practice that a conveyor of a length of 13200 m is operated in Austria. The length of modern conveyor routes reaches 100 km. An increase in the length of conveyors that make up the line causes a decrease in the number of wires, tensioners, electrical equipment, starting equipment and various auxiliary equipment,

which increases the reliability and productivity of the line, reduces capital and operating costs [1].

The main direction of mechanization is the introduction of conveyor transport into production, which, in terms of its technical and economic indicators, is higher than the rail and road transport. A comparison of the belt conveyors, rail and road transport of a capacity of 5-25 million tons per year and a transportation range of 5.25km, speaks in favor of the former. Thus, with relatively identical capital investments, the operating costs (for conveyors in galleries) are 1.42 times more and 3.4 times less; the reduced costs are 1.15 times more and 2.85 times less; The metal consumption is 1.46 and 1.29 times less; the energy consumption is 1.2 and 6.48 times less; the track area is 4.5 and 4 times less than in rail and road transport, respectively. Labor productivity using the belt conveyors is comparable to productivity in railway transport and 33.8 times higher than productivity in the road transport [2].

The belt conveyors are capable of overcoming slopes

up to 20% can be automated, preserve the landscape of the area, they are characterized by the absence of noise. The use of belt conveyors in open-pit mining makes it possible to develop a productivity of 15,000 m/h. which is 40% higher than the productivity of railway transport and 20% higher than the productivity of automobile transport. In addition, the transportation path is reduced by 13.3 times and 3.2 times compared to the named transports, respectively [3].

An increase in productivity and an increase in the length of belt conveyors with an increase in drive power, which is limited by the strength of the belt and its adhesion to the drum, is one of the most important questions of this construction.

Currently, the industry produces tapes made of synthetic fabrics (nylon, dacron, viscose) with a tensile strength per gasket and rubber, which significantly increases the productivity and length of belt conveyors. Thus, the Alexandrovsky Machine-Building Plant Karaganda city, Kazakhstan produces KRU-350 conveyors with a length of 1,500 m

The most effective means to significantly increase the length and productivity of the conveyor is the use of an air cushion (AC) to support the belt instead of roller supports. This allows to reduce the resistance to the movement of the belt, increase the safety of the transported cargo and the environment. The absence of rotating roller supports in an air cushion conveyor belt (ACCB) will reduce the component of resistance to movement from deformation of the load and belt when moving along the roller supports, reaching 40-70% of the total resistance, increase its reliability and safety of operation. The ACCB does not require the construction of galleries [4].

The air cushion field is analyzed using theoretical inference, numerical modeling and experimental research. An intelligent experimental platform is developed. A three-dimensional distribution of the air film pressure and the distribution of the air film thickness along the conveyor belt in the width direction are obtained. The experimental result is analyzed by comparing with the theoretical calculation and numerical simulation. The numerical and theoretical results are in good agreement with the results obtained in the experiments. A model of the air film formation behavior of the air cushion belt conveyor under stable load is presented. The optimized film thickness and pore distribution are obtained based on the comprehensive energy consumption. This study provides a basis for optimizing the design of the air cushion belt conveyor [5].

The disadvantages of the ACCB include:

- the need for additional energy for the formation of the AC under the conveyor belt;
- the difficulty of starting the ACCB in case of blockages;
- the ACCB are of large concentric loads on the tape and the asymmetry of the location of the load along the width of the tape;

- the efficiency factor of the fans providing the AC with air is low, which causes significant energy consumption for its formation.
- the flat tape in ACCB has low transverse stability, which limits its use.

However, some of these disadvantages are eliminated by known means. The development of the ACCB is of a great importance both in the Commonwealth of Independent States and abroad. To date, the research of this type of continuous transport machines has been carried out by the teams of the Leningrad Institute of Water Transport (LIWT) Russia city Saint Petersburg, the Bauman Moscow State Technical University Russia city Moscow, the Moscow Mining Institute Russia city Moscow. According to the results of the Higher Technical School in Twente (study, ACCB are manufactured for the foreign market. One of them, purchased by Belarus, was installed for the grain transportation at the Minsk bakery, Minsk, Belarus.

2. Methods

2.1. Systematization of a special design development of an air-cushion conveyor for transporting the large-piece cargo

The most effective means to significantly increase the length and productivity of the conveyor is the use of an air cushion. Therefore, the development and creation of conveyors and hovercraft devices is an urgent task.

The study of these schemes, and the design of the hovercraft conveyor, made it possible to identify common features by which their classification is possible.

A fan pumps air into the chamber under the device, which creates an excess pressure necessary for air to flow out along the periphery under the edges of the chamber. Under the devices of the first group [1-2], excess pressure is created and maintained by a jet curtain formed when air flows through a slit nozzle on the periphery of the device. In the devices of the second group [1-2], the lifting force is created by excessive pressure under the wing of the device when it moves near the support surface. This scheme is effective at high speeds of movement of the device.

For example, to move over an unprepared (uneven) surface without contacting it, in vehicles such as ships and all-terrain vehicles, the gap between the elastic fence and the support surface ranges from several to tens of centimeters. This gap, which requires significant air consumption, can be ensured by using a chamber or nozzle air cushion formation scheme in the design of vehicles.

At the same time, in an air cushion of this type, the excess pressure is negligible (several hundred pascals), which determines the low load capacity per unit area of the device. This practically eliminates the possibility of using such devices (or hovercrafts) for transport

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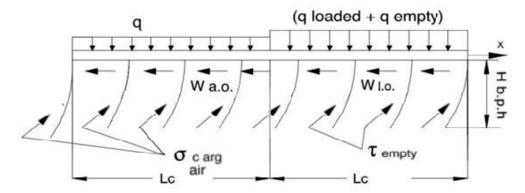


Figure 1 Calculation model of a conveyor with an air cushion pneumatic drive

operations, since the airflow flowing out from under the device with high speed and significant noise, having high kinetic energy, causes intense dust formation.

To reduce the friction between the mutually touching surfaces, gas-lubricated "air bearings" are used in a number of special devices and mechanisms. In such bearings, an air cushion is created between the sleeve and a shaft or the shaft end and a bearing, as a result of external blowing, which, according to the method of formation, can be attributed to slot-type pillows.

Hovercraft devices of this type are increasingly referred to in the technical literature as aerostatic supports (AS). This name is due to the fact that the external load on the support is balanced by the resultant aerostatic forces of overpressure. In various industries, aerostatic supports with an elastic diaphragm are mainly used for transport operations.

2.2 Increasing the efficiency of a special air-cushion conveyor

Increasing the efficiency of a special air-cushion conveyor operation using tools an air cushion and special devices, is a popular and urgent task.

The novelty of the work is the consideration of the main parameters characterizing the efficiency of using an air cushion, that is, the flow rate and air pressure to maintain the load-bearing body.

Valves are used to reduce air consumption in conveyor structures. In the absence of a load on the load-bearing organ (belt), the valves will block or completely close the holes through which air exits under the load-bearing organ (belt) and thereby reduce its consumption. When a load appears above the valve, the spring is compressed and the valve is compressed, while the outlet opens and air enters under the belt. Depending on the load, the passage section of the outlet will be larger or smaller, and therefore the air flow will be maintained automatically, depending on the need for it. The disadvantage of this device is the contact of the load-bearing body (tape) with the valves, which causes its wear. Due to the compression of the springs

of the balls, there is resistance to their rotation, which somewhat reduces the efficiency of using an air cushion.

In the conveyor design, the role of the air flow control device is assumed by the belt crest with beveled sides that overlap the air supply openings in the belt chute upwards. With an increase in the load on the load-bearing organ (tape), it, bending down with a ridge, opens a large part of the cross-section of the opening, and the air supply under the load-bearing organ (tape) increases; with a decrease in the load on the load-bearing organ (tape), the ridge will overlap and the compressed air consumption will decrease.

2.3. The basics of calculating a conveyor with an air cushion pneumatic drive

The creation of promising conveyor designs that allow the transportation of bulk cargoes according to a non-unloading scheme is a popular task.

The novelty of this work is a development of a methodology for calculating the parameters of a new design of an air-cushion pneumatic conveyor for largevolume cargoes.

The structural formula of this conveyor, according to the classification of special types of conveyors, developed taking into account the regularity of the distribution of forces in traction and driven circuits, has the following form:

$$\frac{\left[\left(\left(C_{\operatorname{argo}}*L_{\operatorname{co}}\right)_{\operatorname{canvas}}+\left(e*B*h\right)_{\operatorname{airbag}}\right]\right]}{\left[\left(\left(C_{-\operatorname{argo}}*L_{-\operatorname{co}}\right)_{\operatorname{canvas}}+\left(e*B*h\right)_{-\operatorname{airbag}}\right)\right]},\,(1)$$

where:

L.C.O - load-carrying organ,

Canvas - canvas of the load-carrying organ.

The principle of operation of this conveyor is as follows: the energy of the jet of air supplied under pressure is used simultaneously as the air and the driving force of the load-bearing conveyor web.

The use of an air cushion makes it possible to reduce the coefficient of resistance to the movement of the load-bearing body, increase the speed of its movement, therefore, reduce the energy consumption of the conveyor and, accordingly, significantly increase the length of the shaft per drive. Due to the outflow of compressed air at an angle to the vertical, the load-bearing web receives translational movement. The calculation model of the conveyor with pneumatic air cushion drive is shown in Figure 1 and is presented in the form of a rod of a constant cross-section and stiffness along the sections of which stresses: σ_{air}^{cargo} on the cargo and τ_{air}^{empty} empty branches.

The blades have the following geometric parameters: R is the radius of the blade sector shape, m;

H b.p.h is blade pad height, m;

 $B_{{\it C.a.c.b.w}}$ is conveyor air cushion blade width and $l_{s.b.a.l.t.v}$ is spacing of blades along the length of a transport vehicle.

The amount of lifting and traction (driving) forces created by the air jet is significantly influenced by: the applied pressure, the size of the guaranteed gap between the support and bearing surfaces, the angle of inclination of the air jet, as well as the geometric parameters of the blade (R, B^{Canvas} , h^{Canvas} and $l_{s,b,a,l,tv}$).

The condition for creating a lifting force, that is, an air cushion, can be written as follows:

$$\sigma_{air}^{cargo} * \sin \alpha \ge 0.5 \sin \alpha \ge (q_{loaded} + q_{empty}) *$$

$$* \cos \beta * e_{sbaltv},$$

$$\tau_{air}^{empty} * \sin \alpha \ge 0.5 \sin \alpha \ge 0.5 * q_{empty} *$$

$$* \cos \beta * e_{sbaltv}.$$
(2)

where:

 σ_{air}^{cargo} and τ_{air}^{empty} are the pressure forces of the compressed air jets , respectively, on the cargo and empty branches , N;

 α is the angle of inclination of the nozzle for supplying a jet of compressed air to the blade, deg;

 $(q_{loaded} + q_{empty})$ is the linear weight of the load and the load-bearing web, respectively, N/m;

 \upbeta is the angle of inclination of the conveyor, deg; $e_{\it sbaltv}$ is the installation step of the blades along the length of the conveyor, m.

Condition the creation of a traction (driving) force should be written as follows:

$$\begin{split} &\sigma_{air}^{aargo} * \sin \alpha \geq 0.5 \sin \alpha \geq (q_{loaded} + q_{empty}) * \\ &* \cos \beta * \omega_{air}, \\ &e_{sbaltv} + (q_{loaded} + q_{empty}) * \sin \beta * e * \omega_{air} + \\ &+ (q_{loaded} + q_{empty}) * e_{sbaltv} * \alpha/g, \\ &\tau_{air}^{empty} * \cos \alpha \geq 0.5 [q_{empty} * e_{sbaltv(e * \omega_{air} * \cos \beta - \sin \alpha)} + \\ &+ q_{empty} * \alpha * e_{sbaltv}/g, \end{split}$$

$$(3)$$

where

 ω_{air} is the coefficient of resistance to the movement of the load-bearing web in the presence of an air cushion $g = 9.81 \text{ m/s}^2$ is the acceleration of gravity.

Movement resistance force for the conveyor is:

$$W_{p} = W_{air} + W_{t.m.f.l.c.f}, (4)$$

where:

 $W_{t.m.f.l.c.f}$ - Motion resistance force of traction driving force

 W_{air} - Air cushion movement resistance force.

Determination of the power of the pneumatic conveyor drive.

The power of the pneumatic system, as is known, is the following dependence:

$$N = P_{air} l/t = \rho S l/t = \rho S v_{launch}, \qquad (5)$$

where:

 $P_{\it air}$ is the pressure force created by the compressed air jet, N; l is the distance of movement of the air jet, m; t is the expiration time of compressed air before contact with moving elements, s; S is the air pressure area, m; $v_{\it launch}$ is the expiration rate of the compressed air jet, m/s. As mentioned earlier, the compressed air jet performs two functions, that is, it creates an air cushion, lifting the supporting elements, and a driving force to move the load-bearing body.

- It has been established, that open-air circulation circuit requires less energy to form air space, and a closed circuit can be successfully used when transporting goods that have a harmful effect on the environment.
- 2. It was revealed that maintaining the load-bearing body of the air cushion over the entire supporting surface requires less energy consumption than discrete; maintaining the loaded and empty branches of the power body with air flows creates greater vertical stability than the general flow, but requires greater energy expenditure for the formation of an air cushion, and maintaining both branches of the power body of the conveyor with a common air flow requires less costs when the flow moves from the loaded load-bearing body to empty than vice versa.
- Based on the analysis of existing designs of aircushion devices and vehicles, taking into account their characteristic features, a systematization has been developed and the areas of application of aircushion devices have been established.
- 4. It has been established that devices for increasing the efficiency of the air cushion mostly have practical application in stolports. The use of labyrinth seals can reduce the air consumption from the air cushion by 30%.
- 3 Experimental studies and methods for calculating the basic parameters of a special AIR cushion conveyor

3.1 The object of the study and the methodology of experimental research

In order to verify the main theoretical dependencies, study the cargo transportation process, clarify the main

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parameters, evaluate the performance of a special air cushion conveyor and the effectiveness of using air cushion to maintain the load-carrying body, studies were conducted at an experimental laboratory facility at Abylkas Saginov Karaganda Technical University.

The specific objectives of the study were:

- verification of the main theoretical dependencies obtained earlier;
- clarification and justification of the main design parameters of a special air cushion conveyor;
- assessment of the operability of a special air cushion conveyor and the effectiveness of using air cushion to maintain a load-bearing body.

The research program included the following main stages:

- determination of the efficiency of a special air cushion conveyor and the effectiveness of using air cushion to maintain the load-carrying body;
- determination of the rational aerodynamic parameters of a special air cushion conveyor during the transportation of bulk cargo;
- verification of theoretical dependencies for determining the air flow rate for the formation of air cushion.

The experimental research program also included visual observation of the operation of a laboratory installation simulating the movement of a load-bearing body using the air cushion and an assessment of the operability of the design of individual components. The laboratory experimental installation was developed and manufactured at Abylkas Saginov Karaganda Technical University, which has the following technical characteristics:

width of the load-bearing body B=0.4 m, length of the conveyor installation $L_{\rm conveyer}$ = 6.5 m, diameters of the drive and tension drums 0.4*e, speed of movement of the load-bearing body, m/s: first gear-1.54, second gear-2.81, third gear-5.04, fourth gear-7.8, fifth gear-11.7, conveyor belt thickness, tensioner stroke, electric motor power N = 4.0 kW, rated rpm, n =1, 500, efficiency = 78 \%, gearbox-gearbox of the GAZ-53 car, the gear ratio of the V-belt gears:

the belt of the loading device: length $L=4\,m,$

fan motor: type -AO2-41-2,

efficiency = 0.84%,

the first is 1.66,

the second is 0.98,

nominal number of revolutions per minute 2890, the gear ratio of the V-belt transmission is 1.04, $\,$

fan: type - VVD-5, developed pressure -4875 N/m2 (ati), capacity $Q_{\rm air}$ = 1365 $m^3/h,$

thyristor frequency converter: type - TP4-40, power N =39 kW, frequency control limits - 4.88 to 58.5 Hz, voltage change-20 to 230V, diameter of the central pipeline d = $0.127\,\text{m}$, diameters of the pipeline sections d = $0.06\,\text{m}$.

3.1.1 The experiment plan

The nature of the functional dependence of the coefficient of the load-bearing body resistance to movement on the air flow rate at different pressures and air densities, the speed of movement and linear load, the scheme of formation of the air cushion is unknown in advance, which makes it impossible to determine the intervals between the experimental points of this function. The nature of other functions is also unknown.

To identify the nature of the functions, six to seven experimental points with different air flow intervals were selected, determined by the area of economic feasibility of using air cushion to support the load-carrying body and the maximum capabilities of the air supply source.

The experimental research program included: a general assessment of the performance of a special air cushion conveyor; establishment of rational aerodynamic and geometric parameters of the system; determination of linear load; determination of the speed of movement of the load-bearing body; determination of the power consumed by the drive engine.

The experiments were carried out according to the following method:

- one of the hovercraft schemes was created;
- a certain linear load was created on the loadbearing body of the conveyor;
- the measuring equipment has been adjusted;
- compressed air was supplied by a fan in the same amount to all sections of the gutter;
- the conveyor was started and, with a steady movement of the load-bearing body, the quality of creating an air cushion was monitored by measuring the power consumed by the electric motor of the drive;
- in the absence of problems in the installation, the oscilloscope recorded the signals of load cells measuring the traction forces in the load-bearing body and the force of resistance to movement of the loading device, the air flow and speed of movement of the load-bearing body were measured, the air pressure under the load-bearing body along the width and in the gutter sections;
- the conveyor stopped;
- the compressed air supply stopped;
- the installation of the initial readings of the devices was checked;
- compressed air was supplied in the same amount to the conveyor chute and the previous positions were

performed, starting from the fifth position;

- the air flow rate changed and the previous positions were performed starting from the fifth position;
- the speed of movement of the load-bearing body changed and the previous positions were performed, starting from the fourth position;
- the linear load was changed and the previous positions were performed, starting from the fourth position;
- the scheme of formation of the air bag was changed and the previous positions were fulfilled, starting from the fourth position;

The waveforms were processed using the method of variation statistics [1-2]. With the existing methods of obtaining variation series by ordinates and peaks, preference is given to the peak method. The sequence of operations for obtaining the values of the measured parameter with a set confidence interval was carried out according to the methods [1-2]:

- the measurement results were presented in the form of a grouped series of variations,
- the mathematical expectation was determined $m_x = \sum X_i P_i$,
- with the standard deviation $\sigma_x \sqrt{(X_i m_x^2)^2} P_i$. A confidence probability was assumed:
- half of the relative interval for the standard deviation was found,
- the value of half of the confidence interval d was determined.

The experimental graphs were constructed using the least squares method.

3.2 Analysis of the results of experimental studies of a special air cushion conveyor.

The hypothesis of a "flexible" cargo-carrying body was tested by experiments. To do this, a material (sand) with a volumetric weight, Y_{gr} =16328 N/m³, was poured onto the load-bearing body, freely lying in the gutter,

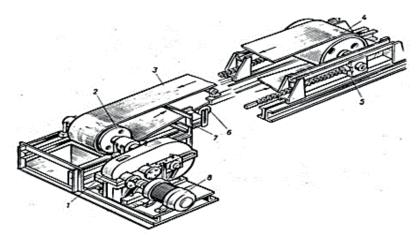
consisting of three meter sections. The height of the material in the center of the load-bearing body above the drainage holes, located along the perimeter of the section of the middle section of the gutter, was measured by means of chips.

Air was forced under the supporting body of the conveyor using a fan, and after separating it from the chute with uniform air movement, the pressure under the supporting body was measured with pressure gauges connected by flexible tubes to drainage. holes. By measuring the pressure in the middle part of the gutter, the influence of atmospheric pressure through the ends of the gutter is eliminated. The experimental results and calculated data show satisfactory results. The result increases with increasing linear load (the height of the load on the load-bearing body) and at nominal loads, and the discrepancy between the experimental and calculated results is 8.6%, which is explained by the small influence of the rigidity of the load-bearing body and the forces of internal friction of the load.

Throttling of the air flow was performed by changing the cross section of the outlets. Experiments have revealed that the highest air bag with a nozzle formation scheme both in the center of the load-bearing body (Figure 2) and along the edges of the load-bearing body occurred with the ratio of the total area of the through holes of the nozzles to the reference area of the load-bearing body K=0.02.

With a change in this relationship, in one direction or another, the height of the AB is smaller both in the center and along the edges of the load-bearing body. Thus, with an increase in the ratio to K=0.048, at linear loads of 143 and 207 N/m, the height of the air cushion is less from 13.1% to 89% and from 11.21% to 101% in the center of the load-bearing organ; from 15.02% to 42.5% and from 7.02% to 42% along the edge of the load-bearing organ, respectively, loads when changing the complex indicator from 0.074 to 0.06.

Due to the dependence of the height of the air cushion, with a nozzle formation scheme, on a complex



1- gearbox, 2 - drive drum, 3 - conveyor belt, 4 - tension drum, 5 - tensioner, 6 - roller supports, 7 - conveyor frame, 8 - electric motor

Figure 2 Tension station of a special air cushion conveyor

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indicator of the air parameters, it has a linear character, which indicates an increase in the proportion of dynamic pressure in total pressure, especially with an increase in the height of the AB. The height of the AB, with a nozzle formation scheme, is greater along the edges of the load-bearing body than in the center.

In order to identify the best scheme for the formation of AB, experiments were conducted with the chamber scheme.

The tension of the grooved load-bearing body is uneven in width due to the difference in distances between the extreme and middle points of the drum and the gutter. Experiments have revealed that at low values of the complex index (0.06-0.061), the load-bearing body contacts the gutter with the edges, and not the center. Therefore, in the air cushion conveyor with a nozzle scheme, maintaining the load-bearing body of the AB will probably be the best, since in this case, the height of the AB is 7.02, 42% larger.

3.3 Comparison of diagrams of the air pressure distribution in the air cushion at rest and in motion.

The air pressure in the air cushion during the movement of the load-bearing body decreases compared to the pressure at rest by 1.95, 4.88% along the edges of the load-bearing body and by 11.7 to 17.6% along the center of the load-bearing body for the nozzle formation scheme, which indicates an increase in the height of the air cushion. Consequently, the air consumption, required for the formation of air cushion during movement of the assembly line, should be taken to be 9.75 to 14.6% less than at rest, which will reduce the energy consumption and increase the vertical stability of the assembly line.

The tension of the monocoque body before running into the chute and after escaping from the chute, as well as the resistance force to the movement of the loading device, were measured using load cells.

The readings of the load cells were recorded by an oscilloscope on photographic paper. The air cushion conveyor with a nozzle circuit reacts more strongly to changes in the linear load and the speed of movement of the load-bearing body. For example: an increase in the linear load by 42% causes an increase in the coefficient of resistance by 3* to 49%. An increase in the speed of movement of the load-bearing body by 2.69 times causes a decrease in the coefficient of resistance to movement in the HC with a nozzle circuit by 22 to 45%. An increase in the air flow rate in a low-load area will cause a sharp increase in resistance in the nozzles, as a result of which air consumption will decrease. In an area of a large load, a decrease in the flow rate through the nozzles will lead to the opposite phenomenon.

4 Conclusion

- 1. Analysis of the systematization of air-cushion conveyors revealed the presence of a wide variety of air-cushion conveyors, the further development of which will make it possible to obtain new types of structures and schemes that are currently unknown. From the above systematization of air cushion devices, it has been established that the use of one or another air cushion formation scheme is explained by the compliance of the capabilities that this scheme can provide with the operational requirements for a particular device.
- 2. To increase the efficiency of the air cushion in a conveyor, the authors propose to use the energy of the air jet supplied under pressure, to simultaneously use both the air cushion and the moving force of the supporting conveyor belt. At the same time, it is necessary to develop the new, more modern devices for protecting the air cushion and air circulation circuits, which have priorities at the level of inventions.
- The obtained dependencies make it possible to determine the main parameters of a conveyor with a pneumatic drive on an air cushion.
- 4. Experimental studies have confirmed the operability of a special air-cushion conveyor and the effectiveness of using an air cushion to support the load-carrying body when transporting cargo with uneven loading of up to 18%.
- An engineering methodology for calculating and selecting the main parameters of a special aircushion conveyor has been developed.
- 6. The adequacy of the theoretical assumptions of the essence of the air cushion, in the promising design of a special air cushion conveyor, to the real conditions was confirmed, i.e. the discrepancy between theoretical and experimental studies is no more than 12 to 13%.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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EVOLUTION OF THE PRODUCT AND PROCESS REQUIREMENTS DURING THE PROJECT LIFETIME

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Resume

The automotive industry, known for its dynamism and innovation, relies on effectiveness of product and process requirements management. Effective collaboration with OEM (Original Equipment Manufacturers) is essential for success. The article analyses how product and process requirements evolve during different project phases, following the APQP (Advanced Product Quality Planning) approach, depending on OEM type. The study focuses on Tier 1 organizations, direct suppliers to the automotive industry, and their diverse approaches to product development. It underscores the need for Tier 1 organizations to maintain flexibility in their operations and to be prepared for changes in OEM demands. The study emphasizes the role of effective communication and coordination among all the levels of the supply chain to ensure the successful implementation of the APQP approach.

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Nomenclature

OEM: Original Equipment Manufacturer is a company that manufactures components or products used by another company.

Tier: Refers to different levels within the supply chain. **Supply chain:** is the network of people and entities involved in creating a product and delivering it to its consumer.

APQP: Advanced Product Quality Planning is a framework of procedures and techniques used to develop products, particularly in the automotive industry. It aims to ensure consistent quality from the product planning phase to its serial production

PPAP: Production Part Approval Process, procedure whose purpose is to ensure that parts manufactured by suppliers consistently meet quality expectations.

1 Introduction

The automotive industry, characterized by its dynamism and innovation, is pivotal in shaping modern transportation. Successful collaboration with Original Equipment Manufacturers (OEMs) hinges on a thorough grasp of product and process requirements. These requirements evolve throughout the automotive sector's project phases, guided by Advanced Product Quality Planning (APQP) principles. The following research analysis delves into the intricate dynamics between Tier 1 organizations and three distinct types of OEM customers, each contributing their unique approach to product development, specifically, the creation of cars. As direct suppliers to the automotive industry, Tier 1 organizations grapple with diverse product design strategies, testing methodologies, and risk management practices. The ripple effect of these decisions reverberates across the entire supply chain. Juggling multiple OEM collaborations simultaneously, Tier 1 suppliers adapt

their approaches to cater to individual customer needs. This necessitates meticulous adherence to established quality planning standards, such as ISO 16494 or VDA requirements, alongside the strategic deployment of supplementary tools. By aligning with the APQP methodology, these suppliers enhance their efficiency in achieving project goals across subsequent phases [1-3].

2 Research object

This research, of significant importance, delved into a comparative examination of the elements that impact both the product and process prerequisites. Those factors, crucial to the efficiency and effectiveness of project execution, as per the APQP methodology, were studied within the automotive sector. The study was conducted for three distinct customer categories, with their respective characteristics outlined in Table 1. Notably, the research methodology was firmly rooted in the practical experiences and observations gathered within the Tenneco Automotive Eastern Europe organization, lending credibility and relevance to the findings.

The process of creating a car shock absorber, a testament to the complexity and innovation in the automotive industry, is unique. Its flexibility in design alterations allows the customer to modify certain specifications, referred to as "Tuning Parameters" in the context of the article, even after the product has moved beyond the design and development stage (also known as phase 2 in the APQP). These modifications can encompass a variety of elements, such as the damping characteristics, which control the speed and ease of motion, the parameters of the suspension springs, which contribute to the vehicle's stability and comfort, or the rigidity of the rubber-metal components, which can affect the overall performance and durability of the shock absorber. This collaborative approach ensures that the final product aligns with the OEM's requirements and expectations, while allowing adjustments based on the real-world performance and feedback. This iterative process is crucial in achieving a high-quality, reliable, and efficient shock absorber that meets the dynamic needs of the automotive industry.

However, one of the significant challenges, faced during this iterative process, is managing the variability of client requirements. Throughout the project lifecycle, customers may request changes due to evolving performance expectations, new regulatory standards, or advancements in competing technologies. Such variability can introduce complexity into the supply chain and necessitate agile and adaptive project management practices. The extent and quantity of potential modifications are mutually agreed upon between the organization and the OEM during the product planning and quality phase (Phase 1, according to APQP). This agreement ensures that both parties

clearly understand the project's scope and the flexibility allowed within the product's specifications. Continuous communication and feedback loops are essential to navigate these changes effectively, ensuring that the project remains on track, while meeting the evolving needs of the customer. This dynamic interaction between the supplier and the client underscores the importance of maintaining flexibility and responsiveness within the automotive industry's product development processes [4-7].

3 Research methodology

Research methodology employed in the study, focusing on the systematic approach taken to investigate the optimization of development processes for electronically controlled dampers within the automotive industry. The methodology integrates the Advanced Product Quality Planning (APQP) framework, a recognized standard in the automotive sector, to structure the project phases and ensure a comprehensive and iterative process [8-9]. The preparation of the analysis was divided into six stages (individual numbers correspond to the numbering in Figure 1):

- Project Phase Breakdown Structure: The project
 was segmented based on the APQP methodology,
 which provides a structured path from the product
 planning and definition to product and process
 validation. This phase breakdown ensures that all
 the critical stages of development are meticulously
 planned and executed, adhering to industry best
 practices.
- 2. OEM Client Classification: To enhance the relevance and applicability of the research, OEM clients were classified according to specific criteria. This involved identifying distinct types of OEM clients and establishing clear criteria for their classification, enabling tailored approaches to different client needs and expectations.
- 3. Data Collection from Selected Projects: Data was collected from a variety of past projects conducted within the organization. This step was crucial for identifying the input data provided by OEM clients and the corresponding project phases (as per APQP), when these inputs were communicated. By analyzing the historical data, insights were gained into typical OEM interactions and data provision patterns.
- 4. Tier 1 Supplier Response Analysis: Responses from Tier 1 suppliers to the input data provided by OEM clients were collected and analysed. This analysis focused on the timeliness and adequacy of supplier responses, which are critical for maintaining project timelines and ensuring quality outcomes.
- Defect Occurrence Curve Development: Based on the collected data, a curve, representing the moment of defect occurrence during the project

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implementation, was developed. This curve illustrates when defects typically occur, although they often remain undetected at the time of occurrence, providing insights into potential areas for process improvement.

6. Defect Removal Costs Curve: Utilizing the 1-10-100 rule, a curve, depicting the potential costs of defect removal, depending on the project phase in which they were detected, was drawn. This rule highlights the escalating costs of defect resolution as the project progresses, emphasizing the importance of early detection and intervention.

4 Tenfold rule basic principles

Figure 2 presents an analysis that identifies factors that impact product or process requirements and

pinpoints the potential instance of defect origination. This is correlated with a curve that represents the cost implications of rectifying these defects, contingent on the phase of their emergence. One of the key principles of quality management is the 1-10-100 rule, also known as the tenfold rule (firstly published by George Juran, a quality management expert in his book Juran on Quality by Design [10]). This rule describes how the costs of finding and fixing a defect increase exponentially with each stage of the production process. For example, let us assume that the cost of detecting and removing a defect at the stage of preparing the technical documentation were 1 euro. Then, if the same defect was found at the stage of creating the prototype, the costs of correcting it will rise to 10 euros. If the defect was discovered at the mass production stage, the cost will soar to 100 euros. If the defect is detected at the stage of product operation, the cost will reach

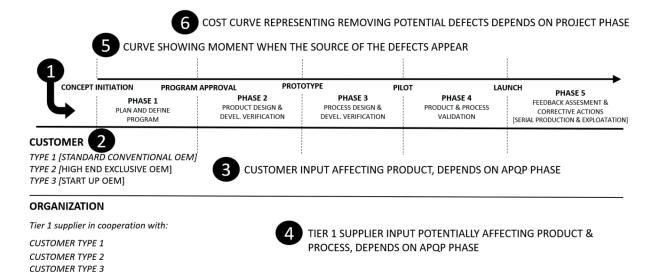


Figure 1 Steps how data was collected and organized for analysis and assessment

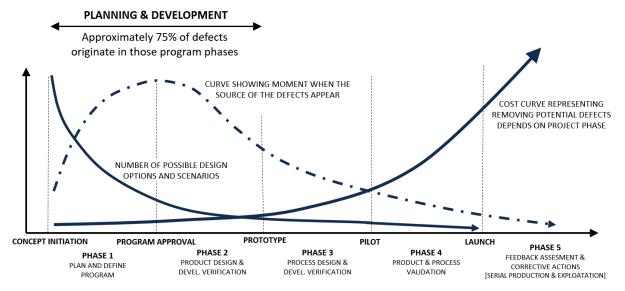


Figure 2 Basic principles of 1-10-100 rule (tenfold rule) in correlation with defect origin moment and level of freedom with choosing different design proposals and scenarios (own elaboration based on [5])

Table 1 Definition of the three types of OEM customers

CUSTOMER	DEFINITION
CUSTOMER 1 STANDARD CONVENTIONAL OEM	Standard conventional OEMs (Original Equipment Manufacturers) produce reliable, affordable cars designed for a wide range of consumers. These manufacturers focus on mass-market vehicles, balancing quality, performance, and cost-efficiency to make them accessible to the average person. Highly structured and well-organized in their product development processes, they employ rigorous quality control measures and adhere to industry standards. This ensures that their vehicles are dependable and meet consumer expectations for functionality, safety, and value. Examples include Toyota, Ford, and Volkswagen, known for their strong market presence and commitment to everyday transportation needs.
CUSTOMER 2 HIGH END EXCLUSIVE OEM	High-end luxury car manufacturers create meticulously crafted vehicles using the finest materials and cutting-edge technology. Designed for power, speed, and sleek aesthetics, those cars offer an unparalleled driving experience. Despite their complexity, these companies maintain a highly structured development process. Leveraging extensive product development expertise, they ensure precision and consistency at every stage. Detailed planning outlines specifications, timelines, and resource allocation. By maintaining a methodical development process, luxury car manufacturers produce sophisticated vehicles that meet the highest standards of excellence, satisfying discerning customers.
CUSTOMER 3 START-UP OEM	Start-up car manufacturers are new companies known for their innovative approach to manufacturing, design, and features. They often focus on technologies like autonomous driving, advanced safety, and cutting-edge infotainment systems. Typically producing environmentally-friendly vehicles, powered by electricity or alternative fuels, their product development process is often less structured, with frequent design changes and feature modifications. Driven by rapid technological advancements and evolving requirements, these alterations usually occur in the latter project stages. This flexible approach aligns with APQP (Advanced Product Quality Planning), enabling start-ups to quickly adapt and integrate new features to enhance vehicle performance and sustainability.

1000 euros. These escalating costs impact the project's budget and pose significant risks to the project's timeline, customer satisfaction, and overall success.

The 1-10-100 rule emphasizes the importance of early defect detection and prevention in the project lifecycle. By identifying and eliminating defects as soon as possible, the project team can save time, money, and resources, as well as improve customer satisfaction and loyalty. Early defect detection also reduces the risk of product failure, legal liability, and reputational damage. Therefore, implementing the effective quality control and assurance methods at each stage of the production process is essential and highly beneficial, such as design reviews, testing, inspection, and feedback. These methods ensure the final product's quality and contribute to the overall success and reputation of the project and the organization [11-12].

5 Types of OEMs

Table 1 presents the authors' definition of three types of Original Equipment Manufacturer (OEM) customers in the Automotive industry. In most cases, the factors influencing cooperation with a given OEM are the sector's experience and know-how and the level of product advancement. The product is designed to meet the end user's requirements and/or expectations.

Customer 1 holds the largest market share. In most cases, they choose reliable, proven suppliers with

considerable experience in the industry. Customers 2 and 3, on the other hand, are more interested in innovative solutions due to the high technological advancement of the final product and the end customer's expectations. These solutions will give them a competitive edge and a larger market share. Understanding different types of OEM customers, and the factors that influence their cooperation, is crucial for the industry's strategic planning and decision-making processes.

Results and discussion

The analysis depicted in Figures 3 and 4 is paramount as it outlines the factors that influence product or process requirements and indicates the potential stage of defect origin. This is further correlated with a curve that illustrates the costs of removing the defects that have emerged, depending on the phase in which they occurred.

Upon careful analysis of the data, it becomes evident that there are potential risks that an organization (tier 1) might have to face when collaborating with a specific type of Original Equipment Manufacturer (OEM). The most significant risk is associated with a start-up type OEM, where the intense focus on innovation and new technologies often hinders a structured product development process [13].

It is important to note that the risk of partnering with a start-up type OEM is more than just a theoretical concept. It stems from their intense focus on rapid

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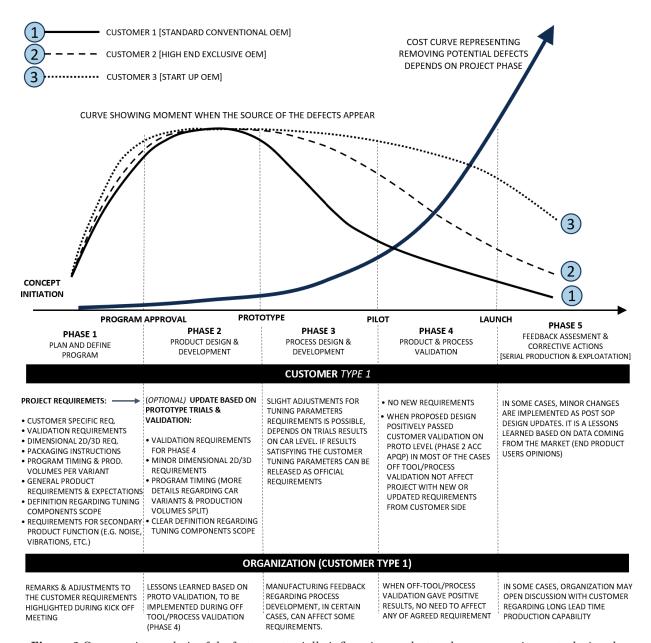


Figure 3 Comparative analysis of the factors potentially influencing product and process requirements during the project lifetime for OEM Customers type 1 (based on [4-6])

innovation and adoption of new technologies. While this can lead to groundbreaking products and services, it can also result in a lack of structure and predictability in the product development process. This can pose significant challenges for tier 1 organizations that require stability and predictability in their supply chain.

Furthermore, the start-up-type OEMs may need more established processes and resources of more mature OEMs. This can lead to potential issues with quality control, production capacity, and timely delivery. Additionally, start-ups often face higher business volatility, including financial instability, which can pose additional risks to the tier 1 organization.

According to the research results, most product quality problems originate at the design and development stage. It is not connected to the OEM type. It relates to

how dynamic and structured the development process is in an organization. A model way to detect the potential defects early in the project is the product validation based on prototypes (phase 2 according to APQP), often preceded by computer simulations. This is the optimal time to make changes to the project, as it is associated with relatively low costs. However, a necessary condition is for the customer to specify the requirements for the product to be created as soon as possible (already in phase 1 according to APQP), and the supplier should scrutinize them meticulously, emphasizing all the inconsistencies or requirements that are not fully defined. Incomplete or improper requirements increase the risk of late defect detection, which can negatively affect the schedule and profitability of the project [14-18].

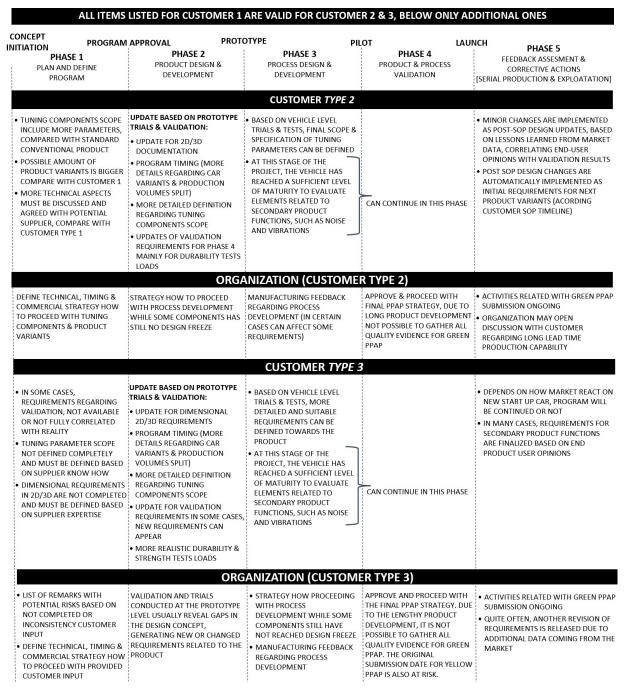


Figure 4 Comparative analysis of the factors potentially influencing product and process requirements during the project lifetime for OEM Customers type 2 and 3 (based on [4-6])

7 Conclusions

The costs of eliminating defects escalate as the project progresses. It is crucial to note that changing or introducing the new product requirements after the completion of phase 2, as per APQP, is a risky move. This is because most defects detected in the product occur during the product design and development phase. The later changes are made in the project, the higher the risk associated with late defect detection, which can lead to significant financial outlays to rectify those.

The flexibility in decision-making during the design phase, particularly in implementing various technical solutions, is directly tied to the phase in which the project is situated. In the initial stages, as per APQP (product planning and design), the costs of changing the concept or modifying project assumptions are manageable, reducing the additional costs that organizations might face in unforeseen situations.

To elaborate, the decision-making flexibility during the project's design phase is a critical aspect of a project management and execution. This flexibility, which includes the ability to implement various technical m B258

solutions, is intrinsically linked to the project's current phase.

As per the APQP approach, there is a greater degree of flexibility in the early stages of a project. During those stages, changes to the project's concept, or modifications to the project's assumptions, can be made relatively cheaply. This is because the project is still in its formative stages, and changes can be more easily integrated into the project plan without causing significant disruptions or delays. Therefore, maintaining the flexibility in decision-making during the design phase is not only beneficial but the cost-effective as well, as it allows for adjustments to be made early on, thereby reducing the potential for costly changes or corrections later in the project lifecycle. This approach, therefore, contributes to more efficient and effective project management, ultimately leading to the better project outcomes and success.

A Tier 1 organization must make every effort to secure the product development process, regardless of the type of customer with whom it collaborates. This is crucial to ensure the organization's highest quality and efficiency to be positively recognizable

in the automotive industry.

Any deviation from good practices during the project implementation should be officially reported to the client, along with the consequences it carries. This allows control over costs and the project's schedule, strengthening the organization's market position.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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TECHNOLOGICAL PROPERTIES OF CYLINDER LINERS OF AUTOMOTIVE INTERNAL COMBUSTION ENGINES RESTORED BY CENTRIFUGAL INDUCTION SINTERING

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Resume

Cylinder liners of an automotive internal combustion engine are subject to significant losses during operation. Severe operating conditions of cylinder liners lead to the appearance of various defects that must be eliminated to ensure the performance of the internal combustion engine. Currently, several methods have been developed for restoring and strengthening the inner surface of cylinder liners of automobile and tractor engines. Analyzing the considered methods for strengthening and restoring cylinder liners, their advantages and disadvantages from the point of view of increasing their durability, it can be assumed that the high-quality restoration of cylinder liners will be provided by a method of applying a coating by centrifugal induction sintering of powder material. Self-fluxing powders were used as baked powder material.

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1 Introduction

Engine life, first of all, depends on the wear resistance of the cylinder parts - piston group, which during the engine overhaul are replaced with new ones or restored. Cylinder liners of automotive internal combustion engines are subjected to significant loads during operation. Severe operating conditions of cylinder liners lead to the appearance of various defects that must be eliminated to ensure the performance of the internal combustion engine. For each type of liner defects, there are various methods and devices for their eliminating, in particular for restoring the geometry and dimensions of the worn working surface. All these methods and devices for their use have their advantages and disadvantages, which must be taken into account when choosing a rational method for restoring the working surface of cylinder liners.

Currently, several methods have been developed for recovery and strengthening the inner surface of automotive cylinder liners engines, which, according to their technology, are divided into boring for repair size and restoration to nominal size. For restoration of cylinder liners to nominal size, the following methods are used: metallization, galvanic methods, pressing wear-resistant plates, surfacing of wear-resistant powders on the inner surface, restoration by heating, etc.

The most common material used for the manufacture of cylinder liners for automobile and tractor engines is gray cast iron - a cheap and technologically advanced material that, under normal operating conditions, has sufficient durability and reliability. At present, when production is faced with the task of increasing standards for engine reliability indicators, gray cast iron requires further improvement through the introduction of wear-resistant alloying elements or hardening of its surface. For the manufacture of monometallic sleeves, a chromium-silicon alloy of the following composition has been developed: C - 2%, Cr - 12 to 15%, Si - 1.0%, Mn - 0.8%, Ni < 0.3% [1]. Performance tests of chromium-silicon cylinder liners indicate that their wear is approximately 4 times less than the wear of gray

cast iron liners. The advantages of the alloy include its increased rigidity, which is 1.5 to 2 times greater than that of combined sleeves. However, the given alloy has poor machinability and low workability.

Scientific Automotive Institute (SAI) has developed two more types of wear-resistant chromium cast irons with carbides in the structure and compact graphite - ICHK-33K, with carbides in the structure and lamellar graphite - ICHK-33, which exceed the wear resistance of gray cast iron by 1.9 and 2.2 times, respectively. However, all of the above wear-resistant alloys have a common drawback - excessive consumption of expensive scarce material, poor machinability, and therefore have not found wide application in production.

To increase the wear resistance of cylinder liners made of gray cast iron, volumetric, isothermal or surface hardening of the inner surface of the liner is carried out. At the same time, due to the finely dispersed structure of martensite or troostite in austenite and the high hardness of the hardened surface (HRC 42 to 46), the wear resistance of the surface during bulk, isothermal, and high-frequency hardening increases by 1.4, 1.6 and 1.7 times, respectively, [2]. However, despite the widespread use of hardening of sleeves in production, this method has such disadvantages as significant warping of the part, instability of the process, and poor machinability of sleeves after hardening. In addition, hardening no longer meets the increased requirements for liner wear resistance due to the creation of forced engines. Due to the listed shortcomings in production, hardening of sleeves has not found widespread use.

Another way to increase the wear resistance of the working surface of the liner is nitriding [3], in which a layer of nitrides with high microhardness (Hµ = 12500 to 13000 MPa) is formed on the working surface. Nitriding is carried out in gas or liquid media at temperatures of 793 to 8I3 K (520 to 540 °C). According to data [4], the wear of nitrided cast iron is 3 times smaller than that of non-nitrided alloyed cast iron. The disadvantages of this process include the duration of the process, warping of parts and heterogeneous properties across the thickness of the nitride layer, especially on cast iron.

Works [2-3] consider increasing the durability of liners using thermal diffusion sulfidation. In this case, relatively thick and easily wearing films are formed, which facilitate processing and protect against jamming in the initial period of operation, but do not allow long-term protection of the friction surface from intense wear.

Increased wear resistance of cylinder liners is achieved by chrome plating [5-6]. This type of hardening allows to increase the service life of liners by 2 to 3 times. High hardness and good adhesion of the coating to the base metal up to 600 MPa are ensured by smooth chrome plating, but it has poor run-in and insufficient oil-holding ability. The best results are obtained by porous chrome plating, which eliminates the above disadvantages. Its antifriction properties depend on the porosity and hardness of this coating. Minimal wear of a

rubbing pair with a chrome-plated sleeve is observed at microhardness $H\mu=10000$ to 10500 MPa and porosity 20 to 30%. Electrolytic chrome plating of liners, while providing working surfaces with high resistance to chemical, electrochemical, temperature and mechanical influences, however, as a method of strengthening worn liners does not satisfy all the requirements of modern production. The main reasons are low productivity and high cost of the coating deposition process. In addition, chromium has low resistance to adhesion to aluminum, its alloys and other materials. An important disadvantage of chrome plating, as well as other galvanic processes, is the need to have expensive treatment facilities at the plant to protect the environment.

Increasing the wear resistance of cylinder liners should include surface plastic deformation [7], which involves rolling out the inner surface of the liners with balls of a diameter of 8.23 and 9.53 mm under the following modes: speed - 100 to 150 m/min; feed - 0.01 to 0.03 mm/rev, tension - 0.03 to 0.05 mm. GAZ-53 and ZIL-130 cylinder liners processed using this technology showed an increase in wear resistance by 1.2 times compared to serial ones. However, this is no longer enough for modern high-performance engines; in addition, the disadvantages of this method include the fact that the process does not provide the required accuracy, usually obtained by honing.

To increase the efficiency of processing by surface plastic deformation, the author proposed to carry it out in combination with heating the surface layers with electric current, which leads to an increase in wear resistance up to 2 times. The disadvantages of this method include low tool life, small thickness of the hardened layer since a significant part of the hardened layer is removed by subsequent honing, as well as the presence of deformations of the cylinder liners.

For ZMZ-53 engines, a method of manufacturing combined liners was used by pressing a special insert made of an alloy - Ni-resist - into the upper part. At the same time, an increase in the durability of liners by an average of 2.5 times was achieved [8]. However, the use of inserts has a number of significant disadvantages. Pressing inserts with an interference fit along the diameter of 0.14 to 0.30 mm causes warping of the sleeve, and the slightest deviations in size and failure to maintain the cylindricality of the seating surfaces lead to the insert being squeezed out of the sleeve after it is pressed. During the engine operation, the insert moves in the liner, resulting in formation of an annular gap between the lower end of the insert and the flow line in the liner, which leads to the penetration of oil, which carbonises and makes it difficult to remove the heat from the working surface of the insert to the coolant. It has been established that in sleeves with inserts the ovality in the upper belt is approximately two times greater than in the lower, while in sleeves without inserts the change in ovality is the same.

Increasing the durability of cylinder liners is possible

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by creating an oil-retaining surface. For this purpose, phosphating of cylinders is used [9], artificial creation of porosity and oil-retaining relief [10]. When phosphating an oil-retaining surface is formed when cast iron liners are treated in Majef salts. In this case, pearlite is etched, and the phosphide eutectic, which does not interact with Majef salts, forms protrusions. After phosphating, the surface of the sleeve has a height of microroughness of 3.0 to 6.0 microns. Phosphated cylinder liners are approximately 3 times more wear-resistant than the serial ones. However, the more phosphide eutectic in cast iron, the higher the efficiency of phosphating. However, phosphorus is an undesirable impurity in cast iron sleeves. A disadvantage of phosphating is the increased wear of the rings, despite their good running-in properties.

The oil-retaining relief on the working surface of automotive engine liners was created using vibratory rolling [3, 11-12]. At the same time, an increase in the wear resistance of the liners by 1.5 to 2 times was noted. The disadvantages of this method include increased oil waste and deformation of the liners during running-in.

Analysis of methods for restoring cylinder liners, from the standpoint of increasing their durability, shows that not all the methods satisfy this requirement. Thus, methods for restoring the cylinder liners using repair dimensions, thermal shaping, installing an easily removable bushing, pressing in easily removable inserts, and welding steel strips do not allow increasing the durability of the liners and have a number of significant disadvantages, such as weakening the rigidity of the liner, increasing its deformation and thermal stress in operation. In addition, the inclusion of additional parts in the dimensional chain of the cylinder - piston group tightens the tolerances, which, in conditions of mass production, significantly increases the cost of the finished product.

In contrast to methods for the restoring cylinder liners using additional parts (compensators), methods for creating a monolithic liner through metallization and surfacing, in principle, make it possible to restore the functionality lost by the interfaces and increase its wear resistance.

In [13], a method was proposed for restoring the internal surfaces of cylinder liners by surfacing austenitic cast iron (Ni-resist). The metal in the molten state was poured into a previously prepared internal bore of a sleeve rapidly rotating around the vertical axis, heated to a temperature of 1173 K (900 °C) and it was welded to its base. At the same time, the rigidity of the sleeve and its operational characteristics increased; the disadvantages include separate heating of the deposited material and the use of fluxes, which significantly complicates the surfacing process. Restoration of the internal cylindrical surfaces of a number of parts by centrifugal induction surfacing with a sormite-type hard alloy ensures fast and uniform heating of the part and sormite over the entire restored surface. The wear

resistance of the deposited surface increases by $2.0\ \mathrm{to}$ $2.5\ \mathrm{times}.$

In [14], a method was proposed for increasing the wear resistance of cast iron tractor liners through centrifugal induction surfacing with self-fluxing powder material PG-KhN80SR4, which ensured an increase in the wear resistance of cylinder liners by more than 5 times.

However, surfacing methods have significant disadvantages; the high temperature at which surfacing is carried out causes a change in the structure of the substrate and the deposited material, which negatively affects the wear resistance of coatings. In addition, due to the high deposition temperature, noticeable deformations occur during rotation of the part, which entail the introduction of additional treatments to eliminate them. The disadvantage is the use of special fluxes and the difficulty of subsequent mechanical processing.

These disadvantages are eliminated in works [1-2], in which, with the centrifugal induction method of applying powder coatings, thermal diffusion sintering of powders is proposed instead of surfacing. When choosing a powder material for sintering, it is necessary that it contains at least 85% ferromagnetic elements. The melting temperature of the powder must be close to the melting temperature of the base metal so that they simultaneously reach a sintering temperature that lies within 0.7 to 0.85 of the melting temperature. The powder must contain activating elements (such as boron, silicon, etc.) that can act as a flux and form a liquid phase at lower heating temperatures than the powder hase

In work [15], the issues of applying the PG-SR2 powder coating to the inner surface of cylinder liners were studied, equipment for centrifugal induction sintering was developed, and the issues of mechanical processing of the powder coating and baked liner by boring followed by honing were studied.

Analyzing the considered methods for strengthening and restoring cylinder liners, their advantages and disadvantages from the point of view of increasing their durability, one can assume that the high-quality restoration of cylinder liners would be provided by a method that satisfies the following basic requirements:

- the least temperature influence on the metal base of the liner, excluding changes in its microstructure and the appearance of significant residual deformations;
- high-quality adhesion of the applied layers to the base:
- increasing the wear resistance of restored liners by 3 times or more;
- availability of materials used in equipment restoration;
- the ability to perform subsequent mechanical processing using standard equipment available at repair plants;
- high productivity of applying layers;

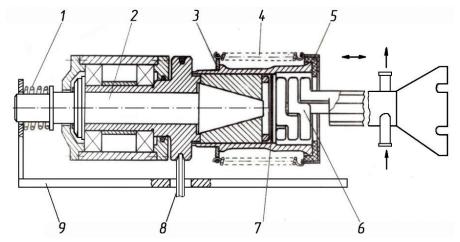


Figure 1 Installation diagram for restoring cylinder liners: 1, 4 - spring; 2 - rod with a conical head; 3 - ring; 5 - cover; 6 - inductor; 7 - gasket; 8 - V-belt drive; 9 - bed

- technology and equipment must meet safety requirements;
- application of the method must be economically feasible.

An analysis of the methods for strengthening and restoring the cylinder liners, discussed in the article, shows that the most promising method for strengthening and restoring the cylinder liners is centrifugal induction sintering with metal powders. This method is carried out at temperatures that do not significantly affect the structure of the metal base of the sleeve and the applied material, with small deformations of the sleeve. Sintering makes it possible to obtain a wearresistant layer on the surface of the liner by preserving the physical and mechanical properties of the powder material and creating an oil-resistant surface due to the optimal porosity of the coating. When baked, a monolithic sleeve is obtained, which increases its rigidity and reduces deformation when installing it in a block and during operation. The process of subsequent machining requires standard metal-cutting machines in the form of boring and honing machines. The process of sintering a powder coating onto the inner surface of the cylinder liner and subsequent machining can be automated [16].

The main method of restoring the worn cylinder liners is boring for repair size, which entails a reduction hardness of the inner surface and the need for organization production of oversize pistons and piston rings. Methods of restoration of cylinder liners to nominal size is not widely available applications due to the fact that they do not meet the requirements of the standard for quality and have a high cost. In this regard, the development of a method for restoring the cylinder liners to the nominal size meeting the requirements of the standards is urgent task of repair production. When deciding on the choice of a method for restoring parts, the most important factor is the issue of processing the coating of the restored liners. Currently, many methods of applying materials have been developed.

The industry supplies a fairly wide range of wearresistant and hard materials for creating coatings. However, many of them have not found widespread use due to the difficulty of processing coatings.

If scientific work on the mechanical processing of hard-alloy coatings applied to parts of the shaft type is to some extent carried out, then the work on the processing of internal holes restored by the same coatings is very limited. Therefore, the issue of processing the inner surface of cylinder liners seems quite complicated.

2 Materials and research methods

2.1 Technological process for restoring cylinder liners

The proposed technology for restoring cylinder liners of the ZMZ-53 engine, includes: washing, defect detection, removal of the insert from the liners, preparation of their surface, coating by induction sintering and mechanical processing (boring, rough and fine honing).

The cylinder liners of ZMZ-53 engines that had worked for two overhaul periods were used in this study. Before coating, wear-resistant Ni-resist inserts were removed from the liners. In laboratory wear tests and comparative performance tests, liners with inserts were also examined in addition to remanufactured ones. The powder material to be baked was self-fluxing powders.

Research on applying a coating of metal powders to the restored part of the inner surface of the cylinder liner was carried out on a device specially manufactured for this purpose. Figure 1 shows a diagram of the installation for restoring cylinder liners. The cylinder liner is mounted on an expanding four-jaw mandrel. The mandrel ensures reliable fastening of the sleeve, its rotation in a horizontal axis and the ability to quickly change the sleeve. The ETO 2-20 electric drive and V-belt drive allow for stepless regulation of the liner rotation speed in the range from 100 to 1200 min⁻¹.

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The sleeve was heated by an internal multi-turn inductor (Figure 1), made of a rectangular copper pipe. To increase the electrical efficiency of the inductor, ferrites were installed in it. The inductor is mounted on the rod of the pneumatic cylinder, which ensures the input and output of the inductor from the cylinder cavity. The inductor was powered by a VChG 1-100/0.066 high-frequency unit with a power of 100 kW and a generated current frequency of 66 kHz.

The coating application mode is carried out at the following indicators: grid current - $I_{\rm s}=1$ A; anode current $I_{\rm a}=5$ A; anode voltage U $_{\rm a}=5$ kV; load voltage on the circuit - U $_{\rm n}=0.45...0.5$ V; heating time, t = 150...180 s ; cylinder liner rotation speed - n = 950 to $1000~min^{-1}$.

The coating used in this work, although it has a low hardness HRC 32 to 42, has poor workability. This is due to the presence of porosity in the coating up to 10 to 15%, solid inclusions with a hardness of up to $\rm H_{100} = 29\cdot10^3$ MN/m 2 (2.9 kN/m²) and viscous nickel base. All this together creates unfavorable conditions for mechanical processing of the coating. The coating was applied with a thickness of 2 mm per side.

There were no cracks, holes or large pores in the coating. However, this coating had a microporosity of 12 to 15%. The mechanically processed surface of the coating met the requirements.

The individual sintering time for one sleeve was 10 minutes or 0.166 hours with a basic time of 3 minutes. In the future, by improving the sintering installation and reducing the auxiliary time, the piece time can be reduced. The boring and honing time for the restored cylinder liners was 0.25 hours. The longer processing time for restored liners was due to the difficulty of machinability of the coating compared to the machinability of gray cast iron.

Based on the above and physical and mechanical studies, one can conclude that this process of centrifugal induction sintering with metal powder can be recommended for use when restoring cylinder liners that are subject to rejection after using their second postrepair resource. This process can be used not only when restoring the liners that have wear-resistant inserts, but when restoring monometallic liners, as well. In this case, it is necessary to bore the space under the coating to a depth of 0.5 mm. Here, one obtains savings in the applied material due to the fact that the thickness of the applied layer is reduced from 2.0 to 0.5 mm.

Processing of the restored cylinder liners was carried out using standard equipment.

Boring of the sleeves was carried out on a high-precision finishing and boring machine, type 2E78PN. A boring cutter with a replaceable multi-edge plate made of VK8 material was used as a cutting tool. The use of such cutters significantly reduces the time required to prepare them when they become dull. Boring was carried out in two passes (at a cutting depth of $t=0.5\,$ mm). The first pass treated only the coating. During the

second pass, the sleeve was processed along its entire length. The cutting speed and feed were assumed to be equal: $V = 35.0 \text{ m/min (n} = 120 \text{ min}^{-1})$, s = 0.2 mm/rev. The durability of the cutter with the VK8 plate made it possible to process up to 10 cylinder liners.

Honing was carried out on a 3G833 machine. To obtain the higher accuracy of the machined hole, an extended honing head was used. Honing modes: rotational speed V = 45.6 m/min; reciprocating speed $V_{\rm p} = 8$ m/min; pressure in the system P = 0.1 to 0.2 MPa.

For preliminary honing we used diamond stones ACP 100/80 M1 100%, for final honing we used diamond stones ACP 80/63 P11/P9 50%.

This technology for mechanical processing of restored cartridges made it possible to obtain processed surfaces with a roughness corresponding to class 9a, ovality and taper of the hole not exceeding 0.02 mm.

The individual time spent on boring the liner and honing was 0.25 hours.

2.2 Selection of material for rebuilding the cylinder liners

When choosing a material for restoring the cylinder liners, it is necessary to take into account their operating conditions and its physical and mechanical properties when working in tandem with piston rings. In this case, it was necessary to apply a coating that would be superior in wear resistance to serial liners, have good wearability and low tendency to scuff, have sufficient adhesion strength to the metal base of the liner and the ability to subject it to machining. Finally, the material should be relatively inexpensive. All these factors should have determined the choice of material for restoring cylinder liners.

The three pre-selected materials met the requirements for the coating according to individual parameters. To make the final selection of one material, studies were carried out on its sinterability and sinterability to the base, and the workability of the material. A number of physical and mechanical properties were compared according to literature data.

The three most common types are: PG-SR, SPGN, and NPC. One material was selected from each type. When choosing a material, its costs, hardness, workability and other physical and mechanical properties obtained from literary sources, were taken into account.

The chemical composition of self-fluxing metal powders selected for preliminary studies is given in Table. 1.

Sintering and sintering modes for each material were selected individually. When selecting modes, we varied the heating rate, temperature, heating duration and centrifugal force of pressure of the powders to the base (sleeve rotation speed). At the same time, we achieved a baked coating without cracks and with good adhesion to the base, especially in places where there

Table 1 Chemical composition of s	self-fluxing metal powders
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Brand				Ele	ment cont	ent in %					Hardness,
material	C	Cr	Si	Mn	В	Fe	Ni	Cu	P	S	HRC
PG-SR2	0.2-0.5	12-15	2.0-3.0	-	1.5-2.1	5.0	ost	-	0.04	0.04	38-42
SNGN-55	0.7-1.0	14-17	3.5 - 4.5	up to 1.0	3.2-4.0	up to 4.0	ost	-	-	-	53-58
NPC-1	0.1-0.3	-	1.3-1.5	-	1.2-1.5	0.1 - 0.7	ost	4-5	-	-	HB 190-230

was a stepwise transition of the inner surface of the liner, where there was an insert.

The assessment of the sinterability of the powders and their adherence to the base was determined visually by chipping the sleeve. As a first approximation, the adhesion of the coating to the base was considered satisfactory if their fracture was monolithic.

When selecting a material, the machinability of the baked material was linked to its hardness. Coatings with high hardness (SNGN-55) are difficult to process and thereby increase the costs of restoring parts.

The choice of material was also carried out taking into account the costs of the powder material. For example, the NPCh-1 alloy is slightly different in its properties from the PG-SR2 alloy, but the costs are twice as much. Even more expensive is the SNGN-55 alloy.

Therefore, based on preliminary experiments to determine adhesion and obtain a high-quality coating, as well as taking into account the hardness of the material and its costs, powdered hard alloy PG-SR2 was chosen as a material for restoring cylinder liners. This material met the requirements for the product being repaired. Restoring the cartridges with the specified material was supposed to ensure their normal performance and increased their service life.

3 Results

3.1 Determination of run-in and adhesion of coating

Research has shown that samples worked in tandem with tinned rings ran in faster (by 15 to 25%) than in pairs with chrome-plated rings. This can be explained by the fact that tin, compared to chrome plating, is a softer and more ductile material and increases the wearability of rubbing pairs.

The coated samples, which were paired with tinned rings, took significantly longer to break in than the samples with an insert and gray cast iron samples. The running-in time was about 25 hours. After finishing the running-in process, the coating had a shiny surface.

Samples with an insert ran in slightly better than the samples with a coating. Their break-in time was 15 to 17 hours when working with tinned rings.

For samples made of gray cast iron without coating and inserts, the running-in process was the least. Their break-in time was 10 to 12 hours when working

with tinned rings. They had a uniform running-in surface, which was explained by the homogeneity of the material.

Testing the samples for adhesion showed that the lowest values were for the coated samples. The operating time with a load on the sample of 1.1562 kN, under boundary lubrication conditions, was about three minutes. For samples with an insert, under the same conditions, setting occurred within the same time as for the samples with a coating. However, the load on the sample was slightly less than 1.187 kN. The adhesion of gray cast iron samples appeared a little faster than that of samples with an insert (2 to 3 min). The load was the same.

Tests have shown that the presence of solid inclusions in the coating somewhat increases the process of their breaking-in. However, this structure of the samples significantly reduces their setting when working with tinned rings.

3.2 Study of the coating wear resistance

When testing samples of sleeves in conjunction with chrome-plated rings (Figure 2), the wear resistance of sleeves with an insert (red curve) and experimental sleeves (green curve) was almost the same.

Over 100 hours of testing, linear wear was 0.085 and 0.082 mm, respectively. The wear of gray cast iron samples (blue curve) was 1.866 times greater than the previous ones and amounted to 0.153 mm during the same testing time.

When working with tinned rings (Figure 3), the wear of the sleeve samples with an insert (red curve) remained the same as when working with chrome-plated rings, and amounted to 0.084 mm over 100 hours of testing. However, the wear of coated liners (green curve), wear value 0.04 mm, decreased by half compared to samples of liners with an insert and four times compared to samples of gray cast iron liners (blue curve), wear value of which was 0.162 mm.

At the reversal points or at the so-called dead points MT1 and MT2, the wear value is greater than at other friction areas between MT1 and MT2. This can be explained by the fact that at these points the speed of movement of the counter samples (piston rings) drops to zero, while the specific pressure increases. This nature of the work of the rubbing pair causes rupture of the oil film and thereby creates the condition

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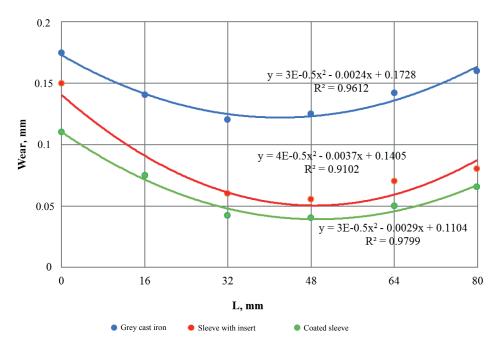


Figure 2 Wear distribution between dead points MT1 and MT2 along the length of samples with chrome rings

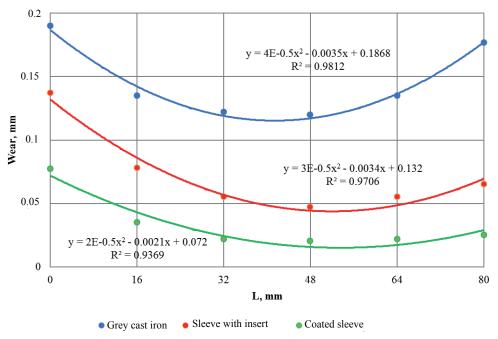


Figure 3 Wear distribution between dead points MT1 and MT2 along the length of samples with chrome rings

of boundary lubrication. In this case, at the indicated points, interaction occurs between the metal surfaces of the sample and the counter-sample. These conditions cause increased wear of the samples at the reversal points.

The reduction in wear of coated liner samples when working with tinned rings can be explained by the fact that tin, having a low melting point, significant ductility, and the ability to be deformed many times without destruction, acts during friction as a liquid lubricant, localizing the process of metallic

interaction in the tin coating layer, and thus eliminates the intense destruction of surfaces during the initial period of operation of mating samples, and facilitates the running-in. The favorable running-in process has a noticeable effect on the period of established wear.

The high wear resistance of coated liner samples can also be explained by the high hardness of the coating itself and its porosity, which creates an oil-intensive friction surface. With an optimal coating porosity, a reliably separating film of lubricant is retained on the friction surface of the liner samples, making it difficult

to form large adhesion units, their growth and long-term existence between the contacting surfaces.

The high hardness of the coating ensures minimal sizes of damage spots on its surface in comparison to the sizes of damage to the surfaces of cast iron unstrengthen liner samples.

Analysis of the wear distribution curves on the formation surface of the liners considered above also showed that in the reversal zones of the piston ring sample, i.e., at dead points MT1 and MT2, the amount of wear is greater than in other areas, where the sliding speed is higher and the lubrication film is more reliable. This wear topography is generally characteristic of cylinder liners of internal combustion engines and indicates the influence of sliding speed on the thickness of the lubricant film and the intensity of damage to the friction surface itself. In places where the direction of movement MT1 and MT2 changes, a thin film of

lubricant does not provide reliable separation of the surfaces. In this zone, characteristic damage due to microcontact setting is observed and maximum wear is obtained. An increase in sliding speed leads to the manifestation of a hydrodynamic effect, an increase in the thickness of the lubricant film, a decrease in the likelihood of metal contact, and less damage is obtained.

The wear of the chrome-plated and tin-plated rings themselves (compression rings) is shown in Figure 4. It shows that the wear of unhardened tin-plated rings is approximately 1.50 to 1.65 times higher than the wear of chrome-plated rings. However, rings of both types have approximately three times less wear when paired with samples of experimental liners with a coating than when paired with samples of liners made of gray cast iron, and somewhat less (1.3 to 1.4 times) compared to pairing samples with sleeves with a Ni-resist insert.

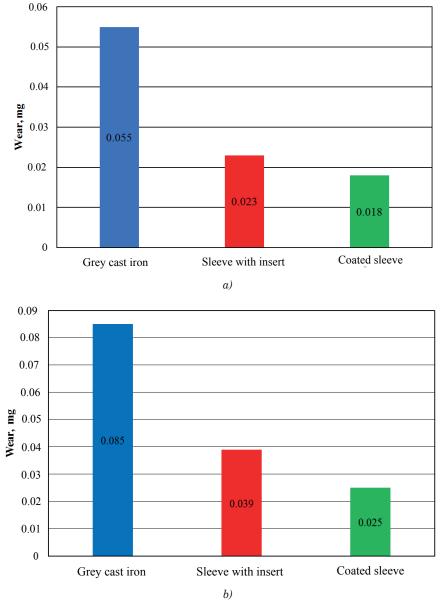


Figure 4 Wear of tin-plated (a) and chrome-plated (b) rings during friction with liner samples: 1 - for gray cast iron; 2 - with insert; 3 - coated

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4 Discussion

- Research has shown that the coating of cylinder liners obtained by centrifugal induction sintering (viscous nickel base with solid inclusions) has lower machinability than the gray cast irons used for cylinder liners.
- 2. It has been established that boring such a coating is possible when using cutters with VK8 carbide inserts at a cutting speed of 35 m/min and a feed of 0.2 mm/rev. It is recommended to do boring in two passes with a cutting depth of 0.5 mm.
 - Honing after boring can be done with diamond stones type ABH 100x8x4x2x ACP 100/80 M 1 100 % at the mode: $V_0 = 45$ m/min, $V_p = 8$ m/min, pressure (1.5 to 2.0) x 10 ·5 Pa). Final honing using ACP 80/63 P11/P9 stones 50 %.
- Sleeves with a carbide coating have worse running-in properties than the serial cast iron sleeves (with an insert). The running-in time for coated sleeves was about 25 hours, and for sleeves with an insert - 15 to 17 hours.
 - The adhesion of coated sleeves when working with tinned rings occurred after 3 minutes at a load on the sample of 1.562 kN, and for serial sleeves under the same conditions (the same time) at a slightly lower load of 1.187 kN.
- 4. The presence of hard inclusions in the coating structure of the liners provides the mirror of the cylinder liners with high wear resistance. Laboratory wear tests of these sleeves showed that sleeves with a wear-resistant coating, when mated with chromeplated rings, had approximately the same wear resistance as sleeves with Ni-resist inserts and 3.5 times greater than those of gray cast iron sleeves.

When working with tinned rings, coated sleeves had half the wear of sleeves with an insert and four times less wear than the gray cast iron sleeves.

The wear of chrome-plated and tinned piston rings, when working with restored liners, is 1.3 to 1.4 times less than when working with liners with Ni-resist

inserts, and three times less than when working with gray cylinders cast iron. In this case, the tinned rings wear out slightly more (1.5 to 1.65 times).

5 Conclusions

Analyzing the test results of samples of liners unstrengthen and subjected to local hardening due to a hard coating, one can see that the intensity of destruction of the reversal zones has a significant impact on the wear of zones located in more favorable friction conditions.

From the data obtained, it is clear that strengthening the liners in the zones of change in the direction \of the piston rings movement by applying a coating with high oil-retaining ability and hardness, reduces the likelihood of the formation of micro-setting units, their sizes, and the intensity of damage by fixed wear products to the unstrengthen surface of the liner samples. At the same time, a decrease in piston ring wear is observed, which indicates a strong influence of the nature of mutual damage to the surfaces of the friction pair under consideration.

Research shows that local hardening of cylinder liners is an effective means of reducing wear of the friction unit.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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ROBUST ADAPTIVE SPEED CONTROL FOR THE DC MOTOR BASED ON A MODIFIED MRAC

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Resume

The aim of this research was to develop a high performance adaptive control strategy based on the model reference adaptive control (MRAC) approach, using the MIT (Massachusetts Institute of Technology) law rule as an adjustment mechanism to control the speed of a DC motor. In this work, we propose a modified model reference adaptive control (MRAC) to exploit the advantages of adaptive control within the classical feedback loop. This new control strategy is a hybrid between the classical control loop and MRAC, designed specifically for the control of a DC motor system. The modified MRAC demonstrates remarkable robustness and superior control performance, particularly in terms of overshoot percentage, settling time, rise time and disturbance rejection. The effectiveness of the proposed control strategy was evaluated with the use of various reference signals.

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1 Introduction

Direct current (DC) motors are electrical machines that convert the DC energy into mechanical energy [1-2]. The speed of a DC motor can be set over a large range. They have excellent control characteristics, such as ease of control and high performance. The fact that the DC motors are simpler to control than AC motors is a major reason for their wide application. In addition, the DC motor drive circuits are both simple and cost-effective compared to AC motors. The DC variable speed drives have made their mark in variable speed applications, due to their simplicity of design. DC motors are often used in industrial applications requiring speed and position control, such as electric trains, winding machines, winches and robot arms, as a result of their very good speed characteristics [3-4]. The DC motors have certain disadvantages, such as the need for periodic maintenance caused by contact between brush and commutator, and they cannot be used in all environments, as well.

The DC motors are widely used in industry. There are several ways to control the speed of these motors, by varying the armature resistance, the field resistance or the armature voltage, depending on the motor structure. For DC motors, the most effective method is to vary the armature voltage, as varying the armature resistance and field resistance increases losses. There are several methods for varying armature voltage, which can be divided into two broad categories: classical methods, such as the use of a PID controller, and intelligent methods, such as neural networks, genetic algorithms and fuzzy control [5-6]. Sensitivity to system uncertainty is a challenge for the commonly used PID controller. Faced with time-varying system parameters and external disturbances, the control performance of the traditional PID method degrades considerably and may even fail. However, the use of a hybrid PID controller with different methods of setting, the PID controller values is the most common method for controlling a DC motor [3, 7]. The authors designed

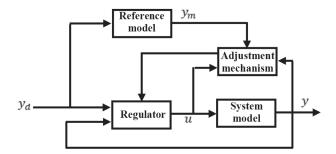


Figure 1 Schematic block diagram of the MRAC

an adaptive PID controller for motor speed control and adopted the gradient descent method for on-line control gain adjustment. When the motor parameters change, the PID parameters are automatically adjusted to the optimum value [8-9]. Adapting, the PID parameters using optimization methods can result in high energy consumption. For this reason, researchers are looking to design a controller that is easy to calculate and robust in the face of uncertainties, such as variations in motor parameters and loads.

For systems that are partially unknown or whose parameters vary, adaptive control has proved to be an effective control solution. In this context, MRAC has become very attractive due to its algorithmic simplicity, easy implementation, and the fact that it requires neither identifiers nor observers in the control loop [9-11]. However, these algorithms are limited in noisy or disturbed environments, which can make them inefficient or uncompetitive. Unfortunately, very few industrial control processes are free from these practical problems, which can adversely affect product quality and process performance.

In this article, we present a solution based on modified robust adaptive control, designed for applications with an unknown or changing model over time and circumstances. This solution uses the fundamental stability property and exploits the MIT law rule as a function of an adaptation mechanism [11-12]. This is achieved by calculating and constructing a control vector, also known as a regression vector, to satisfy the desired condition of "almost ideal tracking" taking into account parametric changes in the model. This approach guarantees the robust stability of the nonlinear adaptive controller [10, 13].

The main contribution of this work is to improve the robustness of the adaptive approach by implementing a hybrid control strategy that combines model reference adaptive control (MRAC) with classic state feedback action. The effectiveness of the proposed MRAC controller, and its advantages over other algorithms, were clearly demonstrated through comparative analysis of transient responses. The results are illustrated with a simulation example of a DC motor model using different reference curves.

This paper is structured as follows: In section 2 presents the definitions and theory of MRAC. Section 3

the mathematical modeling of a DC motor is formulated and introduces the principles of modified adaptive control based on the concept, then the main results of modified MRAC are presented in section 4.

2 Model reference adaptive control (MRAC)

The MRAC is a control system that adapts to process variations. Its aim is to automatically make real-time adjustments in the control loop to achieve or maintain a specified level of performance, even as the parameters of the controlled process change. This usually means minimizing the deviation between the reference and actual performance [14-15]. Figure 1 shows a diagram illustrating the MRAC approach.

The parameter adjustment mechanism can be achieved in two ways: by the gradient method or by applying the stability theory [11, 15]. The main challenge of MRAC is to define an adjustment mechanism that stabilizes the system, while reducing the error to zero, which is not a simple task. In the original MRAC, the parameter adjustment mechanism, known as the MIT rule, was used.

The MIT rule is the original approach to MRAC, so named because it was developed at the MIT Instrumentation Laboratory. To illustrate the MIT rule [11, 16], consider a closed-loop system where the controller has a vector of adjustable parameters, θ . The desired system response is defined by the output y_m of the reference model. We denote by e the error between the output y of the closed loop and that of the reference model y_m . The parameters are adjusted to minimize a cost function J defined by Equation (1) [11, 17]:

$$J(\theta) = \frac{1}{2}e^2. \tag{1}$$

Therefore, to minimize J, one must change the parameters in the direction of the negative gradient of J, i.e.:

$$\frac{d\theta}{dt} = -\gamma \frac{\delta J}{\delta \theta} = -\gamma e \frac{\delta e}{\delta \theta}.$$
 (2)

It is assumed that

$$\frac{d\theta}{dt} = \gamma e \varphi \,, \tag{3}$$

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where $\varphi = -\frac{\delta e}{\delta \theta}$ is the regression (or measures) vector and γ is the adaptation gain.

Equation (2) is the famous MIT rule. The influence of the adjustable parameters on the error is expressed by the partial derivative $\frac{\delta e}{\delta \theta}$, known as the sensitivity derivative of the system. Assuming that the variation of the parameters is slower than the other variables in the system, the derivative $\frac{\delta e}{\delta \theta}$ can be evaluated by considering θ to be constant, as illustrated in Figure 2.

The control problem based on the reference model can be described as follows: $G_{\scriptscriptstyle m}(s)$ is the transfer function of the reference model that defines the desired performance. $G_{\scriptscriptstyle CL}(s,\theta)$ represents the transfer function of the closed-loop process, where θ is the vector of adjustable parameters and $y_{\scriptscriptstyle d}$ is the reference control signal, using a feedforward controller defined by Equation (4) as input of the system model.

$$u = \theta y_d. \tag{4}$$

To set an adaptation feedforward gain, assuming that the process is linear, with the transfer function, $k_1G(s)$, where G(s) is known and k_1 is an unknown parameter. The design problem is to find a feedforward

controller that gives a system with the transfer function $k_0G_m(s)$, where k_0 is a given constant, and the feedforward controller is given by:

$$u = \left(-\frac{\gamma}{s}\right) y_m e y_d. \tag{5}$$

3 Proposed model reference adaptive control (MRAC) controller

3.1 Mathematical model of the DC motor

DC motors are electrical machines that convert electrical energy into mechanical energy. In accordance with Faraday's law, an electric motor can function both as a motor and a generator, when the appropriate conditions are met [2, 18-19]. Figure 3 shows a DC motor model.

According to [1, 20-21], the open loop transfer function of a DC motor (for $T_L = 0 \text{ N} \cdot \text{m}$) is given by:

$$G_{DCM}(s) = \frac{K_m}{(L_a s + R_a)(J s + f) + K_b K_m}.$$
 (6)

Substituting the DC motor parameter values into

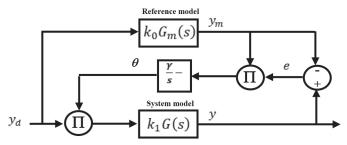


Figure 2 Scheme of the classic MRAC algorithm

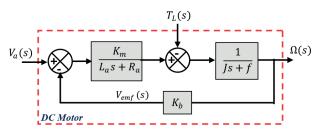


Figure 3 DC Motor model

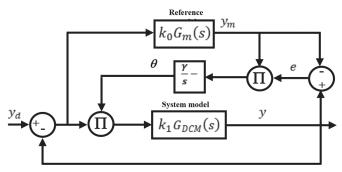


Figure 4 Scheme of the proposed MRAC algorithm

Equation (6) yields the following open loop transfer function:

$$G_{DCM}(s) = \frac{\Omega(s)}{V_a(s)} = \frac{15}{1.08s^2 + 6.1s + 1.63}.$$
 (7)

The DC motor parameters are shown in Appendix (Table A).

3.2 Proposed MRAC controller

In this work, we propose a modification of the adaptive control scheme (Figure 2). The aim of this modification is to achieve a hybridization between the classical state feedback action and the Model Reference Adaptive Control (MRAC) action. Figure 4 shows the Modified MRAC of DC motor, where, k_1 , k_0 and γ are constants to be defined. The first step in the conception of the adaptive control of a DC motor is to choose the reference model.

According to Figure 4, Equation (5) becomes:

$$u = \left(-\frac{\gamma}{s}\right) y_m e(y_d - y). \tag{8}$$

By distributing Equation (8) we obtain the equation below:

$$u = \left(-\frac{\gamma}{s}\right) y_m e y_d - \left(-\frac{\gamma}{s}\right) y_m e y. \tag{9}$$

Furthermore, we note that Equation (9) is composed of two parts, the first representing the classical MRAC control, the second takes the form of a high-gain control [22], so that it tends towards zero when the system reaches permanent state and the system response stabilizes.

The DC motor is modelled in the form of the secondorder transfer function Equation (7). Equation (10) shows the second order transfer function:

$$TF(s) = \frac{k}{\left(\frac{s}{\omega_n}\right)^2 + 2\xi \frac{s}{\omega_n} + 1} \tag{10}$$

By writing Equation (7) in its canonical form Equation (10)), we obtain:

$$G_{DCM}(s) = \frac{9.2025}{\left(\frac{s}{1.2285}\right)^2 + 2(2.2987)\frac{s}{1.2285}s + 1}$$
(11)

and then we deduce the transfer function parameters of the DC motor as follows:

$$k = 9.2025, \omega_n = 1.2285$$
 and $\xi = 2.2987$.

Figure 5 shows the indicial response of the open-loop DC motor transfer function. It can be observed that the response is very slow, with a settling time of 14.1039 seconds and a static error of 9.1981 p.u. (the parameters of this response are summarized in Table 1). To effectively control the DC motor, it is necessary to select the second-order transfer function as a reference model, to simulate the desired motor response.

The chosen reference model is represented by the transfer function of Equation (12), with the following parameters, selected to guarantee a very fast, overshoot-free response for the DC motor.

$$k=1, \omega_n=1500$$
 and $\xi=1$,
$$G_m(s)=\frac{1}{(4.444\cdot 10^{-7})s^2+(1.333\cdot 10^{-3})s+1}. \quad (12)$$

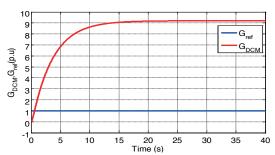


Figure 5 Indicial response of the DC motor transfer function

Table 1 Step Response characteristics of a DC motor's transfer function

Criteria	Value
RiseTime	7.8262
SettlingTime	14.1039
SettlingMin	8.3104
$\mathbf{Settling}\mathbf{Max}$	9.1981
Overshoot	0
Undershoot	0
Peak	9.1981
PeakTime	27.4446

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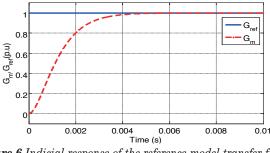


Figure 6 Indicial response of the reference model transfer function

Table 2 Step Response characteristics of the reference model transfer function

Criteria	Value
RiseTime	0.0022
SettlingTime	0.0039
SettlingMin	0.9024
${\bf Settling Max}$	1.0000
Overshoot	0
Undershoot	0
Peak	1.0000
PeakTime	0.0091

Table 3 Comparative transient response results

Controller type	D [%]	$T_{_{s}}\left[s ight]$	$T_{r}[s]$
MRAC [Proposed]	0.0000	0.002	0.0012
[1]	0.0000	0.0339	0.0214
[21]	0.0000	0.0780	0.0429
[23]	0.0000	0.0616	0.0376

Figure 6 shows the indicial response of the transfer function of the reference model. The parameters associated with this response are summarized in Table 2.

4 Simulation results and discussion

To evaluate the effectiveness and robustness of the proposed control approach for the DC motor, various simulation scenarios in the Simulink Matlab environment were carried out. Then the results were compared to other studies.

We began by choosing a square-wave reference signal, which we passed through a low-pass filter to avoid singularities. Figure 7 shows that the DC motor follows the reference perfectly without the overshoot, demonstrating the robustness of our control approach.

The MRAC (Model Reference Adaptive Control) approach has a learning effect, as illustrated in Figure 7b, where the speed curve corresponds to the ideal response. Figure 7c reveals that the frequency response of the DC motor is very fast, with a settling time of 0.002 s and no overshoot. The parameters in this figure are summarized and compared to the results of

other studies in Table 3, where we list indicators such as maximum overshoot in percent (D [%]), settling time (T_s [s], with a tolerance of ±2%), and rise time (T_s [s], for $10\% \rightarrow 90\%$).

The simulation results obtained with the parameter set of the modified MRAC approach were compared to other recent methods, such as those described in [1] and [21], to verify the design, as explained in the following subsections. Those methods were chosen because they use the same motor parameters and parameter limits. In addition, they have determined the best controller parameters so far. The results of this study can be easily verified by the reader with the use of MATLAB commands. In summary, the modified MRAC approach is slightly easier to implement and requires slightly more computing time than the optimal PID controller. However, it offers the shortest stabilization and rise times, without the overshoot. The hybrid algorithm developed (modified MRAC) offers significant advantages over conventional MRAC, including better operational capabilities, the ability to find the solution closest to the global optimum without getting stuck in a local minimum, and a faster convergence rate.

Then, at this stage, a sinusoidal function is applied and considered as a reference signal at the system

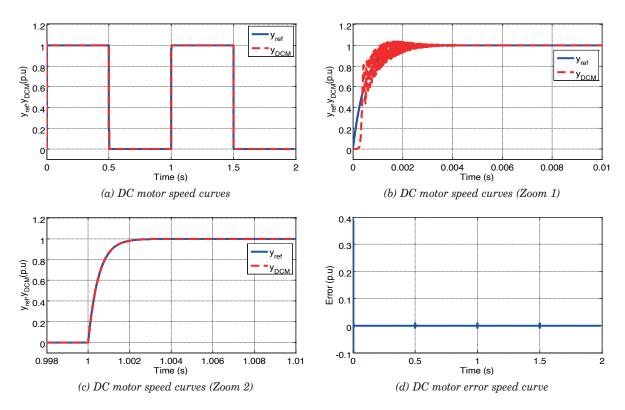


Figure 7 The DC motor response under square wave reference signal

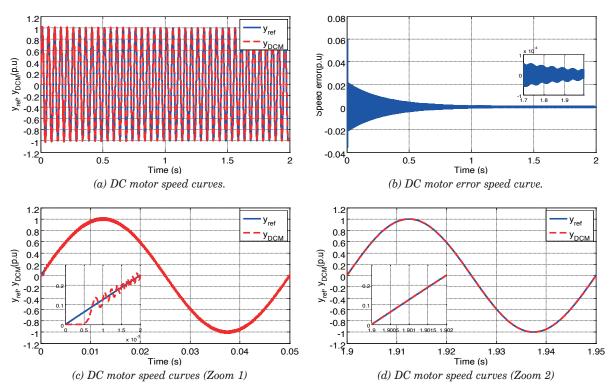


Figure 8 The DC motor response under sinusoidal wave reference signal

input. The results of simulating the DC motor control using the proposed MRAC approach are shown in Figure 8.

As Figure 8a clearly shows, the modified MRAC approach provides faster and more accurate reference signal tracking, with minimal learning time (Figure 8c

illustrates the learning phase). A comparison of Figure 8c and 8d shows that our control method improves over time. This learning effect is due to the self-adjustment of controller parameters, meaning that the proposed MRAC approach adapts to parametric variations and automatically adjusts controller parameters.

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Figure 8b shows the desired speed tracking error. It can be seen that the error curve presents continuous damping, indicating that the control strategy, based on learning and parameter self-adaptation, is effective.

5 Conclusion

In this work, a Model Reference Adaptive Control (MRAC) approach is presented to control the speed of a DC motor under conditions of model changes and unknown uncertainties affecting the base model. The proposed modified MRAC control strategy is applied to the DC motor control, and its performance is evaluated and compared to other studies in the literature.

Based on the obtained simulation results, several criteria such as percentage overshoot, settling time, rise time, and disturbance rejection can be highlighted. We found that the proposed modified MRAC control outperforms other techniques illustrated in the literature due to its superior performance and robustness. The steady-state performance of the proposed modified MRAC control is better than that of other conventional

techniques, thanks to its adaptive parameters and the learning effect inherent in the MRAC control.

The proposed modified MRAC approach is slightly easier to implement and exhibits superior performance in terms of speed and tracking accuracy compared to traditional methods. The results of this study can be easily reproduced and verified with the use of MATLAB commands, thus offering a practical and efficient solution for the DC motor control.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Table A DC motor parameters [21]

Parameter	Value
Armature resistance (R_a)	0.4 Ω
Armature inductance (L_a)	2.7~H
Motor moment of inertia (J)	$4 \times 10^{-4} Kgm^2/s^2$
Coefficient of friction (f)	0.0022Nm . s/rad
Motor torque constant $(K_{_{\! m}})$	$0.015\ kg\ m/A$
Back EMF constant (K_b)	0.05~s



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EVALUATION OF PEDESTRIANS' GAZE BEHAVIOR WHEN CROSSING THE ROAD USING EYE-TRACKING TECHNOLOGY: IMPLICATIONS FOR AUTONOMOUS VEHICLE LED COMMUNICATION INTERFACE

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Resume

Since autonomous vehicles (AV) are in the testing process, it is an open question of how pedestrians will communicate with self-driving cars. Nowadays, explicit communication pattern is the main way of pedestrian-driver interaction, however, AV may use implicit communication when making crossing decisions. This study aims to analyze pedestrians' gaze behavior when crossing the road using an eye camera and find the most applicable location for the LED interface on AVs. 10 pedestrian crossings in Gyor, Hungary were analyzed using the synchronized eye-tracking (ET) technology and regular video cameras for combined data processing. The data were analyzed using digital image processing techniques and statistical methods to identify where pedestrians looked and whether a pedestrian-driver interaction was captured during the crossing maneuver.

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1 Introduction

One of the biggest obstacles to global health and development is still traffic-related deaths and injuries. Approximately 310,000 pedestrian deaths occurred on roads globally in 2018, making up 23% of all fatalities from traffic incidents [1]. Researchers have worked to better understand pedestrian behavior and decision-making processes to prevent pedestrians from injury. For instance, Gruden [2] used video footage and a micro-simulation model to assess pedestrian movement in a limited location in recent research. This made it possible to evaluate how well the simulation tool estimated pedestrian safety by comparing realworld pedestrian behavior with a simulated setting. In a virtual reality study by Soares et al. [3], pedestrians made crossing decisions based on visual cues (vehicle speed and distance) rather than auditory cues (engine noise or silence). This suggests that communication strategies for automated vehicles should prioritize visual signals for pedestrian safety.

More vehicles on the road without a driver are predicted throughout the next ten years. Mixed traffic will be composed of both human-driven and AVs [4]. As these vehicles become an integral part of our daily lives, it is evident that they will have to interact with humans in various dynamic scenarios. One crucial aspect that demands immediate attention is the need for clear communication patterns between AVs and pedestrians.

Conventional vehicles rely on non-verbal cues, such as hand signals, eye contact, and body language, to communicate intentions, ensuring a smooth flow of traffic. However, with AVs lacking human characteristics, one must find alternative ways to convey their intentions to pedestrians, cyclists, and other road users [5]. In recent times, there has been a surge in testing different external human-machine interfaces (eHMI) worldwide, aiming to enhance the interaction efficiency between AVs and road users. These eHMI designs enable fully AVs to signal their intention to yield to pedestrians. By minimizing uncertainty about AVs' intentions and fostering pedestrians' initial trust and understanding,

these interfaces play a crucial role in facilitating effective communication with pedestrians [6-7]. For instance, a pedestrian who is staring out the front window all the time could be trying to get a driver's attention. More significantly, fixation patterns in various car parts can influence how AVs are designed. Researchers suggested equipping eHMIs with the ability to display AVs' purpose to boost interaction efficiency in the absence of human drivers in AVs. In the context of AVs and eHMI, LEDs are often used as a means of communication between the vehicle and pedestrians or other road users. They can be used to display signals or messages, indicating the vehicle's intentions, such as stopping, yielding, or indicating a turn. To determine the most effective LED interface and its optimal location for facilitating communication between the pedestrians and AVs, an ET experiment was conducted with pedestrians. The objective was to identify the LED interface that would enhance pedestrians' perception and comprehension of AV intentions. Additionally, the study advances the understanding of gender-specific gaze behavior by investigating whether there is a significant difference between males and females in their visual attention during the act of crossing a zebra crosswalk. This exploration adds a valuable dimension to the research, offering insights into potential variations in how different genders interact with the LED interfaces in vehicular environments.

1.1 Eye-tracking technology

With the ability to precisely analyze a subject's perception and behavior during the task execution, the ET technology is an invaluable tool for user testing. The ET is extensively utilized for various assessments in both real-world and virtual environments. It has shown particular value in studying human behavior in the contexts of aviation and motorized transportation [8].

By monitoring eye movements, it becomes feasible to obtain measurable data regarding the distribution of gaze, enabling insights into human perception and cognition [9]. The camera, integrated into lightweight glasses, allows for precise and unobtrusive recording of participants' eye movements as they encountered different AVs. This technology facilitates the collection of accurate and valuable data on pedestrians' visual attention patterns and aided in understanding the effectiveness of communication between the AVs and pedestrians.

Researchers often study eye movements in different fields in terms of fixations (pauses over interesting portions of information) and saccades (fast movements between fixations). Fixation or gaze durations, saccadic velocities, saccadic amplitudes, and numerous transition-based characteristics between fixations and/or regions of interest are examples of common analytical metrics [10]. This can provide information on what pedestrians find

attractive and what cues they need to decide whether to cross the street. In a naturalistic study by Zhao et al. (2023) [11], the ET showed that pedestrians fixated more frequently on nearby lanes and approaching vehicles when making crossing decisions. Notably, pedestrians focused on different vehicle components depending on distance. These findings can inform pedestrian behaviour models and guide the design of pedestrianfriendly information displays on autonomous vehicles. When analyzing the eye tracking data to understand attention, two significant factors come into play. Firstly, the number of times attention is focused on specific locations within a particular area of the visual field is crucial. This reflects the frequency of fixations on specific points, indicating the intensity of the search strategy employed by the individual. Secondly, the dwell time, which represents the total duration of these fixations, plays a vital role. Longer dwell times indicate a higher level of attention directed towards a specific location, highlighting its significance in the visual field. By considering both the number of fixations and the dwell time, valuable insights into how individuals perceive and process visual information, aiding in the comprehension of human perception and cognition can be gained [12]. The study of Lévêque et al. [13] examined how both internal (e.g. age) and external (e.g. road environment) factors influence pedestrians' visual attention during the crossings and highlights the need for further research in this area, particularly regarding the impact of autonomous vehicles on pedestrian gaze patterns.

2 Methodology

2.1 Procedure

A diverse group of 278 pedestrians (172 males and 106 females) aged between 18 and 65 years were recruited for the study. Participants were selected randomly at various pedestrian crossings and road intersections in an urban area of Gyor city, Hungary.

The experiment conducted at zebra crosswalks focuses on pedestrian behavior, visibility, and safety aspects, as it involves direct interactions between the pedestrians and vehicles to accurately assess communication effectiveness. The zebra crossings also offer opportunities to study driver behavior concerning yielding to pedestrians.

The study used the Pupil Labs Core, shown in Figure 1, a wearable ET device with high-definition cameras, to detect visual, manual and cognitive distractions [14]. This head-mounted device contained binocular spectacles with two infrared cameras and a wide-angle Red-Green-Blue (RGB) panorama camera. It was chosen above competitors like the SMI ETG 2.6 and Tobii Pro spectacles 2 due to its greater accuracy [15].

To capture the crossing maneuvers from multiple

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Figure 1 Pupil Core headset [16]



Figure 2 One-point calibration gaze



Figure 3 Capturing pedestrian attention: ET glasses in use



Figure 4 Example of the zebra crossings

angles, conventional video cameras were positioned on tripods on both sides of the road. This setup allowed for simultaneous recording of the pedestrian's actions and behavior of both road users: drivers and pedestrians.

Upon fitting the eye tracker to each participant, a one-point calibration was performed initially. The

calibration process was then reviewed and repeated as needed to ensure precise measurements. Additionally, calibration checkpoints, shown in Figure 2, were incorporated throughout the walks, serving to verify the tracking accuracy after the completion of each walk.

Figure 4 depicts the pedestrian crossing employed



Figure 5 Pedestrian gaze locations

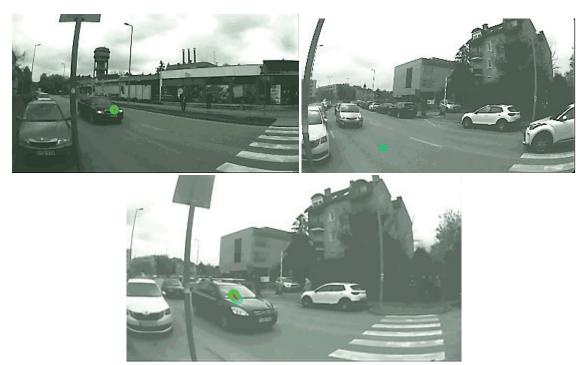


Figure 6 Gaze overlay video showing the Pupil core eye tracker data superimposed on a marked crossing scenario, green circles represent fixations, while red lines indicate saccades

in the experiment. This crossing utilizes white stripes painted on a slightly green pavement to ensure clear visibility for drivers approaching from both directions, thereby conferring upon pedestrians the right-of-way when crossing the two-way road.

In the experiment, participants were instructed to cross the zebra crossing while wearing the ET glasses to have a clear vision of the interaction between pedestrians and vehicles. Figure 3 shows the example of a pedestrian mounted with ET glasses. Crossing movements without any interaction were excluded from the analysis.

Figure 5 shows the focus on four specific directions of pedestrian gaze:

1) Not looking left/right

Instances where pedestrians do not fixate on the left/right side (the direction from which vehicles were approaching) before crossing the zebra crossing were identified through the ET data analysis.

- 2) Road surface area between the approaching car and the zebra crossing
 - When an approaching vehicle was in proximity.
- 3) Car hood
 - When pedestrians' attention fixates on the car hood (the front part of a motor vehicle).
- 4) Windshield
 - Potential visual communication between the pedestrian and the driver.

2.2 Input in excel

The data was organized within a Microsoft Excel spreadsheet using a table format. This table consisted of 10 rows, each representing a pedestrian crossing location of Gyor city. Additionally, the table included 4 columns to capture pedestrian gaze behavior. These

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columns categorized gaze direction based on the side of the road and the specific target of their gaze as mentioned above: Not looking left/right, Car hood, Road surface, and Windshield.

The videos were switched to black-and-white mode to enhance the visibility of eye calibration during the analysis.

Figure 6 presents a gaze overlay video analyzed using the pupil core eye tracker data. This video depicts a marked pedestrian crossing scenario. The green circles on the overlay visualize fixations, which represent moments where a participant's gaze remained focused

on a specific area of interest. Conversely, the red lines indicate saccades, which are rapid eye movements transitioning between fixation points. By analyzing these fixations and saccades, it is possible to gain insights into the visual attention patterns of participants when interacting with the upcoming vehicle scenario.

2.3 Analyses

The video analysis encompassed ten locations within the Gyor city, where pedestrians' gaze behavior

Table 1 Chi-Square Test

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	6.907ª	3	.075
Likelihood Ratio	7.059	3	.070
Linear-by-Linear Association	6.657	1	.010
No of Valid Cases	278		

Table 2 Chi-Squared Test: area of interest and gender Crosstabulation

				Gender	
			Male	Female	
Area of interest	Not looking	Count	24	24	48
	left/right	Expected Count	29.7	18.3	48.0
		% within area of interest	50.0	50.0	100.0
		% within gender	14.0	22.6	17.3
		Adjusted Residual	-1.9	1.9	
	Car hood	Count	60	41	101
		Expected Count	62.5	38.5	101.0
		% within area of interest	59.4	40.6	100.0
		% within gender	34.9	38.7	36.3
		Adjusted Residual	6	.6	
	Road surface	Count	54	30	84
		Expected Count	52.0	32.0	84.0
		% within area of interest	64.3	35.7	100.0
		% within gender	31.4	28.3	30.2
		Adjusted Residual	.5	5	
	Windshield	Count	34	11	45
		Expected Count	27.8	17.2	45.0
		% within area of interest	75.6	24.4	100.0
		% within gender	19.8	10.4	16.2
		Adjusted Residual	2.1	-2.1	
Total	Coun	t 1	72	106	278
	Expected	Count 17	2.0	106.0	278.0
	% within a intere		1.9	38.1	100.0
	% within §	gender 10	0.0	100.0	100.0

was studied using Python programming language. The primary objective was to estimate and compare the gaze behavior across these different locations. In addition to estimating the gaze behavior and comparing locations, the analysis identified the best location for the LED interface on an AVs in the future. This study determined the optimal interface of the LED interface to capture pedestrians' attention.

2.4 Association between the gender and gaze preferences

To determine whether there is a significant association between the gender (categorical) and the preference for looking, a chi-squared test was used. The chi-square test is a test of association between these two variables. The ratio of male to female respondents was the same whether they were looking at the hood, windshield, or the road surface, not looking, or looking elsewhere. In Table 1, the Pearson chi-square shows that the asymptotic significance result is 0.075 and, as it is less than 0.05, there is no association and there is evidence to suggest that there are significant differences between the gender and preferences for where people look.

Table 2 shows the total number of male and female responses. There were 61.9% of males and 38.1% of females.

As can be seen, overall, 17.3% of pedestrians did not look to the side, but in terms of gender 22.6% of females did not look to the side. As the adjusted residuals are almost equal to 1.96, it can be said that females are significantly less attentive when crossing the road. It turns out that it is the opposite for males that negative residuals say that 14% are significantly less than 17.3%.

Looking at the bonnet, there are no differences because the adjusted residuals are either below negative 1.96 or above 1.96, so there is no deviation, which means that 34.9% is not statistically different from 36.3%, the overall value, and 38.7% is not different from the overall value.

For the road surface it can also be seen that there is no deviation. Finally, the windshield results show that males had 19.8% of them looking at the windshield, while females had 10.4%, which is significantly less than the total of 16.2%. The adjusted residual is above than 1.96 and regarding females it gives - 2.1, which is below than negative 1.96.

3 Results

The experiment encompassed observations at ten locations within the Gyor city. Prior to the data collection, pedestrians were provided with instructions on proper zebra crossing techniques and the specific timing for their crossings. During the experiment, participants wore Pupil core eye tracking glasses, and an one-point calibration was conducted to ensure accurate interpretation and recording of the gaze data.

However, it is worth noting that the study encountered instances of the missing data. Participants were excluded from the analysis in such cases. The exclusion criteria were applied to scenarios where all the fixations were present during transitions between the video scenarios, and no fixations were present during the actual crossing scenarios themselves. Additionally, scenarios where participants did not encounter any vehicles and, as a result, did not face any traffic interactions were also discarded from the analysis. The exclusion of these scenarios was necessary to maintain data integrity and ensure that the analysis focused on relevant and informative gaze behavior during the zebra crossings in the presence of vehicles. The analyses were done on the data of the remaining 278 participants.

A heat map was used to visualize the distribution and intensity of pedestrian gaze patterns across the crossing area. This approach facilitated the communication of locations that received the most attention (higher number) and those that received less visual focus (lower number) from pedestrians during their crossing. Figure 7 depicts the frequency of gaze fixations:

- Higher number (0.03) indicates a higher density of gaze fixations in that specific area of the image, a place where many pedestrians looked.
- Lower numbers (0.02 and 0.01) represent areas with lower densities of gaze fixations, showing some attention but with fewer fixations compared to the location with the highest number.

A heatmap in Figure 7 created from the single participant's eye-tracking data was used to show the locations of gaze concentration seen during the pedestrian engagement with the crossing scenario. Figure 7a shows the highest Region of Interest (ROI) as a car hood. This is where pedestrians directed their gaze more often than any other part of the crossing scenario. Right after the car hood, the data revealed another critical area of interest: the road surface between the car and the pedestrian crossing, shown in Figure 7b. This is because pedestrians can use their peripheral vision to detect a vehicle when looking at the road surface.

The graph in Figure 8 highlights the importance of considering vehicle speed when studying the pedestrian interactions, as it influences how pedestrians allocate their attention in these crucial situations. The presented data reveals a notable predilection among pedestrians for focusing on the car hood. This observed phenomenon prompts an exploration of the potential influence of vehicular speed as a determining factor for the heightened focus on the car hood in these contexts (4,7,10). Notably, in locations where the windshield surpasses other regions of interest in elevation, the diminished time required for pedestrian road-crossing due to higher vehicle speeds may elucidate a propensity for clearer interaction with the driver.

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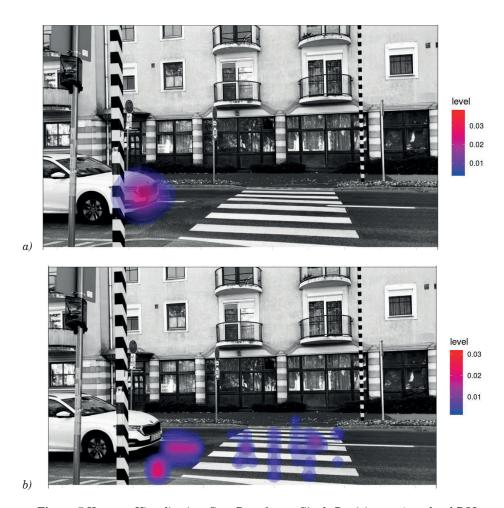


Figure 7 Heatmap Visualization: Gaze Data from a Single Participant; a) car hood ROI, b) road surface ROI

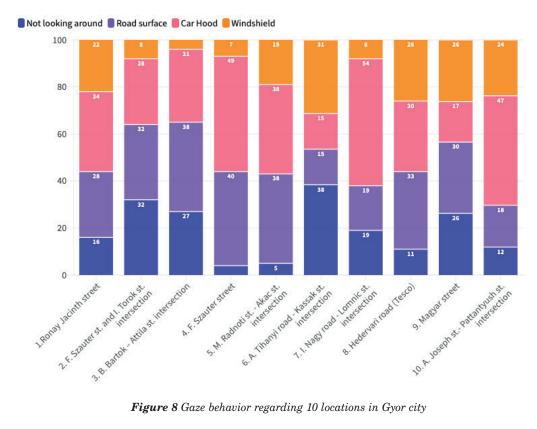


Figure 8 Gaze behavior regarding 10 locations in Gyor city

The Chi-Square test revealed a statistically significant association (p = 0.075) between the gender and pedestrians' gaze behavior when crossing the road. While there was no significant difference in the overall proportion of males and females not looking to the side, females did exhibit slightly less attentiveness (22.6 % vs. 17.3 %). However, in the specific location, such a windshield, there is a significant difference emerged. Males (19.8 %) were more likely than females (10.4 %) to look at the windshield while crossing the road (p < 0.05).

4 Conclusion

The research on pedestrian gaze behavior during the road crossings in diverse locations within the Gyor city offers insightful contributions to the field of sustainable mobility and human vehicle interactions. The study's comprehensive analysis of pedestrians' visual attention patterns, and their interactions with vehicles, provides valuable evidence for decision-making in urban planning and the integration of AV technology.

Previous studies on LED interfaces in vehicles have explored various locations within the car without a targeted understanding of pedestrian behavior. By incorporating the ET technology, this research delves into the fundamental aspect of human attention, providing valuable insights into the visual focal points of individuals during a critical and safety-sensitive activity such as crossing the road. The findings reveal a consistent trend where pedestrians direct significant attention to the car hood during the road crossings from both the left and right sides. Strategically placing the LED interfaces or communication signals on car hoods of AVs can facilitate effective communication

with pedestrians, promoting safer and more sustainable interactions in urban environments. The data also supports the idea that placing LED projectors in front of the vehicle, particularly near the registration plate, could be another effective location for communication with pedestrians. By projecting the relevant signals or messages onto the road surface in front of the vehicle, the AVs can establish a clear and visible means of communication, further enhancing pedestrian awareness and safety.

Following the completion of calculations, a borderline significant association is suggested between the gender and gaze behaviour at road crossings. While overall gaze behaviour was not significantly different, females tended to look less to the side than men. Interestingly, males fixated more on the windscreen than females, suggesting a possible gender difference in where the pedestrians focus their attention when crossing the roads.

The implications of this research extend to sustainable urban planning, optimized traffic management, and the responsible deployment of the AV technology.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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ASSESSING THE STREAM SPEED OF REGULAR TRAFFIC UNDER IMPACTS OF ON-STREET PARKING

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Resume

Stream speed pattern of traffic plays a crucial role in urban transportation. The presence of on-street parking significantly reduces this speed by narrowing the carriageway width available for traffic movement, impeding the traffic flow. Therefore, understanding the traffic flow behavior in the context of on-street parking could be challenging. In this context, the present study explores the influence of on-street parking on the stream speed of regular traffic. To achieve this, data were collected at various ideal and parking sections. The stream speed ranges from 39.28 km/h to 51.47 km/h for ideal sections with significant percentage reduction observed at parking sections, ranging from 39.09% to 81.30%. This speed reduction was then modelled considering the most significant parking parameters conceptualized in this study. The findings of the study offer valuable insights that can be implemented for developing the on-street parking norms.

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1 Introduction

Developing countries like India witnessed rapid advancement and urbanization in the last few decades. These countries have gone through the fast transformations leading to a good lifestyle, especially in urban areas due to the innovation in technologies. People often use personal vehicles rather than taxis or public transport to move from one place to another within the city. As a result, Indian urban roads have become overly crowded, which affects the speed of moving traffic. According to Shangliao Sun's report, the number of vehicles witnessed significant growth over 10 years. For example, in 2009, there were 115 million vehicles in India, and by 2019, this number had risen to 295.8 million, reflecting an approximate increase of 157% in 10 years, as stated earlier. So, every year vehicular ownership increases, but to accommodate the increased number of vehicles, road infrastructure is limited, which results in congestion on urban roads [1]. To accommodate the increased number of vehicles, parking lots are provided in most of the major cities that primarily reduce congestion, however, parking

lots fail to accommodate all the vehicles in peak hours due to limited space and capacity. As a result, the on-street parking seems to be an alternative to parking lots for drivers, as it helps the drivers park their vehicles near their destinations [2]. Apart from this, vehicles in search of parking spaces, meandering here and there along the urban road also create havoc, congestion, more fuel intake, and gas emissions causing air pollution. The on-street parking also affects the performance of the road in terms of stream speed. It causes a reduction in stream speed as it borders the width of the carriageway forcing the traffic to move into the reduced carriageway. Moreover, the frequent parking and unparking maneuvers along the road also interrupt the movement of regular traffic causing a reduction in stream speed. The interaction between the on-street parking and the movement of regular traffic is governed by various other factors as identified in former research. The degree of this interaction is subject to variation in both parking intensity and traffic volume levels. Parking fee is one of the crucial factors that may attract or discourage drivers to park their vehicles on streets resulting in variation in parking intensity [3].

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Further, the day of week or the time of day also plays a significant role in determining the parking intensity, which is generally higher on weekdays [4]. However, the effect of time of day on parking intensity may change depending on the land use pattern. Similarly, the prevailing traffic volume on a street also varies with the day of the week and the time of day [5]. Hence, as the intensity of both parking intensity and prevailing traffic volume increase on the street, it instigates more severe interaction resulting in substantial impact on street mobility. On the other hand, in the case of wider streets with multiple lanes, vehicles of regular traffic often change their lateral position away from the parked vehicles to maintain mobility or minimize the reduction in speed. Therefore, the number of lanes on a street characterizes the impact of on-street parking on stream speed [6]. Numerous research conducted so far has assessed on-street parking and its impacts on the stream speed. However, the limitation associated with the majority of these studies is their treatment of on-street parking as a binary variable considering only its presence or absence. Consequently, the findings of these studies neither proposed any mathematical model nor proposed or suggested any guidelines regarding permissible limits of the on-street parking. Apart from these, some of the previous studies quantified the impacts of the on-street parking considering only limited parking parameters, which may cause inappropriate results and show inconsistencies in the findings of these studies. Therefore, in the absence of appropriate parking data, transportation planners ask for consultation and norms related to on-street parking while designing the urban roads. In this background, the present study tries to examine the intricacies of on-street parking and its impacts on the stream speed. The proposed study tries to consider all the possible parking parameters to develop a speed reduction model.

The research paper starts with the "introduction" that discusses on-street parking, its limitation and effects on the stream speed. This is followed by "literature review" that summarizes the work done in the previous studies and their limitations. The next section is "research methodology" that details site selection, data extraction and procedure for developing the speed models. This is followed by a section on "field data collection" containing the methods used for collecting data. The "results" section presents the developed speed model followed by "validation" section that covers the accuracy of the model. Finally, the "conclusion" section summarizes the key contributions of the study and includes future research directions.

2 Literature review

Ample volume of research was conducted in the past to understand the impacts of on-street parking on the stream speed of moving traffic. In this regard [7-8]

considered parking density (number of parked vehicles) and parking pattern, whether it was the parallel or angled type, to examine the impact of on-street parking. The study shows the 8.05 km/h to 13 km/h reduction in the stream speed. On the same background, authors of [9] conducted their research and found that there was a 12% to 15% reduction in the stream speed for different categories of vehicles. This speed reduction reflects that there could be other parking parameters that may reduce the stream speed more. Then, in [10-11] the influence of on-street parking on the stream speed was examined by considering on-street parking as a binary variable i.e., 0 when the on-street parking was absent, and 1 when it was present. In [10] is suggested that the presence of on-street parking led to a decrease in the stream speed of traffic by 5.1 km/h. The study neither suggested any model, nor quantified the impact of on-street parking with varying intensity. Later, authors of [12] came up with a speed model and quantified the impact of on-street parking on both two-lane and four-lane roads. The study also proposed a parking parameter named the number of parked vehicles. The number of parked vehicles cannot capture the heterogeneity, which means that the parked vehicles may be of any type (2w, 3w, car or lcv, etc.). Here, lcv denotes the low commercial vehicles. Therefore, in [13] the stream speed was defined as a function of several factors, such as traffic volume (FLOW), carriageway width (CW), shoulder width (SW), and side friction (FRIC). Moreover, the FRIC was modelled as pedestrian volume (PED), bicycle volume (BIC), stopping and parking vehicles (PSV), and nonmotorized vehicles (NMV) as described in:

$$FRIC = 1 \times PED + 0.45 \times BIC + 0.08 \times \\ \times NMV + 0.37 \cdot PSV.$$
 (1)

This comprehensive model, aimed to capture the various elements affecting the stream speed and provided the framework for assessing the impact of these factors on traffic flow and road performance. The model suggests that parked vehicles, as a side friction parameter have less significant influence than pedestrians and bicycles. This is in contrast to the existing literature that identified the on-street parking as the most significant side friction factor. In the same way, in [14] was considered the number of parked cars and proposed a quadratic model showing the free flow speed as a function of parked cars. The findings of that study revealed that initially free flow speed increases with an increase in parking density (say, 29 parked cars), while it decreases later (beyond 29 parked cars), showing the discrepancy in the findings of previous research. Therefore, the model becomes unfit and needs justification as to why the free-flow speed increases initially.

Apart from this, in [11] is considered another aspect (safety) of the on-street parking and authors

Table 1 Various Speed Models Suggested by Researchers

Author Name	Speed Models Used	Parameters Considered
[13]	$V = 79.6 - 0.008 \times FLOW - 0.028 \times FRIC - 6.085 \times CW + 11.8 \times SW$	Parking and Stopping Vehicles
[14]	$Y = -0.0837x^2 + 4.856x + 0.2772, R^2 = 1$	Number of parked cars
[15]	$Y = 39.458132x_2126x_3 - 0.280x_4126x_5153x_8$	Parking and Stopping Vehicles
[19]	$V_{\it park} = 50.57 - 0.67 n_{\it man} - 0.09 t_{\it i} - 0.20 n_{\it vp} - 0.11 n_{\it c} - 0.06 n_{\it 2w} - 0.28 n_{\it 3w}$	Number of parking maneuvers/100m
[20]	$Y = 47.788 - 0.166x, R^2 = .7088$	Number of parked vehicles (parking density)

where: V, Y, V_{nark} = Stream speed, Free-flow speed, Stream speed for on-street parking,

FLOW = Traffic volume,

FRIC = Side friction,

CW = Carriageway width,

SW = Shoulder width,

x = Number of parked cars, density of vehicles,

 x_0 = Number of stopping city buses,

 x_2 = Pedestrian movement,

 x_4 = Number of parking/stopping passenger cars,

 x_5 = Number of entry vehicle into the street,

 $x_{\rm s}$ = Number of heavy vehicles per hour,

 n_{max} = Number of parking maneavers per 100m,

 t_i = influence time of parking and unparking vehicles,

 $n_{\rm m}$ = Number of vehicles parked per 100m on sides of carriageway,

 n_{c} , n_{2w} , n_{3w} = Number of cars, two wheelers, three wheelers respectively.

have limited their research to the safety of the passengers. The study discovered that urban roads with the existence of on-street parking have a higher frequency of crashes at stream speed exceeding 35 km/h. However, that study considered the on-street parking as a categorical variable. In later years, some research has been conducted to understand the influence of on-street parking on the stream speed in an improved way. Munawar [15] developed a speed model and considered several parking parameters. It was later found that parking/stopping vehicles (coefficient value is 0.280) was one of the most crucial parking parameters that significantly lowered the stream speed. Rather than this, parking maneuvers were also proved to be one of the prominent parameters in the later studies. In the context of this, a study conducted by [16] focused on on-street parking and found that when the parking maneuvers, such as vehicles entering or exiting the parking spaces, were carried out on the road, there was a significant reduction in the stream speed. This speed reduction was likely to occur due to the need for vehicles to slow down or stop to accommodate these parking maneuvers, which can disrupt the flow of traffic on urban roads. Research conducted in [17] measured the impact of on-street parking on the stream speed. Authors considered a wide range of parking intensity from 0% to 100% for different Volume/Capacity ratios. However, the findings of the study revealed that the stream speed continuously decreased up to 45% parking intensity which was later followed by a sudden increase

in speed from 45% to 75% parking intensity, and then again decreased. The authors could not explain this behavior and it remains unsolved, which needs further investigation to support the research findings.

Similarly, in [18] is assessed the impact of on-street parking on the stream speed and performed sensitivity analysis. The study's findings show that the speed was reduced to 44% with a wide range of 0% to 70% of parking intensity. Later, it was also found that this reduction was 37% for the one-lane and 28% for the twolane urban roads, which means speed reduction can be less on broader roads. In a separate study conducted by [19], the researchers examined the parking maneuvers and developed multiple speed models to assess the influence of on-street parking on the stream speed. The study's conclusions revealed that a significant reduction in the stream speed varies within a range of 27.5% to 37.2%. This reduction was observed over different traffic volumes ranging from 1000 PCU/h to 3000 PCU/h. Furthermore, this reduction also increases with an increase in parking maneuvers for the same range of traffic volume. Hence, these results underscored the substantial influence of on-street parking on the stream speed. To shed more light on how the on-street parking affects stream speed, authors of [20] researched the impact of on-street parking on the stream speed and considered the number of parked vehicles and encroachment of the carriageway as major parking parameters. That study was further concluded that there was a substantial reduction in speed, which varied in

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a wide range of 45% to 67%. This reduction was observed concerning the number of parked vehicles, which varies from 157-1580 veh/km. A recently conducted research [21] scaled the various side frictions named "SF" and developed the speed model that showed a 51% reduction in stream speed. However, the model did not examine the individual impact of side frictions, i.e., on-street parking, pedestrians, or wrong movement of vehicles at stream speed. In recent years, in [22] was assessed the on-street parking and used the product limit method. The study found a 50% reduction in stream speed in sections with on-street parking. However, the authors of the study limited their research to evaluate the impact in the presence or absence of on-street parking.

In brief, significant research has been considered in the past decades to assess on-street parking and its impacts on stream speed. Few of them considered parking as a binary variable, while others quantified it and presented the speed models. The various speed models, developed in the past research, are tabulated and found in *Table 1*.

Summarily, it is worth noting that a good volume of research has been carried out in the past and various speed models have been developed to assess the impact of on-street parking. Outcomes of some studies underscore the substantial impact of parked vehicles on the stream speed, with an extensive decrease when number of parked vehicles increased along a road while some research was engrossed in assessing how the stream speed is affected by the presence or absence of the on-street parking remiss of considering other specific parameters or local conditions. Though the past research findings provided an esteemed perception of on-street parking and its effects on stream speed, it may be thoughtful for future work to dig deeper into on-street parking problems and gain substantial knowledge of the imprint of the on-street parking on traffic parameters.

3 Research methodology

The presented work was divided into three phases namely: (i) site selection and videography, (ii) data

extraction, and (iii) speed models. Each of these phases is discussed one by one in the manuscript.

3.1 Site selection and videography

To carry out the research work, both base and parking segments were selected in various major cities across India. Base segments were those where the on-street parking was absent, and it was present at segments with considerable space called parking segments. Apart from this, all the selected segments should have the following conditions.

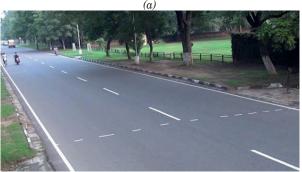
- All the segments should be in straight alignment without any vertical curve or gradient.
- All the segments should be quite far away from the nearby intersections so that there cannot be any distractions other than the on-street parking.
- There should not be any bus stops, pedestrian movements, or access points in the vicinity of the selected segments.
- All the selected segments should be in urban areas and within the city limits.

Based on the above-mentioned criteria, several base and parking segments were chosen in different major cities across India as shown in *Figure 1 (a) and (b)*.

After the selection of segments, the videography was performed to carry out the data collection on weekdays (Monday to Friday) using a video camera mounted on a 1.5m tall tripod. While performing the data collection smoothly, a tripod stand was kept in such a way that it could capture the entire segment without any interruptions. Later, the video files were taken to the laboratory to extract the required data. Details of various segments chosen in the study are given in *Table 2*.

3.2 Data extraction

All the recorded video files were taken to the laboratory to extract the required data. Three types of data were extracted from the video files, i.e., (i) Traffic data, (ii) Geometric data, and (iii) Parking data. A 30m



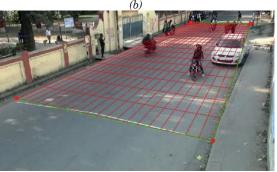


Figure 1 (a) Base Segment and (b) Parking Segment

Table 2 Details of various base and parking sections

Section Name	Type of section	Name of road	Carriageway Width (m)	City
I1	Base Section	Lohia Park Road	6.4	Lucknow
I2		Akbar Road	7.2	New Delhi
I3		Vikas Khand Road	7.9	Lucknow
I 4		Virbal Sahni Road	8.3	Lucknow
I5		Butler Road	8.5	Lucknow
I6		Vigyan Path	9.0	Chandigarh
P1	Parking Section	Sector G Main Road	6.9	Lucknow
P2		Hospital Road	7.0	Dehradun
P3		Kanwali Road	7.5	Dehradun
P4		Janpath Road	7.6	Lucknow
P5		DAV College Road	8.9	Chandigarh

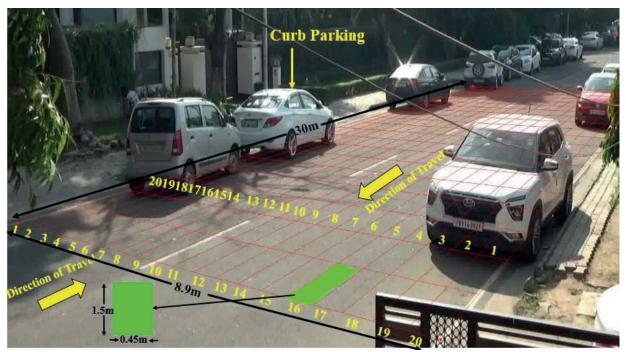


Figure 2 Grid analysis of carriageway width

trap length was temporarily marked by bordering two reference lines on selected road segments. The vehicles observed manually in the segments were classified into different categories. Hence, classified traffic volume was extracted by counting the number of vehicles of diverse categories crossing the segments in each 5-minute interval. The classified speed of each vehicle was measured by noting down the time taken by each vehicle from one reference line to another within the particular interval. Before extracting the data, all the video files were edited using the video annotation software Kinovea [23]. In geometric data, the width of the carriageway was measured manually. To extract the required parking data, some parking parameters, such as parking density, parking maneavers, etc were extracted simply by observing the videos. To extract the parking width, it is required to pinpoint the exact

position of the parked vehicles on the carriageway. To do this, the entire carriageway width was divided into 20 small grids using the video editing software Kinovea [23], as shown in *Figure 2*.

The accuracy of parking width measured in the study is highly governed by the number of segments that the carriageway width is being divided into. More is the However, splitting the carriageway into more than twenty equal segments makes the video clumsy and the wheel positions of vehicles on these segments become indistinguishable. Therefore, it was decided to divide the carriageway width into twenty virtual segments yielding an acceptable 5% error in the extracted data [24].

Finally, the parking width was estimated for each parking segment by counting the segment numbers occupied by the parked vehicles from the edge of the carriageway.

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While estimating the parking width, two attributes were considered i.e., the traffic composition and the dynamic nature of parked vehicles as explained in the following:

a) The parked vehicles were of diverse categories and occupied different lateral distances from the edge of the carriageway. So, it was difficult to estimate the parking width based on their actual widths. In addition, the area covered by the parked vehicles remained unutilized for the moving traffic. Hence, the actual parking width was estimated as the maximum of individual actual widths of the parked vehicles as given in:

$$PW^{m} = maximum (PW_{1}, PW_{2}, ... PW_{i}... PW_{m}),$$
 (2)

where: PW^m = maximum parking width (m) for the trap length within a given time interval t,

 PW_i = individual parking width (m) of vehicle I,

 $n = \text{total number of parked vehicles observed within time } \mathbf{t}$.

b) The actual width of the parked vehicles was not expected to be the same within a given time interval. It varies when a new vehicle is being parked, or a parked vehicle is taken out. To account for this, the parking width was estimated using:

$$PW^4 = \frac{\sum_{i=1}^{n} PW_i^m t_i}{\sum_{i=1}^{n} t_i},\tag{3}$$

where: PW^{A} = Actual parking width (m) for the entire trap length,

 t_i = time duration (minutes) corresponding to ith interval, n = number of time intervals.

3.3 Speed models

3.3.1 Speed prediction models

The classified speeds of the vehicles, estimated at each base segment, were combined and used to develop the speed prediction models for the base segments. In the Indian traffic scenario, speed was dependent on several parameters, i.e., traffic composition (NMV, 2-wheeler, 3-wheeler, standard car, LCV, HCV, etc.) and width of carriageway. The percentage composition of all these parameters for base sections is presented in Figure 3.

Later, a multiple regression technique was used to predict the speed model for the base section, based on different parameters. The best-fitted parameter with good significance was then considered for the model prediction. In this connection, carriageway width, standard car, two-wheeler, and *HCV* were proved to be the most significant parameters and hence selected for the model development. The model was formulated using [25] Statistical Package for Social Sciences (SPSS 26.0). The developed model is shown in:

$$V = 7.399 \times CW + 0.035 \times SC - 0.013 \times 2W - 0.234 \times HCV$$
 (4)
(23.597) (3.601) (2.228) (3.354)

where: 2W = 2-wheeler, CW = Carriageway Width.

The values inside the parenthesis in *Equation (4)* represent the t-stat values of each constant. During the model development, the constant was forcibly kept to zero as predicting stream speed at the road section was not feasible in the absence of traffic proportion. Several significant observations were noted during the data

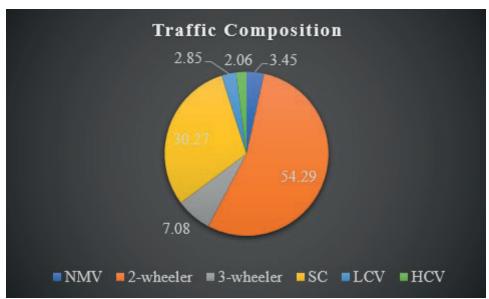


Figure 3 Traffic proportion at various base sections, where NMV = Non-motorized vehicle, LCV = Low commercial vehicles, HCV = High commercial vehicles, SC = Standard car

Table 3 Stream Speed at various sections

Section Name	Section Type	Carriageway Width (m)	Stream Speed (km/h)
I1	Base Section	6.4	51.47
I2		7.2	49.38
I3		7.9	50.52
I 4		8.3	46.21
I5		8.5	39.28
P1	Parking Section	6.9	12.00
P2		7.0	24.57
P3		7.5	26.52
P4		7.6	19.43
P5		8.9	22.15

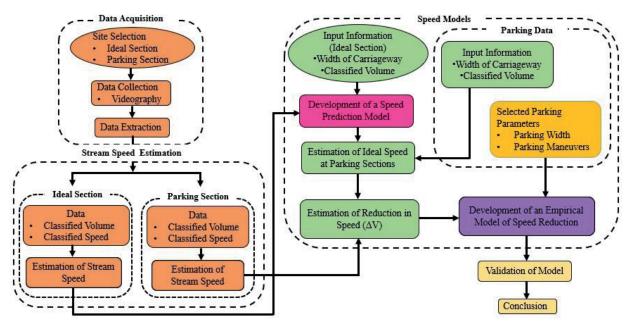


Figure 4 Flow chart of the research methodology

collection for development of a speed model for the base section.

The study employs several independent parameters such as standard car, *HCV*, *2W*, and width of carriageway. As depicted in *Figure 3*, the 2-wheeler and standard cars collectively represent a substantial proportion accounting for 54.29% and 30.27%, respectively, among all the vehicle categories moving on the road. However, the two-wheelers establish a negative correlation with the stream speed, likely due to frequent variation in speed, as well as extensive manoeuvring causing hindrance to the other vehicles along the road. Consequently, a high proportion of the two-wheelers along the road slightly diminishes the stream speed. Additionally, an increase in the carriageway width is associated with the higher stream speed as it provides more room for the movement of the vehicles.

In the developed model, the speed also demonstrates the inverse relationship with the proportion of HCV (high commercial vehicles). This is because the HCV

generally moves at a slower speed along the road. For undivided urban roads, an increase in the proportion of these vehicles in the traffic stream can force the other vehicles to move at a slower speed as overtaking these slow-moving vehicles can be a challenging task. Ultimately, the overall stream speed at the road section was affected. Furthermore, the stream speed exhibits a positive correlation with standard cars as they tend to move at higher speeds and maintain a constant gap between each other indicating the free flow condition to some extent. As a result, the stream speed at a particular road section attains a maximum value (base speed) where the proportion of standard cars is higher.

The presented model for a base section, as given in Equation (4), was further used to predict the stream speed of a regular traffic under the influence of on-street parking. Here, "regular traffic" implies that the usual flow or movement of vehicles on the road under normal conditions excluding the parking and unparking

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maneavers. The procedure for estimation of the stream speed at parking sections is later discussed.

3.3.2 Speed reduction model

Classified speeds at each base and parking section were used to estimate the stream speed of the through traffic at a 5-min temporal aggregation level, and tabulated as given in *Table 3*.

It is confirmed that the stream speed at base sections varies from 39.28 km/h to 51.47 km/h, while it varies within a range of 12.00 km/h to 26.52 km/h for parking sections. In addition, it was expected and can be seen in the table that stream speed at parking sections was comparatively lower than at base sections. Hence, the speed reduction (ΔV) was calculated at all the selected parking sections and a mathematical model was developed by considering the most crucial parking parameters. Before finalizing the model, it is a prerequisite to check the dependency of all the selected parking parameters and their influence on the stream speed using Pearson's correlation coefficients. Finally, the speed reduction model (ΔV) was developed based on the most influencing parking parameters. The procedure adopted in the study is given in *Figure 4*.

4 Field data collection

To conduct the research, field data was collected at five base and six parking sections in different major cities across the country. All the selected sections were the two-lane undivided devoid of any distress or pavement unevenness. In addition, all the sections were straight with no gradient and curvature. Data collection utilized videography techniques at designated locations. All the data were collected for three hours preferably in the morning peak and off-peak hours in a weekday under normal weather conditions. Each road had a 30m stretch marked on the road using white tape or chalk. A high-resolution video camera mounted on

a 1.5m tall tripod was kept roadside at a suitable height in such a way that it can capture the marked section continuously. Subsequently, all the recorded video files were taken to the laboratory and played on the computer screen to extract the required data.

5 Results

The traffic composition and carriageway width play significant roles in estimating the stream speed, especially in the Indian context. The proportion of different categories of vehicles on urban streets and the width of the carriageway significantly affect the stream speed. Hence, the linear base speed equation was derived by considering the traffic compositions and carriageway width as independent variables as given in *Equation* (4).

From the video files, the stream speed at each parking section was estimated and compared to the speed of the base sections. The speed at various parking sections was much lower than the base speed, as given in *Table 4*.

The study revealed that the stream speed significantly reduces within a wide range of 39.09% to 81.30% due to the presence of on-street parking parameters. The results of speed reduction were compiled with parking parameters and multiple regression techniques were used to develop a speed reduction model (ΔV). In this connection, the required parking data from selected parking sections were extracted and analysed for dependency check. The most crucial parameters, influencing the stream speed, were later selected for the model development as given in Table 5.

Finally, the speed reduction model was developed based on the most effective on-street parking parameters as given in:

$$\Delta V = 16.968 \times PW + 0.021 \times PM,$$
 (5)

where: ΔV = Reduction in speed (%), PM= Parking maneuvers (veh/km/h),

Table 4 The reduction in speed due to the presence of on-street parking

Section	Base Speed using Eqn.4 (km/h)	Speed (km/h)	Speed Reduction ΔV (km/h)	Speed Reduction (%)
P1	64.18	12.00	52.18	81.30
P2	41.51	24.57	16.94	40.81
P3	43.54	26.52	17.02	39.09
P4	67.16	19.43	47.73	71.07
P5	80.44	22.15	58.29	72.46

Table 5 Details of the most efficient parking parameters

The range for various parking sections	Unit
728-2900	veh/km/h
0.88-3	m
	728-2900

Table 6 Details of the model

Parking Parameter	Coefficients	t-stat	p-value	VIF (Variance Inflation Factor)	\mathbb{R}^2
PM	0.021	6.904	0.006	2.046	0.983
PW	16.968	5.916	0.010	2.046	

PW= Parking width (m).

The details of the model are given in *Table 6*.

6 Validation

To check or validate the accuracy of the model, another set of data was collected and extracted. Details of the section are given below.

- · Location- Subhash Marg, Lucknow
- Carriageway width = 7.2m, Parking width = 0.897m, and Parking maneuvers = 1333.33 veh/km/h.
- Stream Speed (data extraction) = 28.72 km/h.

Initially, the base speed of the section was estimated 54.83 km/h using Equation (4). Afterwards, the stream speed of the vehicles on the selected section was measured manually by simply playing the video files on a computer screen throughout a 30m trap length bordered by the two reference lines using Kinovea [23]. The speed was estimated as 28.72 km/h. Finally, the values of selected parking parameters were given as input in Equation (5) to obtain the speed reduction (ΔV) following the estimation of speed based on the proposed model as 31.13 km/h. The comparison between the results shows the error as -8.422%, showing the effectiveness of the model. A negative error shows the speed estimated using the model was slightly greater than that extracted.

7 Conclusions

A methodology to estimate the stream speed of the parking section is proposed in the present study. The study conceptualizes the most efficient parking parameters influencing the stream speed of the vehicles. These parameters were compatible with the Indian traffic context. Below are the major findings of the study.

- The speed at parking sections was significantly reduced in the presence of on-street parking that highlights the importance of considering the parking maneuvers and parking width in data analysis. This decline varies within a wide range of 39.09% to 81.30%.
- A speed reduction model was created by considering the two major parking parameters, which predict the impact of on-street parking on the stream speed. Further, the developed model can be a valuable tool for urban planning and designing.
- A favorable agreement (-8.422% error) was established between the speed derived from the data

- extraction and the speed reduction model, which suggests that the proposed model can accurately estimate the stream speed at the parking sections with varying intensity of on-street parking.
- The findings provide valuable insights for developing norms regarding the on-street parking facilities whether on-street parking can be prohibited or allowed and if it is allowed then up to what extent? The model also reveals how the stream speed of vehicles at parking sections enhances or declines in the presence or absence of on-street parking.
- The proposed model can be helpful for urban transportation planners for easy estimation of the stream speed at parking sections saving valuable time in the data extraction process.
- The methodology adopted in this research can be further implemented in the future to extend the work and explore the impacts of different parking patterns such as angled or perpendicular on the stream speed. Additionally, this research also provides suggestions to examine the driver's behavior when vehicles are parked in designated bays or on the roadside.

In summary, the present study can be effective for urban transportation planners, while providing parking regulations. The proposed model offers a straightforward approach for estimating the stream speed under varying intensities of on-street parking, providing valuable insights for the traffic management and urban transportation planning efforts. This research can contribute to better understanding of on-street parking and stream speed, which offers practical solutions to overcome traffic congestion in urban areas.

7.1 Future scope of the study

This study opens several avenues for further research to deal with the impacts of on-street parking on the stream speed.

The type of on-street parking, whether unregulated or with designated parking bays, may instigate a considerable difference in the impact of on-street parking on the regular traffic flow. The impact is expected to be reduced in the case of a designated parking bay, as compared to an undesignated parking bay. However, the designated parking bay on a collector type of road is not common in India. Hence, comparing the impacts of unregulated parking with the designated parking bays is beyond the scope of the present study. Nevertheless, this

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- comparison will be interesting to see and can be investigated in future studies.
- The type of on-street parking (parallel, angled or perpendicular) may play a significant role in determining its impact on the stream speed. However, considering the fact that the parallel parking is the most commonly found parking type on Indian urban roads, the same has been adopted in the present study. Nevertheless, comparing the impacts of different parking types can be a meaningful venture and will be taken up in future studies

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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THE USE OF AUTOMATION IN RAIL TRANSPORT TO ENSURE INTERCHANGES IN REGIONAL PASSENGER TRANSPORT

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Resume

This paper deals with the use of automation in rail transport to provide transfer links in public passenger transport. The methods of railway transport management in the Czech Republic are presented and their suitability for the use of automation in regional passenger transport is assessed. The authors consider the impact of automation only from a technological point of view. In this paper, the authors propose a modification of the train departure using a layout criterion and time stops to provide transfer links using the Automatic Route Setting System. The authors consider the use of the Real Time Rescheduling considering the traffic on the railway line, as well as the traffic connections of the public line transport. The paper proposes the use of automation software to improve the quality of public passenger transport.

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1 Introduction

Quality public passenger transport is one of the tools for development of regional areas [1]. For the development of the rail passenger transport, research and innovation in key areas such as digitalisation, automation of rail operations, sustainable solutions, safety, and increasing the availability of rail transport services to customers must be continuously pursued [2].

Important factors for regional public transport include, among others, the provision of transfer links, the temporal and spatial continuity of connections, and the minimisation of the number of transfers. Passengers often associate transfers with inconvenience and the threat of missing a connection service. This reduces the competitiveness of regional public passenger transport compared to the car transport [3].

The different modes of public transport should be interconnected, including trains and regional buses. In [4], the authors propose a simulation model to be able to assess the timing of public transport connections in terms of passenger transfer. The model can indicate connections (pairs of trains and buses) with insufficient operational stability (high risk of connection loss). The second important feature of the proposed model

is the ability to verify the impacts of possible schedule adjustments (for example, changing the selected service in time) from a comprehensive point of view. This is to prevent that removing one transfer complication does not create a new one. The synchronisation of the public transport connections at the nodes of lines with longer intervals between connections is simulated in [5].

In this paper, the authors propose using the Automatic Route Setting System (ARS) to automatically modify the departure of a passenger train from each transport point along its route. Thus, in the case of delays, it is possible to guarantee transfer links under specified criteria. The links are modelled from the micro-perspective of the transfer and from the macroperspective of the whole railway line and transport network. The authors' proposal is based on their knowledge of the issues in the Czech Republic.

2 Ensuring regional public transport

According to [6], the provision of regional transport services should be based on the requirements of passengers, the requirements of transport customers, transport authorities, and transport demand modelling.

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Line	Connection	Departure	Waiting at the bus stop	Waiting time [min]	Line/train	Connection	From the direction	Arrival
620606	1	14:02	Hermanuv Mestec, nám.	2	620710	23	Chrudim	13:58
620700	101	7:33	Chrudim, aut.st.	6	700703	101	Chroustovice	7:28
840118	104	12:43	Policka, aut.st.	10	Os 15320	X	Svitavy	12:31
620706	15	18:15	Chrudim, aut.st.	5	Sp 1467	X	Pardubice	18:11

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Table 1 Guaranteed transfer times at selected transfer hubs in the Pardubice Region

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In the regional public transport, the key elements of quality are, in particular, the frequency of services and their appropriate timing, travel times, reliability and travel comfort [7]. Geographic extent, the range of regional public transport services, and walking distance to stops are cited as other important aspects [8]. The latter is generally longer for the rail stops than for the bus stops due to the routing of rail lines [9].

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Another important factor in regional public transport is the number of transfers, the continuity of connections, and the provision of transfer links [10]. The most important factors in the choice of a transfer or non-transfer journey are identified as:

- a) travel time,
- b) waiting time for transfer,
- c) transfer walking time,
- d) transfer information,
- e) fares,

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- f) security,
- g) comfort [11].

The willingness of public transport users to use connecting routes increases if the continuity of connections for the planned transfer is guaranteed. The travel time is more important than waiting and walking time for transfers, especially for commuters [12]. In the Czech Republic, there are guaranteed connections and specified transfer times at each transfer hub. For example, in the Pardubice Region in the document "Guaranteed transfer times Pardubice Region" [13]. An example of transfer times at selected transfer hubs in the Pardubice Region is given in Table 1.

The second and third rows of Table 1 show the waiting times for transfers between bus routes. The next three rows of Table 1 show the waiting times for train/bus transfers.

The planning is a key process in public transport. Passengers are informed about how best to use the system for their individual travel needs. Carriers offer journey planning apps on their websites or through mobile apps. For a given travel request, these apps usually offer one or more possible routes [14].

The choice of transport mode is also influenced by the delay in public transport connections [15]. A single public transport delay can influence an individual's behavior (e.g., mode choice), especially if the realtime travel information provides advance warning of potential delays. Therefore, riding on time is always one of the most important factors, and the delays are usually negatively associated with passenger satisfaction [16].

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Delays or cancelations of individual trains affect the planned journey of passengers. Measures are needed to maintain the passenger satisfaction and ensure efficient operations in the event of an emergency. These measures should lead to a return to scheduled operations and they allow the passengers directly affected to continue their journey, as well. Dynamic passenger guidance in the rail transport is the optimal management of current traffic to transport all the passengers appropriately in the event of a delay/emergency. Through the targeted implementation of demand-side measures, passenger flows on the rail network can be effectively managed. The effectiveness of the chosen measures depends on the acceptance of alternative connections by passengers and the provision of information. However, the most critical factor for optimal management is knowledge of passenger decision-making behavior [17].

3 Tools to automate public transport operations

Equipping the lines with the Automatic Route Setting System (ARS) is necessarily required for the authors' proposal. In this section, the basic tools for implementation, including links to ARS, are presented.

The basic application for operational traffic management is the Traffic Management System (TMS). The TMS application is used by the infrastructure manager's staff for, among other things, the overview and editing of planned traffic (train routes). Some TMSs even allow for the resolution of traffic conflicts that arise. Data from the TMS are used to support the direct level of traffic management [18].

Based on the train path data, received from the TMS, the Automatic Route Setting System (ARS) gives commands to the interlocking to set the train route. The ARS is one of the tools to make more efficient use of infrastructure by automatically generating commands to control the train movements in real time. This will shorten the transfers between trains and, consequently, lead to a more efficient timetable [19]. The dispatcher has the possibility to intervene in the ARS, e.g. by manually changing or modifying the data of the selected train in the TMS if the traffic situation requires it [20].

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In the Czech Republic, the ARS is called "Automaticke staveni vlakovych cest (ASVC)". It generates a command to set a departure train route, usually 2 minutes before the expected departure of a train with a stay at a traffic point longer than 1 minute, otherwise 5 minutes in advance. The issue of entry train routes is not the subject of this paper. The user can set the layout criterion (e.g. waiting for another train to pass or waiting until a defined time). The ARS will wait for this criterion to be met before issuing the command to set a train route [21].

Information from the TMS is also transmitted to the train control systems. These are the highest level of automation in train control. There are 5 Grades of Automation (GoA):

- GoA0 no automation,
- GoA1 driver leads the train, automation of signaling equipment,
- GoA2 automation tools control the train, driver supervises their operation,
- GoA3 automation tools fully lead the train, train driver presents on the train and qualified to intervene in case of emergency,
- GoA4 train with no human staff present [22].

One of the train guidance systems is the Connected Driver Advisory System (C-DAS), where the Energy Savings and Driving Strategy (ESDS) module calculates the optimal speed profile for the driver to follow [23]. While C-DAS only issues recommendations for driving and braking, the higher level of automation in the form of Automatic Train Operation (ATO) generates driving and braking commands directly to the train without the driver having to confirm the command. The main function of the ATO is to generate a train path that specifies the speed profile on a given route, considering the timetable and the characteristics of the train and infrastructure [24].

In the Czech Republic currently (year 2024) is applied "Automaticke vedeni vlaku" (AVV). This differs from the European ATO over ETCS mainly in that AVV, unlike ATO over ETCS, does not work with actual dynamic data and AVV requires the driver's interaction, who is still responsible for the train [25]. The AVV system will be applied in the Czech Republic on majority of the selected lines, only on the line Kralupy nad Vltavou - Decin state border is the implementation of the European ATO over ETCS is foreseen [26].

A separate section is the possibility of the so-called self-organisation of transport, where the intelligent trains decide on their own journey. Decision making is based on knowledge of the train's own timetable and the ability of the train to interact with other trains in the area (mutual transfer of information about the location and forecast of the next journey). This would eliminate the traffic conflicts and achieve the desired (optimal) traffic development. This model is based on the European SORTEDMOBILITY project [27] and has been published in [28].

These train control system tools achieve the train

running prediction in cooperation with ETCS and ARS and thus provide the valid input data for decision making and, at the same time, are able to implement the train running according to plan - thus maximising the benefits of the authors' proposal.

4 Safeguarding and controlling traffic on lines of a regional character in the Czech Republic

The operation of the national and regional railway network in the Czech Republic is controlled according to the following regulations:

- "SZ D1 PART ONE" Traffic and signaling regulations for lines not equipped with a European Train Controller,
- "SZ D3" Regulation for the simplified rail traffic management,
- "SZ D4" Regulation for the control of rail traffic on lines equipped with radio-blocking,
- "SZDC (CD) D40" Prescription for the organisation of rail transport on the lines Liberec - Tanvald
 Zelezny Brod; Tanvald - Harrachov; Smrzovka -Josefuv Dul [26].

For application of any of the automation levels, it is necessary to equip the lines and stations with electronic signaling equipment. At 31 December 2022, 7.389 km of lines (out of 9.355 km) and 459 transports (of which 360 transports were included in the DOZ - remotely controlled signaling equipment) met this requirement in the Czech Republic [29].

The application of automation tools is currently (2024) not possible on lines controlled according to the "SZ D3" regulation due to the absence of station and line signaling equipment. On 7 July 2020, a collision of two passenger trains occurred on the line Nejdek -Potucky controlled according to the "SZ D3" regulation (2 persons killed, 22 injured, damage over 1 million EUR). The contributing factor to the accident was found to be, among others, the absence of signaling equipment that would eliminate the possible failure of the human factor [30]. For this reason, the Railway Administration developed a concept aimed at preventing similar incidents. The concept proposes 4 solution options (options 0-3). In variant 2, the implementation of ETCS on lines controlled according to SZ D3 is foreseen. In variant 3, it is foreseen to transfer the control from the "SZ D3" to the "D1" regulation with the addition of category 3 signaling equipment, including ETCS and DOZ [31]. Out of a total of 1.751 km of lines controlled according to the 'D3' regulation, it is assumed that variants 2 and 3 will be applied on up to 1.231 km of lines [32]. Therefore, an increase in the proportion of lines suitable for application of automation of selected activities can be expected.

For the regional character lines in the Czech Republic, the use of ETCS LS STOP for lines with less than 45 trains/day or ETCS L1 LS for busier lines controlled according to the D1 regulation is considered [33]. According to [34], the increase in safety in these lines in the Czech Republic is estimated at 296 million EUR.

network, so that more important interchanges are not disconnected elsewhere, or there is no unwanted transfer of train delays on the single-track line.

5 Modelling the transfer links in the railway traffic control automation

The authors propose that the ARS function will automatically modify the departure of a passenger train from each point on its route. Modifications will be allowed only with a positive increment of the departure time, i.e., delay of the train compared to the regular timetable; departure of passenger trains with a headway is not allowed with respect to the timetable. The train departure time so adjusted must be respected:

- arrival times of connecting public transport connections (train and, within the integrated transport system, bus connections),
- the minimum transfer time at the interchange hub,
- the maximum waiting time at the interchange hub,
- the arrival time of the oncoming delayed service at the crossing,
- time stops (suggestions from the authors of the paper).

The resulting system proposed by the authors combines 2 distinctive levels, the solution of transfers within the interchange and at the same time it also respects the traffic in the surrounding transport

5.1 Micro view - interchange hub

The authors' proposed system must respect minimum transfer and waiting times at each interchange. Waiting time in railway transport in the Czech Republic is determined for each station by the "Connections between passenger trains" [35]. In the case of the integrated transport system, waiting times are set at selected transfer points and connections are guaranteed, for example, in [36].

The authors consider automatic departure modification if inequality (1) is satisfied; otherwise, a dispatcher decision is required.

$$\max(A) + t_{IT} \le t_{WT}; \ A \in \{1; n\},$$
 (1)

where:

A is the set for the arrival times of connecting links [number],

n is the number of incoming connection connections [number],

 $t_{{\scriptscriptstyle IT}}$ is the transfer time [minutes],

 t_{wr} is the waiting time [minutes].

Figure 1 shows a train waiting (in black) at a

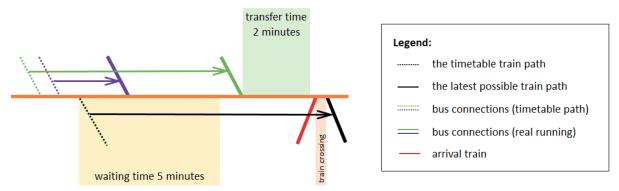


Figure 1 Train path shift on departure from a transfer junction while maintaining all the transfer links and train crossings on a single-track line

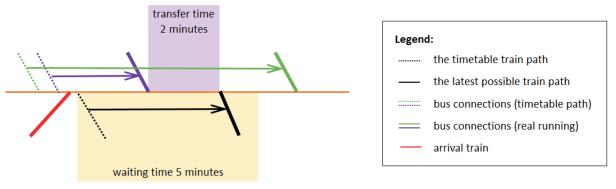


Figure 2 Shifting the train route while maintaining part of the transfer links

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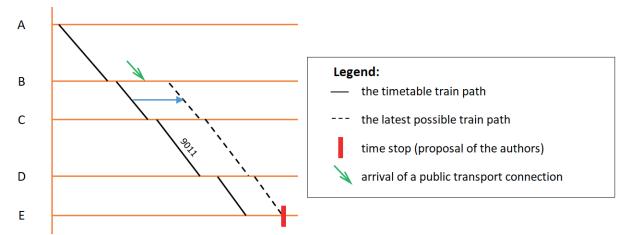


Figure 3 Modification of the train route while maintaining the transfer link and the time stop

fictitious interchange for a connecting line transport service. Even the transfer from the green line beyond the 5 minutes waiting time is maintained when waiting for a delayed oncoming train (in red).

In contrast, Figure 2 shows that the transfer from the green connection of public line transport is not maintained when the coming train is on time (in red), as the waiting time is not met. Thus, the black train only waits for the slightly delayed purple public line transport service connection.

Information about waiting for a delayed connection must be known at the transfer station before the ARS instructs to set the train route (in the Czech Republic, depending on the length of train stay, either 2 minutes or 5 minutes in advance). If this information arrives, then the authors propose to insert an appropriate layout criterion in the TMS for the train departure from the transfer point, which would adjust the train departure time to meet the required continuity.

5.2 Macro view - the whole railway line or transport network

When automatically editing the departure time from a transport point, it is necessary to consider the possible consequences on the line or on the entire public passenger transport network. The authors propose the creation of a "time stop" that defines a time condition that takes priority over the preservation of other links. Train routes are edited in an attempt to preserve passenger transfers and no route may exceed the defined time stop. This time stop can be the latest arrival time at a central interchange hub (e.g., an integrated timetable interchange hub) to preserve all the connections to the backbone lines, or, e.g., the latest arrival time to catch the start of school.

The dynamic prospective traffic modelling is designed by the Real Time Rescheduling using the ARS layout criteria. The inputs to the model are the initial timetable of each train service, which has a well-defined route, and the current location and timetable of the connecting public line transport services. The route modification must respect all the constraints based not only on the train parameter, but on the transport network, as well. Especially on single-track lines, the capacity constraints of the single-track section are crucial, as can be seen from [37].

In the Czech Republic, the principle of Real Time Rescheduling together with ARS was used in [38]. It assumes that the current location of the delayed connection is known and that the expected arrival to the transfer point will be calculated from this location and the forecast of the next journey. According to this value, the prospective traffic will be modified to ensure interchange connectivity while avoiding unwanted traffic conflicts on the railway line (especially on a single-track line). If a traffic conflict arises, it must be identified and resolved immediately [39]. The resolution of traffic conflicts within the Real Time Rescheduling is presented in [38]. In contrast to [38], the authors work exclusively with the adjustment of train stays at traffic points; in [38] the modelling of travel times according to a set of variables is also considered. These variables often cannot be quantified in traffic until the last moment, and then the proposed model might not provide valid results. The relationship between the Real Time Rescheduling and ARS (including the consideration of constants for signaling equipment operation) is published in [40].

Figure 3 shows a possible shift of the train route to meet the condition of maintaining the time stop and at the same time to maintain the transfer link from the delayed public service connection at station B. The delay can be achieved due to the time margin at station E and due to the shortening of stays at the connecting stations. The connection from the delayed public service connection will therefore be maintained.

Modifications of the train paths must also consider technological times (for example, operating intervals or minimum turnaround times at the destination station). Figure 4 shows an illustrative example where, due to

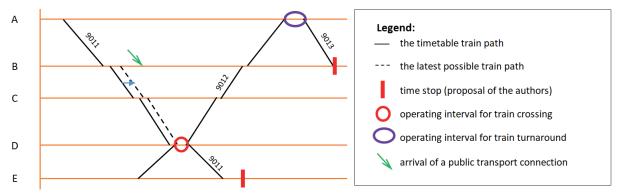


Figure 4 Possible modification of the train route if time stops are preferred without providing a connection link

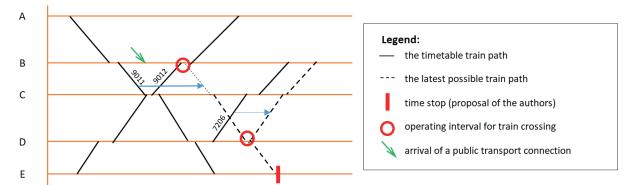


Figure 5 Modification of the train route while maintaining the coupling with a train crossing relocation on a single-track line

the need to run train 9012 on time, it is not possible to provide a connection at station B from the public line service to train 9011. Train 9012 at station A turns into train 9013, which cannot be delayed due to the set time stop, and at the same time the crossing of trains 9011 and 9012 cannot be rescheduled because the time stop of train 9011 at station E would not be respected.

If the time stops are not violated, then it is possible to delay the oncoming train or to transfer the crossing to an adjacent station with a track branching that allows the crossing of trains. An illustrative example is given in Figure 5, where the crossing of trains 9011 and 9012 is moved from station C to station B, while the train 7206 is delayed while maintaining the crossing with train 9011 at station D. The delay of train 7206 is possible as there is no time stop for this train.

The detected train departure value will be incorporated into the TMS using the ARS layout criterion. By incorporating the layout criterion, the train route will be adjusted in all operational applications, and the delayed train route will be known in advance and can be reacted to. The calculation presented by the authors works only with the possibilities of reducing stays at the transport stations or with crossing overlays. These tasks can be solved automatically by the ARS function without the application of additional automation software.

Reduction of journey times in intermediate sections is only possible with the ERTMS, which works with additional data - e.g. the current speed and position of

the train, train parameters, etc. This makes it possible to calculate in an informed way that the train will reduce the journey time. Thus, it is possible to use the algorithm presented in [40], which depends on the detection of the current train position (continuously, or at least cyclically detected, train position at short intervals, for example, 30 seconds).

The ARS function itself does not know the current speed and traction characteristics of the train; the position can be determined at least approximately from the signaling equipment according to the occupied track section, but the exact kilometric position within the track section is not known. If the track sections are so short that a moving train occupies the next section at short intervals (e.g. every 30 seconds), then the conclusions of [41] can be considered even for the ARS alone without ERTMS, where the application of the Real-Time Rescheduling had positive benefits on the path capacity indicators, as well. Figure 6 shows a simplified block diagram of the authors' proposed methodology.

The output of this paper can be used in the Czech Republic for example on the line No. 183 Klatovy - Zelezna Ruda-Alzbetin (commuting to Klatovy, connection to Pilsen, connections in Janovice nad Uhlavou, ARS is applied). After adding the ARS it can be used for example on the line No. 194 Ceske Budejovice - Cerny Kriz (commuting to Ceske Budejovice and train connections there, bus connections in other stations).

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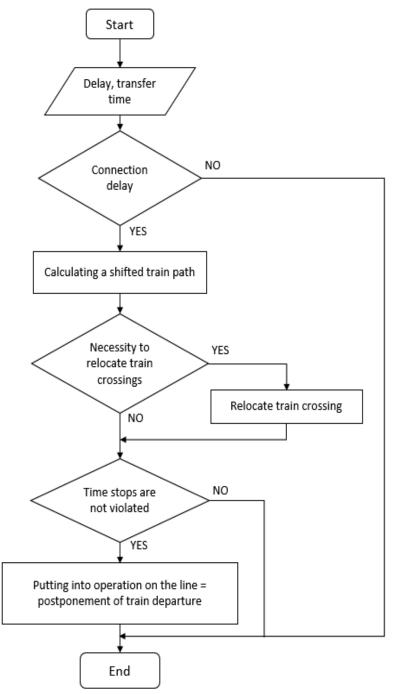


Figure 6 Block diagram of the proposed methodology

6 Conclusion

Providing the reliable transfers is an important factor in encouraging the public to use public transport. This is particularly important in remote regions, where the frequency of public transport services is usually lower, and missing a connection would mean a long wait for the next service. Therefore, when the delays occur, it is necessary to coordinate rail traffic with the operation of public transport services to maintain maximum transfer links according to the planned timetable.

The authors come up with a proposal for automatic provisioning of transfer links in an autonomous railway tool environment with emphasis on the Automatic Route Setting System (ARS). They propose a methodology for when the ARS will preserve a planned transfer link and when it is appropriate to break the transfer link to avoid losing other (more important) links. The authors propose the creation and use of the time stop, which represents the highest level of decision criterion - the time stop can only be violated exceptionally after the intervention of the dispatching apparatus.

The proposed methodology works exclusively

with the modification of the stays of public transport connections at the transport points and the change of the train running order, as these modifications can be done with only the knowledge of the timetable and selected time constants (transfer and waiting times). In the second stage, it allows the use of other automation tools for modelling the journey times, for which it is necessary to know other input data (traction characteristics of the train, etc.).

The proposed methodology would allow for the selection of the optimal option to ensure maximum transfer links. At the same time, essential supra-regional transfer links would be maintained, and commuting to centres would not be delayed (e.g., with regard to the start of school). For these essential criteria, the authors foresee the use of the time stop. The proposed measures would increase the quality and attractiveness through reliable connections even when the regional public transport links are delayed.

The outputs of this paper support the provision of transfer links in peripheral areas where this is particularly important with lower frequency services. When a public transport connection is delayed, according to the proposed algorithm, it is decided whether the connection would wait for the arrival of the delayed

connection or not; whether the possible waiting would not cause more problems elsewhere. Other aspects in the network are taken into account (e.g. crossings on single-track lines, access to the centre of the region, etc.). In practice, the outputs would enable automatic updating of dynamic prospective transport, which are a prerequisite for further decision-making by dispatchers. The authors will further discuss other aspects of the public transport system in peripheral areas and the external influences (delays, transfers, etc.) on operations on lines with a degree of automation of routine operations.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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MULTI-LEG SHEAR REINFORCEMENT OF GFRP AND STEEL LWRC EDGE COLUMN-SLAB CONNECTIONS: A COMPARISON STUDY

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Resume

The behaviour of lightweight concrete (LWC) edge column-slab connections reinforced with two types of flexural reinforcement glass fiber-reinforced polymer (GFRP) and steel bars with different ratios of shear reinforcement are investigated experimentally and analytically using ABAQUS software. The experimental protocol covered evaluation of eight slabs and edge columns measuring subjected to static loading. Slabs are evaluated as supported, free-standing at one edge, and the column connection is included. The slabs are divided into two groupings, with four slabs in each group. The first group was reinforced with steel flexural, while the second group was reinforced with GFRP reinforcement. Within each group, one slab lacked shear reinforcement, while the other was reinforced with a varying shear reinforcement ratio. A good agreement was found between the numerical FE model and experimental outcomes in most tested slabs.

Article info

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1 Introduction

Lightweight concretes (LWC) occupy considerable importance in construction because of their pragmatic and cost-effective benefits. The essential feature of LWC is its low specific gravity, which is caused by the porosity. When constructing the concrete buildings, self-weight accounts for a significant portion of the design responsibilities; thus, decreasing the density of the concrete provides a significant advantage. This characteristics enables the reduction of both the structural and non-structural section dimensions, as well as the construction costs [1]. Flat slabs are one of the most used reinforced concrete (RC) slab systems around the world, as a result of their ease of construction, reasonable construction costs, and ability to provide relatively large spans [2]. Flat slabs are in direct connection with columns with no beams in between. Despite the many advantages provided by this system, there is a major concern regarding its design, which is the two-way shear failure, also known as punching shear failure. It occurs when the principal tensile stresses, produced by the concrete, are equal to its ultimate tensile strength and the nature of failure is a hazardous issue that frequently arises during the fabrication process of flat slabs [3]. Punching shear failure in edge column- slab connections occurs as a result of flexural and shear stress concentration at the proximity area of the columns and it takes the shape of a frustum of a pyramid for square columns and a frustum of a cone for circular columns. The LWC can be reinforced with multi types of flexural reinforcement, however, in this research the two types of flexural reinforcement were mainly used (steel and glass fiber reinforced polymers (GFRP)), with different ratio of multi-leg shear reinforcement. Each type of reinforcement having advantages and disadvantages. For example, compared to steel, GFRP offers many advantages, such as lower thermal expansion, better thermal insulation, low density (between one-sixth and one-fourth of steel's) [4] and high specific strength (GFRP's tensile strength is around two to three times steel's). In contrast, the RC structures, reinforced with steel exhibit ductile behavior, linear elastic-plastic behavior up to collapse with a yielding point, and a higher modulus of elasticity (GFRP's elasticity is approximately one-fourth or one-

third that of steel). When deformed, steel bars form a mechanical bond with one another through bearing on the deformed portions of the bars, unlike GFRP bars. [5]. Considerable effort is devoted to reducing the pushing shear and self-weight in reinforced concrete slabs through the purposeful employment of their beneficial attributes and prevention of their disadvantageous ones. Throughout the previous decades, many experimental and numerical inquiries have been conducted on a wide range of slab types. The punching shear action of four flat plates reinforced with GFRP rods was investigated in [6]. The reinforcing ratio of the slab varies between 1.05 and 1.67%. The length and width of the slabs were 1900 mm, and their thickness was 150mm. A 250 x 250mm column stud was used to apply a concentric load to the flat slabs. According to the experiments, the punching strength of the plates was not considerably enhanced by increasing the reinforcement ratios. The maximum strength of flat plates increased by 14 and 10%, respectively, if reinforcing ratios were 1.18 and 1.67%, compared to the plate reinforced with 1.05%. Using six specimens, authors of [7] assessed the punching shear resistance of steel and GFRP-reinforced concrete slabs. The measurements of each specimen were 2300×2300×150 mm, and the cross-section of the column was 225×225 mm. The column rose 300 mm from the slab in both directions. Using steel or GFRP as reinforcement for flexural strength represented one of the factors considered. The flexural reinforcement ratio of both specimens was 1%. Compared to the slab reinforced with steel reinforcing bars, the one reinforced with GFRP exhibited substantially decreased punched shear capacity, deflection, and post-cracking stiffness, The reason behind this is that the GFRP bars have a lower elastic modulus. Park et al. [8] examined the processes of an imbalanced moment-affected solid flat plate at edge column-slab connections employing nonlinear finite element (FE) analysis. The experiment intended to determine the magnitude and distribution of flexural moments and eccentric shear generated at the interfaces of the edges. Upon comparing the analytical results of the specimen with modern design codes [9], it was found that the distribution and strength of eccentric shear were noticeably different. In addition, a suggested methodology was presented to tackle the issue of edge column-slab connections. An experiment, using fifteen slabs that were 135mm thick, was conducted in [10]. These slabs were supported by columns that measured 180 x 900 mm. The experiment aimed to investigate the effects of column rectangular shape, gravity load stage, and cyclic biaxial loading on the slab-edge column connections' strength, stiffness, flexibility, and drift capacity. Two slabs were analyzed using both uniaxial lateral load and gravity. One slab was just subjected to gravity load, while the other two were subjected to biaxial lateral load and gravity. Shear stresses were found to be highest towards the short side of the column and decreased in amplitude as one proceeded away from the short side. The slab-edge column connections exhibited increased brittleness when exposed to a lateral load perpendicular to the column's shorter side. Rectangular columns enhanced the efficient transfer of moments along their principal axis. Authors of [11] examined eight specimens with varying reinforcement ratios and depths. The initial comparison was made between the two equivalent samples in series one and two. Both series had the same slab thickness but differed in reinforcement ratio and column size. Irrespective of the strength of the concrete, the findings from the initial two sets of experiments, which involved slabs with a thickness of 200 mm, indicated an improvement in load capacities of around 18% and 14% for reinforcement ratios of 0. 7% and 1.6%, respectively. For a slab thickness of 350 mm, the findings indicated a rise of approximately 9% and 14% in load-bearing capacity for reinforcement percentages of 0.3% and 0.7%, respectively. In addition, the punching shear properties of two-way FRP-RC slabs without shear reinforcement have been investigated in multiple studies [7, 12-15]. Applying shear reinforcement to two-way FRP-RC slabs has received scant attention in the literature [3, 16-18]. Research, published in 2019 by Jang et al. [6], investigated how the flexural and shear reinforcement affect the punching shear strength of the slab-column connections. Six slab-column connection specimens, with varying flexural and shear reinforcement degrees, were examined. The specimens were subsequently subjected to gravity load tests. The benchcolumn connection behaved differently depending on the amount of shear and flexural reinforcement, and all the samples failed because of punching, according to the experiment's outcomes. Regardless of the existence or absence of shear reinforcement, the specimens' punching strength was greatly improved by including flexural reinforcement in the slab-column connection. The researchers in [17] investigated the ultimate punching shear strength of slab-column connections in concrete with limited shear reinforcement at the initial phase of the diagonal crack stage. This is because the shear reinforcement is not sufficient to regain the shear strength of the concrete after the commencement of a diagonal fracture. The concrete's shear strength is reduced at the first diagonal fracture but recuperated by the shear reinforcement if sufficient; hence, the ultimate strength is achieved immediately following the first diagonal crack. Authors of [18] investigated methods for enhancing the fundamental strength of lightweight concrete (LWC) flat slabs to avoid punching shear failure. Thirteen specimens of flat slabs made of lightweight concrete (LWC), and reinforced with extra reinforcement were tested in an experimental study. The primary factors examined were the shear reinforcement type (steel bars, high strength bolts, or glass fiber reinforced polymer (GFRP) rods), spacing, arrangement of shear reinforcement surrounding the column, and

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Table 1 Experimental specimen and parameters details

Group No.	Slab Coding	Type of Shear Reinforcement	Shear Rein. Ratio v $ ho$ (%)
	S-L-0	Not Available	0
G 1	SM-L-6	Multi-Leg Stirrups Ø 6	0.1
Group 1	SM-L-8	Multi-Leg Stirrups Ø 8	0.213
	SM-L-10	Multi-Leg Stirrups ∅ 10	0.39
	G-L-0	Not Available	0
G 0	GM-L-6	Multi-Leg Stirrups Ø 6	0.1
Group 2	GM-L-8	Multi-Leg Stirrups Ø 8	0.213
	GM-L-10	Multi-Leg Stirrups ∅ 10	0.39

technique of fixing the shear reinforcement. According to the test results, using radial shear reinforcement with a spacing of (d/2) resulted in the most effective strengthening method. In comparison to the standard specimen, the punching shear capabilities of steel bars, glass fiber rods, and high-strength bolts increased by 77%, 61%, and 54%, respectively. In addition, using high-strength steel bolts connected to the slabs with steel plates demonstrated the greatest ductility compared to the other reinforcing techniques. In addition, the failure mode changed from brittle shear failure to flexural shear failure.

2 Experimental methodology

2.1 Study parameters

In this study, a total of eight square, two-way slabs measuring 1100 mm by 1100 mm with a thickness of 100 mm were fabricated and evaluated. Additionally, edge columns measuring 150 x 150 mm² of height of 150 mm, which were designed according to [19], were subjected to static concentric loading. The primary variables being investigated were the type of flexural reinforcement (steel or GFRP) and the percentage of multi-leg shear reinforcement ($\rho v\%$). The slabs are divided into two groupings, with four slabs in each group. The first group was reinforced with steel flexural, while the second group was reinforced with GFRP flexural. Within each group, one slab was devoid of any shear reinforcement as control specimen, while the other was reinforced with a varying ratio of shear reinforcement. All the mechanical tests were conducted using these specimens. The specimen codes and specifics of these parameters are detailed in Table 1; symbols correspond to different slab codes. For instance, the symbols S,G refer to steel flexural and GFRP flexural slabs without reinforcement, respectively; SM,GM denote the steel flexural and GFRP flexural slabs without reinforcement, respectively; L signifies lightweight concrete slabs; and (0, 6, 8, and 10 mm) represent shear reinforcement bar diameter.

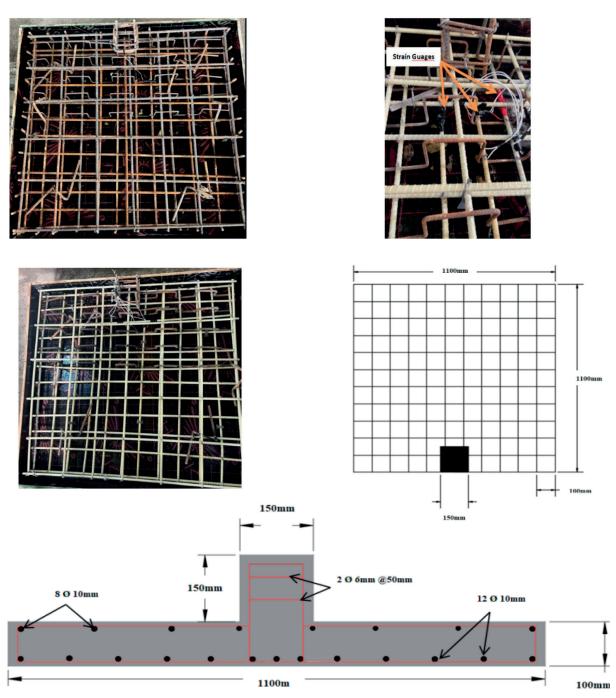
2.2 Slab reinforcement details

The longitudinal tensile reinforcement consists of steel and GFRP reinforcing rebar's (bars) measuring 10 mm in diameter. Additionally, the diameters 6, 8, and 10 mm are used in shear reinforcement, the distribution bars and their associated information are presented as depicted in Figure 1. The steel reinforcement's flexural and shear mechanical properties were investigated through tensile experiments; the results are presented in Table 2. The GFRP bars utilized in this study were produced through the combination of a pultrusion technique process and an in-line sand-coating process for the surface of the bars. The purpose of this sand coating was to enhance the adhesion between the GFRP rods and the concrete in the surrounding area. To ascertain the tensile characteristics of the GFRP bars, three experimental bars measuring 10 mm in diameter were subjected to testing following the (B.2) Test Method of [20]. Table 3 presents the properties of GFRP bars, which were discovered through testing. In the examined slab, the lower surfaces of the reinforcing bars were equipped with three strain sensors arranged in three different orientations. The spacing between those instruments was as follows: 0.5d, 1d, and 1.5d from the face of the column (d :is the effective depth of slab), as illustrated in Figure 1. More specifically, strain indicators (FLAB-6-11) are employed. Prior to affixing the strain measurements to the reinforcing rebar (steel and GFRP), each rebar's external surface must be cleaned and flattened by removing each of the deformed ribs. The strain gauges are encased in the water-resistant tape to prevent moisture absorption and insulate them from the effects of the substances during the concrete installation.

2.3 Materials

2.3.1 Cement, coarse aggregate and fine aggregate

Ordinary Portland cement (type I), bearing the trademark (AL-Maas) and manufactured in Iraq, was



 $\textbf{\textit{Figure 1} Details of (Steel, \textit{GFRP}) reinforcement and strain gauge}$

 $\textbf{\textit{Table 2}} \textit{\textit{Mechanical properties of steel reinforcement bars}$

Bar size (mm)	Surface texture	Yield stress (MPa)	Ultimate stress (MPa)	Elastic tensile modulus ES (GPa)
ø 6				
ø 8	Deformed	420	580	200
ø 10				

Table 3 Mechanical properties of GFRP reinforcement bars

Bar size (mm)	Surface texture	Ultimate tensile strength (MPa)	Ultimate tensile elongation (%)	Elastic tensile modulus $E_{_{\mathrm{F}}}$ (GPa)
ø 10	Deformed Sand Coated	769 ± 23	1.60 ± 0.05	48.2 ± 0.4

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used for the duration of this study. The corresponding properties are detailed and modified to comply with the Iraqi Specification No. 5/1984) As for the coarse aggregate that was used in the research, it is Light Expanded Clay Aggregate (LECA), which is a lightweight aggregate (LWA) manufactured in Tehran and complied with [21]. Table 4 and Figure 2 were obtained from the Leca manufacturing facility. Additionally, a subsequent examination was conducted in the laboratory of Al-Nahrain University to validate and assess the results of the sieve analysis test utilizing gradations ranging from 0 to 8mm. On the other hand, According to Iraqi Specification No.45/84, the fine aggregate of this mixture is natural sand sourced from the Al-Akhedir region, and Table 5 presents its grading. The specific gravity of sand was 2.66, the fineness modulus was 2.9, and the absorption was 1.05%.

2.3.2 Concrete mixture design and procedure

The lightweight aggregate (LECA), utilized in producing lightweight concrete mixtures, with dried sample densities of around 1824 kg/m³, and cylinder compressive strengths of 35.5 MPa, is specified by [22]. To reach the required compressive strength and dry density, a range of mixtures was evaluated during this study; the most effective one was identified by combining the proportions of concrete mix shown in Table 6 with a decreased dry density and increased compressive strength. Three cylinders and three cubes were cast, and two prisms were arbitrarily cast and tested from the identical slab batches to preserve the mix's quality. The results presented here were obtained through the calculation of average values for three specimens that were assessed twenty-eight days

Table 4 Dried density and gradations for lightweight aggregate (LECA)

	Passing				
Sieves	Limits (%)	Typical (%)			
8	100 - 75	90.2			
6.35	93 - 75	82.8			
4.75	70 - 40	47.7			
2.8	35 - 10	22.33			
2	25 - 5	13.7			
1	8 - 0	3.3			





Figure 2 Sieve analysis test for LECA

Table 5 Grading of the sand

Size of Sieve (mm)	Cumulative Passing by Weight (%)	Iraqi Standard IQS No. 45,1984 limitations (%)
9.5	100	100
4.75	93.1	90 - 100
2.36	90.6	85 - 100
1.18	79.3	75 - 100
0.60	66.4	60 - 79
0.30	27	12 - 40
0.15	4.7	0 - 10

Table 6 Proportions of concrete mix

Mix Name	Cement Content (kg/m³)	LECA (Gravel) content (kg/m³)	Sand Content (kg/m³)	W/C (%)	*S.P% by weight of cement
LWC, Mix	550	500	550	0.24	1.24

Table 7 Characteristics of hardened concrete

Mix Name	f _{cu} (MPa)	f' _c (MPa)	$f_{t}(MPa)$	f _r (MPa)
LWC, Mix	42.2	35.5	3.49	3.9



Figure 3 Casting, curing method for slab specimens

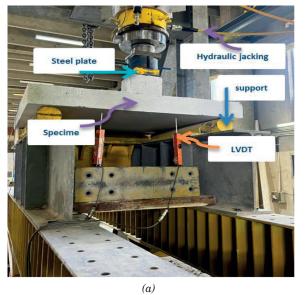




Figure 4 Test setup

after curing: fracturing tensile strength ($f_{\rm t}$), flexural strength ($f_{\rm r}$), and the compressive strength ($f_{\rm c}$ and $f_{\rm cu}$) for cylinders and cubes, presented in Table 7. The mixing method is a critical determinant in achieving the desired homogeneity and workability of the concrete mixture. Concrete components were combined using the mixer after several experimental mixes. The blending process utilized a horizontal drum mixer with a 0.11 m³ capacity. LECA were used as coarse aggregates under saturated surface dry conditions (SSD). The residual concrete from the prior quantity was eliminated prior to mixing. First, after adding the ingredients, the pan and blades of the mixer were cleaned with a moist cloth. After pouring the coarse aggregate into the mixer and

mixing it for two minutes, the pan was filled with the remaining dry components, cement, and grit. They were thoroughly blended for approximately two minutes to facilitate complete dispersion of the fine particles in the pan and ensure comprehensive interaction of the ingredients. After adding half of the necessary amount of potable water and thoroughly mixing the constituents for a few minutes, a specific superplasticizer admixture (PC 600) compliant chemical additives are utilized to increase the mix's workability without sacrificing the concrete's ultimate strength, followed by adding the remaining mixing water to the constituents in the mixer. The blending process lasted between five and eight minutes in total. Immediately after the mixing, molds

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were constructed from plywood planks using concrete. The method of compaction was carried out utilizing a tamping implement. Compaction has been maintained until the very last stratum. All the specimens underwent a remolding process after 24 hours and were cured in water for an additional 28 days; each stage is illustrated in Figure 3.

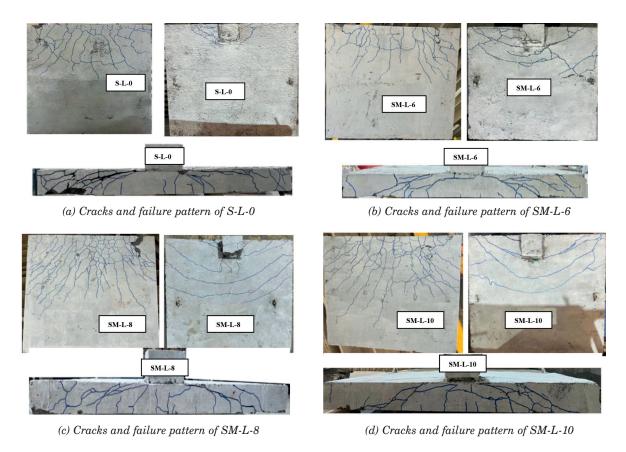
2.4 Testing setup and instrumentation

Static load testing is performed on every slab until the point of failure at the Structural Laboratory of the Al-Nahrain University, Faculty of Engineering. This is accomplished using a Via hydraulics Universal Testing Machinery with a capacity of 2000 kN and simply supported edges at three and free edges, excluding the column connection. Testing continued until failure was detected. The horizontal positioning of the evaluated slabs between the jack and a rigid steel structure was achieved, as depicted in Figures 4(a) and 4(b). To achieve the supported condition in the laboratory, a solid shaft steel section of a 100 mm diameter was manufactured and welded on three sides. Except for the edge of the column-slab connection on one side, this particular segment of the structure was integrated along the complete perimeter of the slab to enable the free rotation at the supports. However, the column indicated that the dimension portion of each specimen was 150 mm by 150 mm. The deflection of each slab is measured at two specific locations: the open edge and the center of the bottom face, utilizing Linear Variable Differential Displacement (LVDT).

3 Static load test results of slabs

3.1 Cracking-pattern and mode of failure for slabs

Firstly, group one (G1) consists of four slabs (S-L-0, SM-L-6, SM-L-8, and SM-L-10); the failure modes with necessary data for all the slab specimens are shown in Table 8. The evolution of the crack pattern detected during the tests for these slabs is summarized below in figures at ultimate failure loading compared with control specimens S-L-0. The increase of the first cracks in this group was 28.1%, 43.5%, and 45.7% for SM-L-6, SM-L-8, and SM-L-10, respectively, compared with the control specimen S-L-0. In the initial phase of the test, the first cracks developed at the bottom surface, starting from the region underneath the loading area. When increasing the load, radial cracks originating at the column's corners, remained stable until 75% of the ultimate load. Beyond that point, circumferential cracks formed as circumferential under-loading area concentrate. Those cracks moved towards the edges as the load increased. Subsequently, the cracks expanded widely diagonally radially in many directions and to the corner; thus, more cracks developed at the bottom surface until the shape of failure was completed (forming the classical punching critical zone with truncated cone failure shape) as shown in Figures 5 (a, b, c and d) for specimen S-L-0, SM-L-6, SM-L-8, and SM-L-10, respectively. On the compression face (at the top face), there were no flexural cracks noticed; at a higher load level of about 50% of destructive force, visible radial cracks as arc shape cracks were formed around the sides of the column due to column penetration inside the slab on the (tension face). Unlike those that appeared using stirrups, shear reinforcement resists shear forces. However, the critical zone for punching shear in the specimen SM-L-6 gets shifted away from the column face and outside the punching shear surface due to the provided multiple leg stirrups reinforcement; this can be explained where the 45° angle crack crosses the path of these vertical bars, they tend to hold the concrete on both sides of the crack together for much longer until they are torn out of the concrete or sheared off. In addition, these reinforced specimens' failure was more ductile than the control specimen (without shear reinforcement). In specimen SM-L-8 with punching shear reinforcement ratio (ρ v) of 0.213% (Ø8 at 100 mm), the first crack became visible at 43.5% of the ultimate load. It continuously increased with an increase in the applied load until the failure occurred under the mixed mode of flexural and punching shear. The cracks on this specimen had a small width. Radial cracks appeared far from the column with a distance of 210 mm outside the shear reinforcement zone without the column perfectly penetrating the slab, as shown in Figure 5(c). When the punching shear reinforcement ratio (pv) increased from 0.213% to 0.39% (Ø10 at 100mm) in the specimen SM-L-10 with the same type of punching shear reinforcement system in SM-L-8 gradually failed under flexural and punching shear failure. The column did not penetrate the slab. The first cracks continued to progress but remained fine. Short radial cracks appeared on one side, as shown in Figure 5(d). The second group (G2) is equipped with flexural reinforcement made of GFRP material and consists of an equal number of case studies G-L-0, GM-L-6, GM-L-8 and GM-L-10. The first visible crack (bending cracks) was observed at the tension face of the tested slab at load level equal to (23 - 47) kN. In all the slabs, cracking on the tensile face began near the area of loading concentrated and radiated towards the free edge and to other direction (semi-random phenomena). As the load is increased in specimen GM-L-6, the cracking migrates to the opposite face. At the same time, the cracks increase in number at around and near the region of column. At higher loads, with increasing the shear reinforcement ratio, in both specimens GM-L-8 and GM-L-10, the existing fractures were expanded as the new cracks begin to develop. The newly created cracks have a mostly round or elliptical shape and are located on the tension surface of the slab, after severe loading



 $\textbf{\textit{Figure 5} Cracks and failure pattern of group one specimens}$

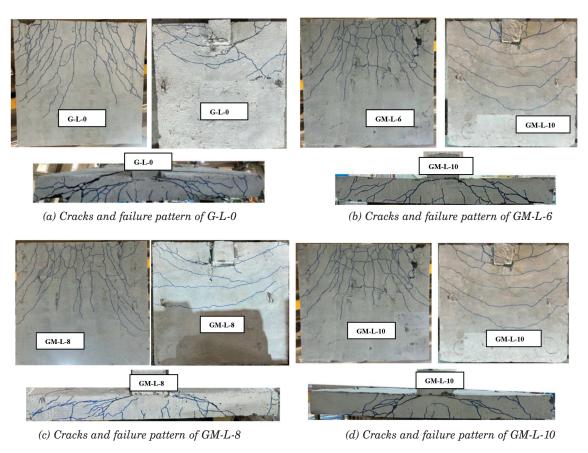


Figure 6 Cracks and failure pattern of group two specimens

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Table 8 Experimental	outcomes o	of tooted alaba	Croun 1 C	1 and Crown 9	(2)
Table & Experimental	outcomes o	ot testea stabs ($(\tau roup \ 1 - (\tau$	i ana Group 2 -	(τZ)

No.	Slab Coding	$P_{u}(kN)$	Δu (mm)	$P_{cr}(kN)$	$\Delta_{\rm cr}$ (mm)	(P _u) % of (G1 with G2)	(Δu) % of (G1 with G2)
G1	S-L-0	71	23.8	35	7.2	14.1	-
	SM-L-6	97	20.4	48.7	8.16	16.5	-
	SM-L-8	110	18.3	62	7.51	17.7	-
	SM-L-10	115	16.7	64.4	6.68	15	-
G2	G-L-0	61	29.3	23	9.96	-	19
	GM-L-6	81	26.9	38	9.55	-	24
	GM-L-8	90.5	25.7	43.2	9.21	-	29
	GM-L-10	97.8	24.2	47.5	8.9		31

and developed to take almost two way shear action. The slab failed when the cone of failure, originating from where the load was applied, penetrated the slab body, resulting in a brittle fracture with little warning. Upon the breakdown, the slab became incapable of bearing any more stress. Type of failure for both specimens GM-L-8 and GM-L-10 were punching shear and flexural failure; the failure shape of group two is presented in Figure 6 (a, b, c and d).

Comparative analysis of specimens occurs between prototypes in the first group that are similar to those in the second group. It is noted that the Specimens SM-L-6 and GM-L-6 are failed in the same way (punching shear failure), but the specimen GM-L-6 has shown an increase in the number of crack lines with an increase in width and depth when compared to the SM-L-6 specimen. With the increase in the percentage of shear reinforcement to 0.213%, was noticed that the failure line moves further away from the face of the column and spreads in different directions, in both the SM-L-8 and GM-L-8 models, and especially in the GM-L-8 model. As for the SM-L-10 and GM-L-10 specimens, in which the percentage of shear reinforcement was increased to 0.39%, this increase led to the failure mode changes from pure punching shear to combined punching shear and flexural failure.

3.2 Load versus mid-free edge deflection relationship of slabs specimen

A load cell was employed to measure the ultimate and cracking stresses, whereas an LVDT was utilized to ascertain the deflections at ultimate and cracking. The LVDT were positioned at three distinct positions relative to the free edge of the bottom face of the slabs. The initial coordinate lies in the midpoint of the edge, whereas the remaining two coordinates are spaced 250 mm separate and face the opposite direction. Through the results shown in the Table 8, in group one, the decrease in load deflection of specimen S-L-0 indicated its failure in punching. All the other reinforced specimens with vertical reinforcement (multiple-leg stirrups) evidently

increased the strength and the deformation capacity of the slab, depending on the shear reinforcement system and (ρ v), as illustrated in Figure 7. Even a small amount of (ρ v) increase the strength and deformation capacity of the lightweight concrete slab. At the same load level 50 kN, the deflection of slab SM-L-6 showed decreases by 14.3% as compared with S-L-0, Although the reduction in the deflection of the slabs was (23.1% and 30%) for SM-L-8 and SM-L-10, respectively, as compared to reference specimen. The overall performance and the maximum deflection of all the slabs improved significantly when the shear reinforcing ratio was increased. Specimens SM-L-6, SM-L-8 and SM-L-10 that were reinforced with multiple-leg stirrups behave in a more ductile manner and reaches a slightly higher strength than the specimen S-L-0. On the other hand, the increase in the amount of shear reinforcement ratio from(0.1% to 0.213% in specimen SM-L-8 caused an increase in ultimate load by about 35.5% and increasing the shear reinforcement ratio from 0.213% to 0.39% in specimen SM-L-10 caused increasing in ultimate load by about 38.3% comparative to the reference specimen. The results indicated that the use of multiple leg stirrups, as a punching shear reinforcement in the steel reinforcement slabs, eventually converted the failure mode from clear punching shear failure to flexure-punching shear interaction failure, as shown in specimens SM-L-8 and SM-L-10. Regarding the second group, From Figure 8, it is clear that using of vertical reinforcement (multiple leg stirrups) has a positive effect evidently enhancing the punching shear strength about 25% and the deformation capacity of the slab by reduced deflection about 8.1% when using shear reinforcement ratio $\rho v = 0.1\%$ for specimen GM-L-6 comparative to the control specimen G-L-0 at the same load level 50 kN. The decrease in slabs deflection was 12.3 and 17.5% for GM-L-8 and GM-L-10, respectively, with shear reinforcement ratios ρ v = 0.213 and 0.39% with improving the ultimate load to 33 and 38%, respectively. Comparative analysis of both groups (one and two) shows that the multi-leg shear reinforcement in different ratios behaves more ductile and reaches a slightly higher strength than the specimens without

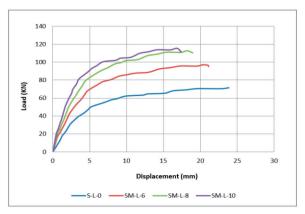


Figure 7 Load-deflection profile of Group 1

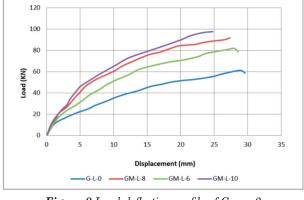


Figure 8 Load-deflection profile of Group 2

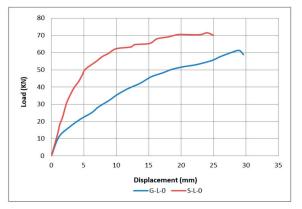


Figure 9 Load-deflection for S-L-0 and G-L-0

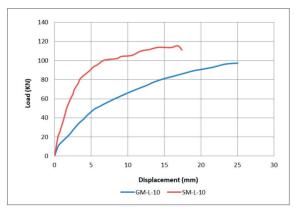
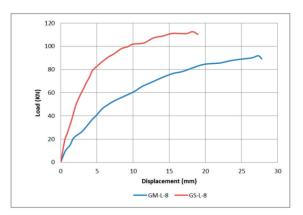


Figure 10 Load-deflection for SM-L-6 and GM-L-6



 $\textbf{\textit{Figure 11} Load-deflection for SM-L-8} \ and \ \textit{GM-L-8}$

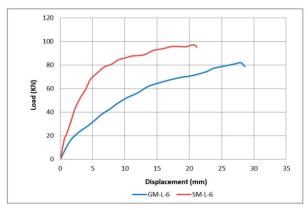


Figure 12 Load-deflection for SM-L-10 and GM-L-10

stirrups. Specimen SM-L-6 gave higher loading failure 97 kN than specimen GM-L-6, but the ultimate deflection of the specimen SM-L-6 was lower than for the specimen GM-L-6. That is attributed to the fact that the modulus of elasticity of GFPR bars is higher than that of the steel bars. Increasing the shear reinforcement to 0.213% in both specimens SM-L-8 and GM-L-8) causing increasing ultimate load by 16.5% for the specimen (SM-L-8) compared to the specimen GM-L-8 that produced increasing in the ultimate deflection about 29%. In the same way, improving the ultimate loading of the specimen SM-L-10 by 15% compared to the specimen GM-L-1) that appears to have a high ultimate deflection

of 31%. All the load-deflection comparisons between groups one and two are illustrated in Figures 9 to 12.

3.3 Flexural stiffness of slabs

Denoted as deflection slope of the load or bending rigidity, it implies the capacity in which a component withstands bending deformation. Moment of inertia, elastic modulus E, effective length of the member, and boundary conditions, all exert an influence on it. The value of the secant stiffness was determined using Equations (1) and (2) [23]. Table 9 displays the

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Group No.	Slab Coding	Pu (kN)	Δu (mm)	Ku (kN/mm)	Pcr (kN)	Δcr (mm)	Kcr (kN/mm)
~-	S-L-0	71	23.8	2.98	35	7.2	4.86
	SM-L-6	97	20.4	4.75	48.7	8.16	5.97
G1	SM-L-8	110	18.3	6.02	62	7.51	8.26
	SM-L-10	115	16.7	6.90	64.4	6.68	9.64
	G-L-0	61	29.3	2.10	23	9.96	2.31
G2	GM-L-6	81	26.9	3.03	38	9.55	4
	GM-L-8	90.5	25.7	3.52	43.2	9.21	4.69
	GM-L-10	97.8	24.2	4.04	47.5	8.9	5.34

Table 9 Cracking and ultimate stiffness for slabs under static loading (Group 1 - G1 and Group 2 - G2)

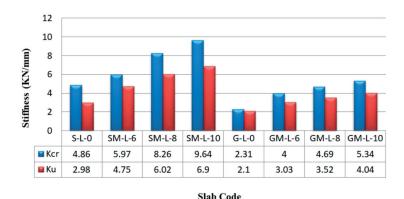


Figure 13 Cracking and ultimate stiffness for slabs (Group 1 - G1 and Group 2 - G2)

estimated secant stiffness (K) throughout the fracture and ultimate phases. The load deflection curves were observed to consist of two lines exhibiting distinct inclinations. The behavior of the subsequent line is less inclined than that of the initial line. The initial line represents the stiffness of the uncracked ($K_{\rm cr}$) section, whereas the second line depicts the stiffness of the fractured ($K_{\rm u}$) segment. Additionally, it was observed that the quantity of fractures on the tension face of the specimens increased in line with the load deflection. The observed expansion in both the depth and breadth of the cracks can be attributed to the development of cracks that endured within the reinforced concrete until its ultimate failure.

$$K_{cr} = \frac{P_{cr}}{\Delta_{cr}},\tag{1}$$

$$K_u = \frac{P_u}{\Delta_u}.$$
 (2)

Overall, the stiffness exhibited a gradual reduction with the application of load, resulting in all values of (K_u) being less than (K_{cr}) . The occurrence of cracks, inadequate adhesion between the concrete and steel bars, and the amplification of crack number, breadth, and length due to applied stress may be assigned to the factors shown in the bar chart in Figure 13. When using the multi-leg shear reinforcement in group 1, due to the main function of the multi-leg shear reinforcement, the tensile strength increases and manages the cracks

propagation leading to reduce concrete failure and increasing cracking resistance of the specimens SM-L-6, SM-L-8 and SM-L-10 comparative to the control specimen S-L-0. The specimen SM-L-10 is superior, as it exhibits the highest cracking and ultimate stiffness levels, reading 9.64 and 6.9, respectively. In group 2, using the GFRP flexural reinforcement rods resulted in a drop in the initial stiffness (K_) of all the specimens. This may be ascribed to the relatively lower modulus of the GFRP rods than of the conventional steel. Regardless of whether or not the shear reinforcement was included, the initial uncracked rigidity of all the specimens was identical. The increase in the amount of shear reinforcement ratio, particularly for the multiple leg stirrups, system from (0.213% to 0.39%) in specimens GS-L-10, exhibited the better one, which has the largest cracking and ultimate stiffness, 5.34 and 4.04, respectively, increasing the ultimate load by about 37.6% Moreover, satisfy a positive effect in enhancing the punching shear strength and reduced deflection by about 17.5% compared to the control specimen G-L-0.

4 Finite element modelling

4.1 Model description and geometry

Nonlinear finite element models (FEM) for the edge column-slab connections reinforced with steel and GFRP as a flexural and steel shear reinforcement are

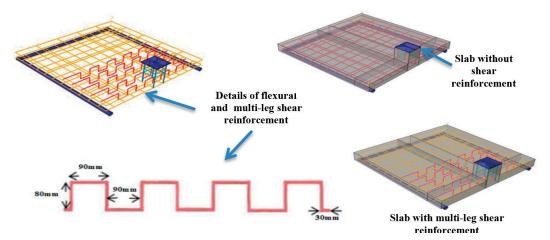


Figure 14 Geometry and details of slabs reinforcement

Table 10 Mechanical properties of reinforcement (steel and GFRP)

Material	f _{sy} (MPa)	f _{su} (MPa)	E (GPa)	f _{lu} (MPa)	€ _u (%)
Steel (\phi6)				-	-
Steel ($\phi 8$)	420	580	200	-	-
Steel ($\phi 10$)				-	-
GFRP ($\phi 10$)	-	-	48	769	25

 f_{sy} and f_{su} : yield and ultimate tensile strength of steel, E, f_{lu} , and ϵ_{u} : modulus of elasticity, tensile strength, and ultimate tensile strain of GFRP, respectively.

developed using [24] and done just for four specimens S-L-0, SM-L-8, G-L-0 and GM-L-8, then validated with experimental work. The geometry of the slabs and the positioning and dimensions of steel and GFRP bars are adopted from the experimental program [16], shown in Figure 14. The flexural reinforcement (steel and GFRP) with a diameter of 10 mm was applied in the tension side of the slab with a reinforcement ratio of 0.93%, whereas a minimum reinforcement ratio of 10 mm-diameter steel was applied to the compression side (as a shrinkage and temperature reinforcement) in addition to different ratios (0.1, 0.213 and 0.39%) as transverse steel bars (shear reinforcement). The concrete slab, steel supports and loading plates were modelled using 3-D-8 node solid hexahedron-shaped brick elements (C3D8R) with a maximum element mesh size of 25 mm. The element size is chosen according to a mesh sensitivity analysis conducted on the model to eliminate any mesh dependency that can affect the results. Steel bars (flexural and transverse) were modelled using the 3-D 2-node truss elements (T3D2), which are only able to carry axial force, with the same element size used for concrete. The GFRP bars were modeled in ABAQUS under the assumption of isotropic linear elastic behavior, without using any damage criteria. It is important to note that the GFRP bars are linearly elastic up to the failure. It is modeled using "Truss" T3D2 elements in all the slab models with a fine mesh of 25 mm [25]. A perfect bond is assumed between the reinforcing steel bars and concrete by defining the concrete slab as a host element and the steel bars as embedded elements. Similarly, a perfect bond is assumed between the concrete and the GFRP. The boundary conditions and loading scenario are modelled to mimic those of the experimental program. The slabs was modelled as being simply supported along three edges to account for the displacement boundary condition and the nodes at the bottom face of the slab were restrained against movement in the y-direction on all the sides, based on the coordinates, but only in the (x and z) directions on two sides. The concentration load was applied to slabs by dividing the total applied load by the column's cross-sectional area (150 x 150 mm²). For the analysis process, linear shape function is used and reduced integration is specified so that one integration per element is conducted [26].

4.2 Material properties and modelling

The main mechanical material properties for concrete and steel bars are adopted with reference to [2], while the mechanical properties for GFRP are adopted from [27]. Table 10 represents the mechanical properties of all types of steel and GFRP bars. The nonlinear behavior of concrete was considered using the concrete-damaged plasticity (CDP) model in the software ABAQUS. The CDP model depicts the mechanisms of crushing and cracking failure that occur in concrete and this study adopted the Saenz stress-strain compression model for concrete. In this study, there are five main parameters of CDP model: eccentricity (ϵ), dilation angle (ψ), the ratio between the biaxial compressive

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stress and uniaxial compression stress of concrete $(f_{\text{bo}}/\ f_{\text{co}}),$ (Kc) which is used for determining the yield surface of the concrete plasticity model, and the visco-plastic regularization parameter with values are 0.1, 36, 1.16, 0.667 and 0, respectively, and the compression strength with density is the same as of experimental cases. Longitudinal, transverse steel bars and loading caps are modeled as elastic-perfect plastic.

5 Test results and finite element validation

5.1 Ultimate load capacity and mid-edge span deflection

The differences between the experimental and FE results involving ultimate loads and ultimate deflection are convergent for four specimens. As shown in Table 11, the selected models for comparison result in accurate values with a 10% variation under static loading. Figures 15 to 18 show a comparison between the load-deflection from the experimental and FE models for validation slabs. Furthermore, the FE models were utilized to create the deflection contours (deflected shape) depicted in Figures 19 to 22 for the same slabs in analysis. Upon comparing the experimental and numerical outcomes, it is obvious a good agreement was found between the numerical FE model and experimental load-deformation curves for most tested slabs. At the linear stage, the FE load-deflection curves exhibit slightly more stiffness than the experimental responses observed for slab specimens. Multiple possible reasons for the increased stiffness observed in FE models exist. Firstly, the stiffness of the actual specimens would be somewhat decreased by microcracks formed through drying shrinkage and handling; in contrast, the FE models do not have microcracks. The failure loads produced by computer analyses are approximately (2-10%) higher than those determined from the experimental results. It is important to note that the failure in experimental work indicates the failure of the whole structure, while the failure in the finite element analysis indicates the failure of one element in the structure. Therefore, it is consistently observed that the experimental results exhibit greater deflections than the finite element results.

5.2 Crack patterns development

An examination of the concrete cracking patterns obtained from FE analysis results and those captured in the experimental test is illustrated in Figures 23 to 26. At failure, the cracking pattern on the tensile side of the slab propagates within the slab adjacent to the column. The first cracks appeared on the lower surface during the initial stage of the test, beginning in the region beneath the loading area. Radial cracks appeared at the corners of the column in response to an increase in load, and those cracks stayed stable for 75% of the ultimate load. Beyond that limit, the circumferential fractures developed due to the concentration of under the loading areas. The cracks tended to spread towards the periphery as the load grew. Subsequently, the cracks had significant diagonal, radial, and corner expansion, forming additional cracks on the lower surface until the failure shape was fully realized (forming the

Table 11 Experimental and theoretical results for slab specimens under static loading

Clab Cadima -	Exp. Re	sults	Theor. Resi	ılts	Pu Exp./	$\Delta u \text{ Exp./}$
Slab Coding	Pu (KN)	$\Delta u \text{ (mm)}$	Pu (KN)	$\Delta u \text{ (mm)}$	Pu Theor.	Δu Theor.
S-L-0	71	23.8	75.2	21.3	0.94	1.098
SM-L-8	110	18.3	117.4	16.7	0.93	1.095
G-L-0	61	29.3	64.3	27.6	0.95	1.062
GM-L-8	90.5	25.7	92.9	23.8	0.97	1.08

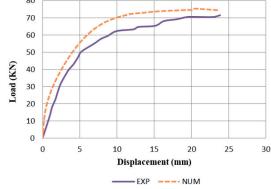


Figure 15 Load-mid edge span deflection of S-L-0

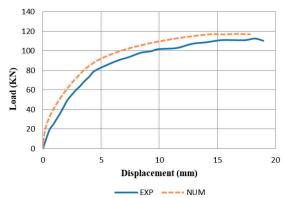


Figure 16 Load-mid edge span deflection of SM-L-8

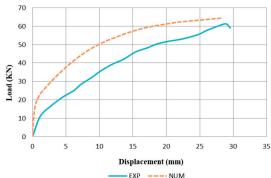


Figure 17 Load-mid edge span deflection of G-L-0

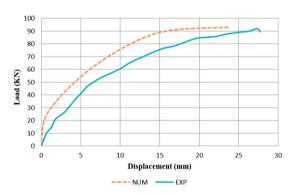


Figure 18 Load-mid edge span deflection of GM-L-8

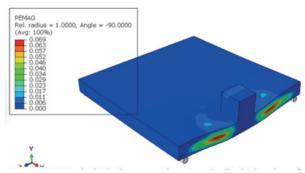


Figure 19 Vertical displacement along longitudinal direction S-L-0

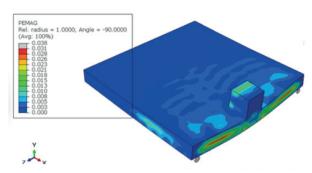


Figure 20 Vertical displacement along longitudinal direction SM-L-8

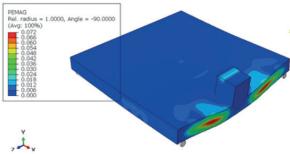


Figure 21 Vertical displacement along longitudinal direction G-L-0

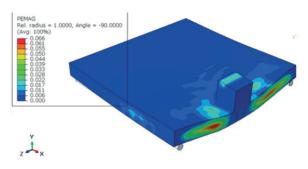
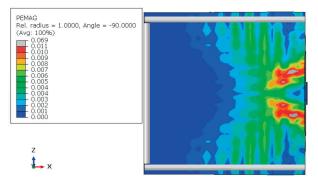
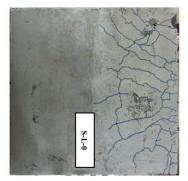


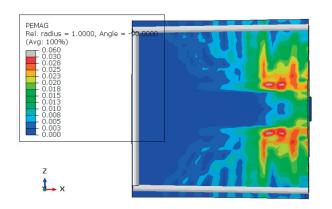
Figure 22 Vertical displacement along longitudinal direction GM-L-8





 $\textbf{\textit{Figure 23} Cracking pattern on tension surface at ultimate load for slab S-L-0}$

classical punching critical zone with a truncated cone failure shape). Assumed by the damaged plasticity model for concrete, cracking starts at the beginning of positive maximum principal plastic strain. Assuming that the orientation of the cracks is perpendicular to the maximum principal plastic strains, the maximum principal plastic strains function illustrate the direction of the cracks. D106 SAEED, HARBA



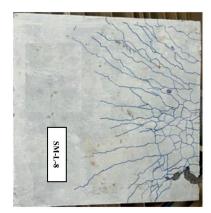
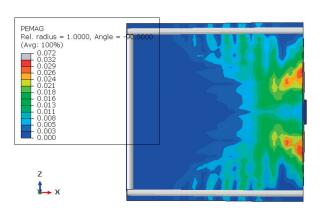


Figure 24 Cracking pattern on tension surface at ultimate load for slab SM-L-8



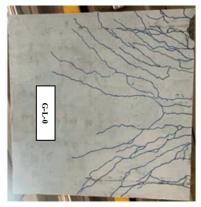
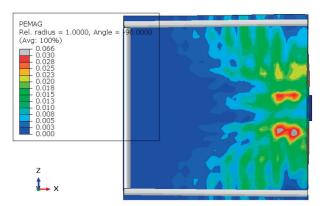


Figure 25 Cracking pattern on tension surface at ultimate load for slab G-L-0



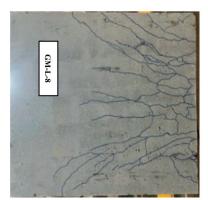


Figure 26 Cracking pattern on tension surface at ultimate load for slab GM-L-8

6 Conclusions

- Lightweight aggregate concrete was produced with LECA aggregate, as it reached a compressive strength of 35.5 MPa, and unit weight of 1824 kg/m³ at the age of 28 days.
- The increase of shear reinforcement ratio causing increase the capacity of element to resist to initiated the first cracks. The increasing of resistance to appears the first cracking in group one was 28.1%, 43.5%, and 45.7% for SM-L-6, SM-L-8, and SM-L-10, respectively, compared to the control specimen S-L-0.
- In group two, with the increase in the percentage of shear reinforcement to 0.213%, it is noticed in both the SM-L-8 and GM-L-8 models that the failure line moves further away from the face of the column and spreads in different directions, especially in the (GM-L-8) model.
- The failure mode of specimens SM-L8 and SM-L-10 with shear reinforcement ratio (ρ v) equal to 0.213 and 0.39%, respectively, were under flexural and punching shear failure. In contrast, other specimens of group one failed under pure punching shear.
- When comparing between groups, it is noted that the

- Specimens SM-L-6 and GM-L-6 failed in the same way (punching shear failure), but the specimen GM-L-6 showed an increase in the number of crack lines with an increase in width and depth when compared to the SM-L-6 specimen.
- It is clear that using the vertical reinforcement (multiple leg stirrups) has a positive effect, enhancing the punching shear strength by about 25% and the deformation capacity of the slab by a reduced deflection by about 8.1% when using shear reinforcement ratio ρ v = 0.1%)for the specimen GM-L-6 comparative with control specimen G-L-0 at the same load level 50 kN. The decrease in slab deflection was 12.3 and 17.5% for GM-L-8 and GM-L-10 with shear reinforcement ratios ρ v = 0.213 and 0.39%, improving the ultimate load to(33 and 38%, respectively.
- Specimen SM-L-6 gave higher loading failure of 97 kN) than the specimen GM-L-6, but the ultimate deflection of the specimen SM-L-6 was lower than that of the specimen GM-L-6. That is attributed to the fact that the modulus of elasticity of GFPR bars is smaller than that of the steel bars.
- During both the cracking and ultimate load phases, slabs reinforced with steel flexural demonstrated an increase in secant rigidity in the specimens SM-L-6, SM-L-8, and SM-L-10, compared to the control specimen S-L-0, which showed a reduction in the flexural rigidity fasting through high deflection as a result of the absence of shear reinforcement leading to decreasing (K_{cr} and K_u).
- GFRP flexural reinforcement rods resulted in a drop in all the specimens' initial stiffness K_{cr} . This may

- be ascribed to the relatively lower modulus of GFRP rods than of the conventional steel.
- The increase in shear reinforcement ratios led to decreased conical failure shape failure angles.
- In both groups, in slabs with punching shear reinforcement, the area and perimeter of the failure area is more significant than in the slabs without reinforcement.
- Specimens GM-L-10 and SM-L-10 had the highest energy absorption of 1356.7 and 1345.2 kN.mm, respectively, compared to other specimens.
- Deformability and ductility increase with the shear reinforcement ratio; the maximum value is for specimens GM-L-10 and SM-L-10.
- Upon comparing the experimental and numerical outcomes, a good agreement was found between the numerical FE model and experimental loaddeformation curves for most tested slabs. The difference was not more than 10%.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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ORIGINAL RESEARCH ARTICLE Civil Engineering in Transport D109



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INVESTIGATING THE CHARACTERISTICS OF MODIFIED BITUMEN WITH POLYPHOSPHORIC ACID POLYMERS AND RECYCLED RUBBER

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Resume

The impact of polyphosphoric acid (PPA) polymers and crumb rubber (CR) on bitumen's properties to enhance its performance was examined in this study. Laboratory samples were created with varying percentages of PPA (0.5% to 2%) and CR (6% to 18%) and subjected to extensive testing. Findings indicated that the combination of PPA and CR led to notable improvements in bitumen performance, including increased viscosity, softening point, elasticity, and recovery rates at elevated temperatures. Specifically, samples with 18% CR and 1.0% or 2.0% PPA demonstrated exceptional rheological properties and strength. The optimal combination (18% CR and 1.0% PPA) resulted in a uniform structure, while the maximum CR content did not compromise bitumen integrity. Both additives effectively minimized temperature sensitivity and aging, enhancing the bitumen's performance class significantly.

Article info

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1 Introduction

Bitumen, a solid waterproof and thermoplastic adhesive, serves as a crucial component in bonding aggregates together. The incorporation of additives, particularly polymers, stands out as an effective strategy to enhance the performance of asphalt pavement [1]. Over the course of history, numerous research endeavors have been devoted to the bitumen additives and the enhancement of bitumen properties [2-3]. For instance, Padhan and Gupta conducted a study on bitumen modified with Polyethylene Terephthalate (PET), derived polyurethane polymer, employing a battery of standard bitumen tests and Superpave bitumen tests to assess its impact [4]. The inclusion of this additive yielded significant improvements in the performance and properties of bitumen. A study analyzed the post-hardening changes in epoxymodified bitumen, finding that aging levels correlate with epoxy modification and sulfoxide compounds indicate oxidative hardening [5]. Moreover, the findings underscored that epoxy augmentation bolstered the resistance of bitumen against aging. Furthermore, in 2019, researchers explored the rheological and microstructural characteristics of carbon nanomaterials-modified bitumen [6]. Their investigations revealed that Carbon Nanotube (CNT (and Graphene(Gr)-modified bitumen outperformed unmodified bitumen in terms of rheological and microstructural properties, with the optimal blend identified as modified bitumen containing 1.5% CNT and 1% Gr.

Lin et al. highlighted the challenge posed by the increasing production of Waste Express Bags (WEB) in the context of population growth and the logistics industry [7]. Their study aimed to explore the potential of using WEBs to enhance bitumen properties. Through a series of tests on varying doses of WEB-modified bitumen, they observed significant improvements in key bitumen characteristics such as penetration, ductility, softening point, and rotational viscosity. Building on this, asphalt experts delved into emulsion bitumen modification using nanocomposites, noting changes in penetration and softening point alongside enhanced rheological behavior [8-9]. Subsequent research in 2020 investigated the impact of natural rubber (NR) on bitumen performance, revealing enhancements in rutting, fatigue resistance,

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thermal cracking, and moisture sensitivity. Further studies in the same year examined the use of Nano-silica composite and Waste Denim Fibers (WDF) to enhance bitumen rutting performance, leading to improved performance grades [10]. In one study, the PPA value obtained from ATR-FTIR may serve as an indicator for the modification of PPA/CR. The mechanism of PPA/CR modification is elucidated. Additionally, the rheological properties and storage stability of asphalt are influenced by the composition of Asphalt. Moreover, the addition of PPA enhances the stability of the CR-modified asphalt during the thermal storage process. The rheological properties of the CR-modified asphalt are improved through the incorporation of PPA [11]. Another study investigates the impact of poly phosphoric acid (PPA) on the rheological properties of styrene butadiene styrene (SBS) and crumb rubber (CR) modified asphalt binders at elevated temperatures, with varying PPA concentrations and comparison to a reference binder with 5% SBS. Various laboratory tests were conducted to evaluate the asphalt binders' rheological behavior, indicating that the addition of PPA improved resistance to permanent deformation and elastic recovery, with the most significant effects observed in PPA-SBS mixtures followed by PPA-CR mixtures, showcasing enhanced anti-aging characteristics and loading resistance in CR-modified asphalt binders, particularly at a minimum PPA content of 0.8% [12]. Moreover, the utilization of polymers, particularly polypropylene, was noted to enhance the thermal-mechanical performance of bitumen [13]. Notably, the study on waste polystyrene (PS) as a bitumen modifier demonstrated compliance with regulations and superior performance compared to conventional binders, offering a sustainable solution to the environmental challenges posed by the PS production. Experts in the asphalt industry also point out that improving the self-healing properties of bituminous mixtures to increases the life of pavement, and road safety, and they investigated the effect of bitumen modification with different percentages of polyurethane polymer toluene diisocyanate (TDI-Co) on the self-healing properties of asphalt, and found that the use of polyurethane polymer increases the selfhealing performance of bitumen [14]. In another study in 2022, palm oil clinker (POC) was studied as an additive to asphalt, and it was found that it substantially improves the properties of bitumen, including reducing penetration, and increasing the softening point [15]. In another study, the intermolecular behaviors of PPA/SBR modified asphalt were investigated through molecular dynamics (MD) simulation. The high temperature performance of SBR modified asphalt was found to improve with the addition of PPA. The incorporation of PPA was observed to hinder the diffusion and mobility of SBR asphalt molecules, ultimately enhancing the stability and orderliness of the molecular structure. Those findings highlight the potential benefits of using PPA in SBR modified asphalt for improved performance [16]. The researchers discussed the possibility of mixing the polymer, and hydrocarbon molecules with fossil origin as well as industrial polymerization, but did not mention the functional difference between these materials [17-18].

Several research studies have been undertaken to examine the impact of incorporating CR and PPA on the characteristics of bitumen. Nevertheless, only a limited number of these studies have specifically explored the consequences of simultaneously introducing PPA and waste CR into bitumen [19-20]. Behavioral changes due to adding numerous additives usually occur within the range of linear viscoelastic performance. However, it is necessary to investigate the behavior at higher temperatures, higher stresses and higher loading rates. Although there are many articles on the use of recycled rubber powder, and much research has been done, this study intends to study the simultaneous use of rubber powder, and polyphosphoric acid polymer. Therefore, the main purpose of this study is to investigate the effect of PPA, and waste rubber powder on properties and performance of bitumen. For this purpose, samples of bitumen with different percentages of PPA, and CR were prepared in the laboratory, and subjected to various tests.

2 Research method and experiments

In this study, the focus was on examining the impact of PPA and CR on the characteristics and behavior of bitumen. Through the addition of these materials in varying proportions as additives to bitumen, the modified bitumen underwent testing, based on the performance grade (PG) and Sharp supplementary grade (PG+). Statistical analyses were employed to scrutinize the results and determine the influence of different parameters on the performance of the asphalt mixture. The materials used in the research included PG 58-22 bitumen, CR with specific grading, and polyphosphoric acid polymer at varying concentrations. Tables 1, 2 and 3 present some of their specifications. The selection of bitumen with high penetration was based on the modification of lower-quality bitumen, with additives chosen based on prior research and experiences. Notably, the addition of CR ranged from 6% to 24%, with concentrations exceeding 20% leading to mixing challenges and the formation of agglomerates. The study excluded the 24% concentration and focused on 6%, 12%, and 18% levels. The CR percentage, or crumb rubber percentage, represents the ratio of rubber crumb weight to the weight of bitumen, excluding any additional additives. Figure 1 illustrates the gradation graph depicting the CR particle distribution, while Figure 2 provides a visual representation of the materials involved in the preparation process, including waste rubber powder, polyphosphoric acid polymer, and the mixing apparatus.

Table 1 Physical characteristics of bitumen used in this research

Bitumen tests	Measurement unit	Test Results	Standards ASTM
Specific gravity	-	1.0179	D75
Needle penetration	0.1 mm	90	D5
Softening point	$^{\circ}\mathrm{C}$	45.8	D36
$\label{eq:High-temperature} \mbox{High-temperature viscosity of bitumen with rotary viscometer} \\ (RV)$	Pa.s -135 °C	0.245	D4402
Flash point	° C	322	D92
Solubility in trichloroethylene	%	99.7	D2042

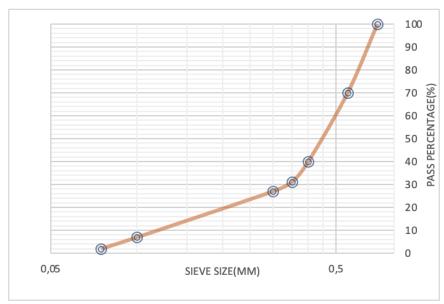


Figure 1 Gradation graph representing the CR particle distribution

Table 2 Physical characteristics of CR used in this research

Specifications	Unit	Result
Humidity	Percent	0.15
Weight density	Astm D7263 (g/cm ³)	0.33
Contaminants	Percent	0.07
Abrasion resistance	ASTM D1630-06	Appropriate level, below 20%
Compression capability	ASTM D395-14	Excellent

The use of PPA as an additive to enhance bitumen properties has shown promise in recent investigations, with its reactive nature playing a significant role in improving the physical and rheological properties of bitumen. Understanding the structure of this compound and its impact on asphalt mixtures can provide valuable insights into enhancing bitumen properties through the utilization of PPA.

In the process of preparing a specimen containing waste rubber powder, a meticulous approach was followed to ensure optimal blending. The bitumen was heated to 150 °C, and CR was added at 2500 rpm. Subsequently, the temperature was raised to 180 °C, and a thorough mixing operation was carried out for 120 minutes at 3500 rpm. Specific temperature ranges and mixing durations were adhered to for specimens containing PPA to ensure

proper blending. For specimens incorporating both PPA and CR, a detailed procedure involving sequential heating, material addition, and controlled mixing was meticulously executed. Following the preparation of bitumen specimens, experiments were conducted to evaluate properties such as PG and Sharp plus grades (PG⁺), essential for determining the suitability of the bitumen for various applications [20].

The impact of heat and air on a thin moving layer of bitumen is assessed using the Rolling Thin Film Oven (RTFO) test method, which investigates approximate changes in bitumen properties, including rheological properties, at around 150°C, by conducting tests at 150°C, our goal is to simulate real-world conditions to uncover valuable information about the behavior of bitumen in various scenarios. Bitumen remaining

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from this test retains similar properties to the bitumen used in hot asphalt mixtures after mixing and can also determine mass changes in bitumen. This test is conducted following the ASTM D2872 standard. The pressurized aging tank (PAV) accelerates the aging of bitumen by exposing them to pressurized air and high temperatures to simulate the changes in bitumen rheology that occur during pavement service, as per ASTM D6521. The ASTM D6521 standard outlines the standard PAV test, with temperatures ranging from 90 to 110 °C (depending on climatic conditions), lasting 20 hours under an air pressure of 2.1 MPa. For this research, the selected temperature was 100 °C, with the test performed once. This choice reflects the conditions typical of a hot climate, specifically at 110 °C, which may influence the material properties under investigation.

The determination of flexural creep stiffness of bitumen is done using the Bending Beam Rheometer (BBR) device that operates in a temperature range between 0 and -36°C [21]. Creep hardness (S) in this test reflects the stress-strain behavior of bitumen at low temperatures, with the rate of creep changes (m-value) serving as criteria for measuring bitumen performance at low temperatures. This test is carried out following the ASTM D6648 standard. The Dynamic Shear Rheometer (DSR) test method is employed for bitumen with a dynamic shear modulus range between 100 Pa and 10 MPa [22]. The tests were conducted

using a Dynamic Shear Rheometer (DSR) equipped with a 25 mm plate and a 1 mm gap. Each testing cycle consists of 1 second of loading followed by 9 seconds of rest, with 10 cycles performed at a stress of 0.1 kilopascal, immediately followed by another 10 cycles at a stress level of 2.3 kPa. The total time required to complete all the loading cycles is approximately 300 seconds. The DSR must be capable of recording stress data every 0.1 seconds and should also be able to capture recovery data at least every 0.45 seconds. This testing method is thoroughly described in the ASTM D7405 standard [23]. Typically, an oscillation frequency of 10 radians per second (10 rads per second or 1.59 Hz), which is equivalent to the motion of a vehicle traveling at a speed of 90 km/h, was followed in this study.

The Linear Amplitude Sweep (LAS) test serves a critical function in evaluating the viscoelastic properties of bitumen, particularly in relation to its performance under varying temperature conditions. By measuring the hardness values at specified initial temperatures, this test provides insights into the material's hardness and brittleness at intermediate temperatures, both of which are pivotal in assessing the likelihood of fatigue cracking in bituminous samples. The increased brittleness observed at these temperatures can significantly elevate the risk of fatigue damage, thereby impacting the longevity and structural integrity of asphalt pavements. For standardization in LAS testing,

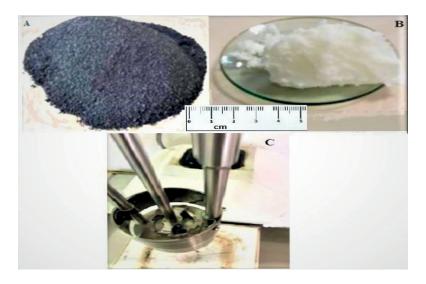


Figure 2 A) waste rubber powder, B) polyphosphoric acid polymer and C) preparing specimen with a mixer (Silverson L5M-A Laboratory Mixer)

Table 3 Characteristics of PPA used in this study

Product Name	Polyphosphoric acid polymer
Acronym	PPA
Chemical formula	HO[P(OH)(O)O](n)H
Boiling point	530 °C
Melting point	-20 °C
Density (at 20 °C)	$2.03~\mathrm{g/cm^3}$

the relevant international standard is AASHTO TP101, which delineates the methodologies and requirements necessary for consistent and reliable test results.

3 Results and discussion

3.1 Characteristics of bitumen rheology by shear rheometer

Performance degree of bitumen at high temperature

To determine the degree of performance at high bitumen temperature, the rheology properties of bitumen are evaluated by DSR, and the parameter $G^*/\sin\delta$ is a measure of bitumen behavior at high temperature. According to the Superpave guideline (ASTM D6373), this parameter should be greater than 1.0 kPa for virgin, and non-aged bitumen, and greater than 2.2 kPa for aged bitumen after the short-term aging process (RTFO) as shown in Figure 3. In other words, in Figure 3, the column on the left is virgin bitumen and the right column is for aged bitumen.

One aspect to contemplate is the impact of the aging progression on the specimens. The initial phase Base bitumen specimens, and in subsequent phase, specimens altered by discarded CR have marginally reduced efficacy post RTFO; nevertheless, specimens encompassing PPA even displayed enhanced efficacy in certain instances. The addition of PPA to rubber bitumen also improved the performance of the samples after RTFO, and arguably PPA reduces the adverse effects of the aging process.

High temperature creep test

The temperature creep test was used to measure the two parameters G^* , and δ , to simulate the conditions of temperature changes, and was performed on non-aging,

and short-term aging (RTFO) samples. All samples showed a decrease in G*, and an increase in at high temperatures. Bitumen exhibits viscous behavior at high temperatures, and its resistance to deformation is significantly reduced, which is a principle accepted by all researchers. However, additives have reduced bitumen yield at different levels, although this varies from sample to sample (Figure 4).

In addition, all samples showed better performance after aging, which shows that both additives applied in this study have reduced the sensitivity of bitumen to aging. Comparison of G^* values in samples containing only one of the two additives, Figure 4, showed that PPA was more capable of increasing the strength of bitumen, and the higher the result of this additive, the higher the G^* value. The best performance is related to bitumen containing 2.0% PPA after aging. Additionally, samples containing 1.5%, and 1.0% PPA showed higher resistance than samples modified with rubber powder.

Comparing the phase angle values (δ) of these samples, Figure 5, shows that CR has been more successful in increasing the elasticity of bitumen, and bitumen containing 18% CR has significantly improved the elasticity. Another interesting point that emerges from this comparison is the trend of phase angle changes in bitumen containing 12, and 18% CR; as the temperature rises, the values of δ first increase slightly, and then begin a decreasing trend. Actually, when the base bitumen loses its elasticity with increasing temperature, the particles of CR in the sample help to restore the elasticity of the bitumen, and to some extent preserve the bitumen performance, and structure.

Comparison of G^* values for samples containing two additives, Figure 6, showed that the combination of 1.5% PPA with 6%, and 12% CR showed higher G^* values at initial temperatures. However, with increasing temperature (around 50 °C), these values drop sharply,

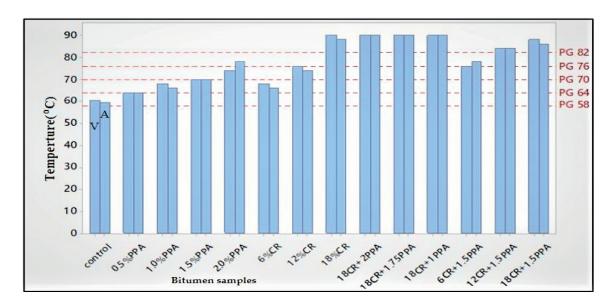


Figure 3 Performance of high-temperature modified bitumen samples, the left column for virgin bitumen(V) and the right for aged bitumen(A)

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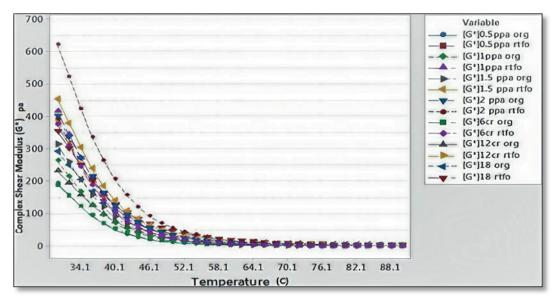


Figure 4 Complex shear modulus (G*) values for the first-stage samples

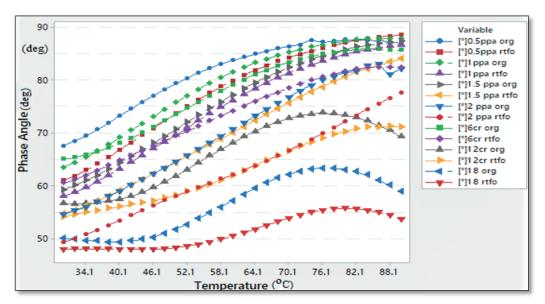


Figure 5 Phase angle values for the samples containing the first stage

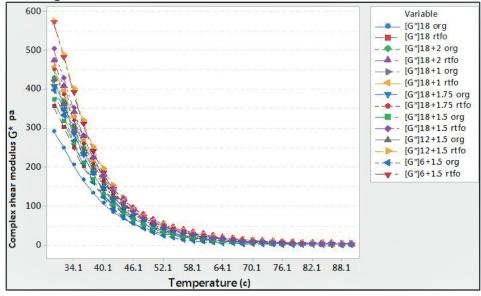


Figure 6 Complex shear modulus values for the second-stage samples

and show poorer performance than other samples, In general, it can be said that the combination of two additives has increased the resistance of samples to permanent deformation, and samples (18% CR+1.0% PPA) and (18% CR+2.0% PPA) had a lower rate of G* than other samples.

The best performance for bitumen containing 18% CR with 2.0, and 1.0% PPA is after short-term aging. The bitumen melting point in the sample (18% CR+2.0% PPA) is about 56 °C, and in the sample (18% CR+1.0% PPA) is about 52 °C. Bitumen at previous temperatures has a significant elastic property, and certainly at higher test temperatures, δ shows a slight increase rate. Two samples (6% CR+1.5% PPA), and (12% CR+1.5% PPA), which showed high G* at initial temperatures, showed fragile elastic properties, which reveals the need for simultaneous attention to both G*, and δ parameters.

Results related to the BBR test

One of the objectives of this study was to increase the high degree of performance of bitumen, without affecting the low-temperature performance of bitumen. From this point of view, CR additive seems to be successful, because, in addition to improving the performance of bitumen at high temperatures, it has also improved the low-temperature performance of bitumen, and all levels of this additive have succeeded in doing so, and as the result of CR increased, the performance of bitumen also improved (albeit slightly). The best performance related to bitumen contained 18% of CR which managed to improve the performance of bitumen at low temperatures by one rank. Bitumen containing 1.5% PPA has a similar function to rubber powder, and slightly improves the behavior of bitumen at low temperatures. Samples containing 1.0%, and 2.0% PPA did not show a significant change in m-value, which was confirmed by statistical test (P value > 0.13). However, the sample containing 2.0% PPA caused a decrease in bitumen performance. The m-value for all samples can be seen in Figure 7.

Regarding the combination of two additives, actually the sum of the two additives reduced the m-value. Although this drop in performance varies at different levels, for example, 1.0% PPA caused a slight drop in bitumen yield containing 18% of CR; with increasing PPA, this rate of decline has increased. It seems, the

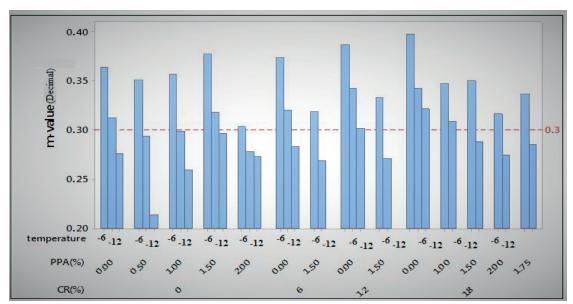


Figure 7 Creep change rate (m-value) based on other variables

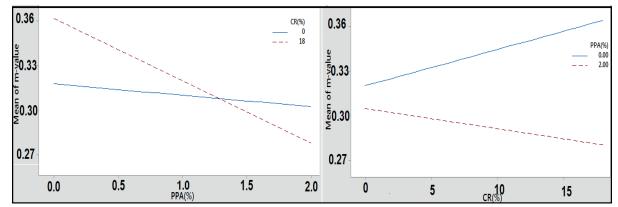


Figure 8 Effects of PPA(Left), and CR(Right) based on m-value parameter

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reason can be found in the double increase in bitumen hardness due to the combination of two additives, and, of course, the increase in its brittleness, and fragility at low temperatures, Figure 8.

Results related to the LAS test, compliant with the standard [24]

Figure 9 shows some modified samples compared to the base sample 100-85. As it turns out, all the specimens, except the base bitumen, are above the specified mark, and meet the requirements of the fatigue law.

Results related to the Multiple Stress Creep Recovery (MSCR) test

This test provides two parameters of percent recovery (R%), and non-recoverable creep

compliance(Jnr) under 0.1, and 3.2 kPa load levels at a test temperature of 58-76 °C. Typically, the higher the bitumen recovery capacity (R%), the more desirable it is. In addition, the closer the non-recoverable creep compliance is to zero, the higher the bitumen resistance to deformation.

At a stress level of 0.1 k Pa, it is observed that the higher the result of CR or PPA, the higher the bitumen recovery rate. Samples that have been modified by only one of the two additives in this study have experienced a decrease in R% with increasing temperature. The samples that combined the two additives also had an increasing R% parameter, albeit a small one. At high levels of the two additives, little change in R% is observed. This level of stress does not seem to be able to distinguish between additive-content samples. The best example of recovery at this stress level is a combination

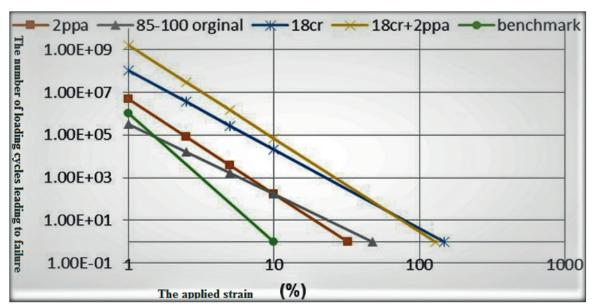


Figure 9 Comparison of multi-sample fatigue model (at -20 °C after PAV)

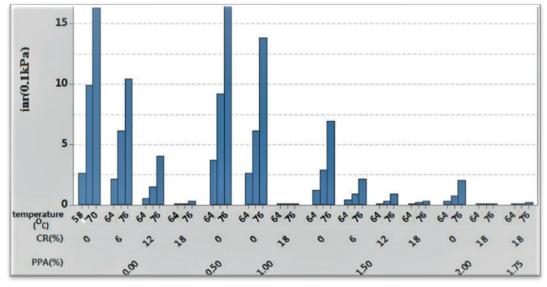


Figure 10 The effect of test variables on the R% parameter at a stress level of 0.1 kPa

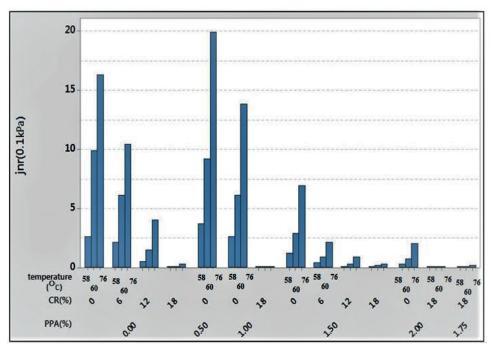


Figure 11 The effect of test variables on the j_{nr} parameter at a stress level of 0.1 kPa

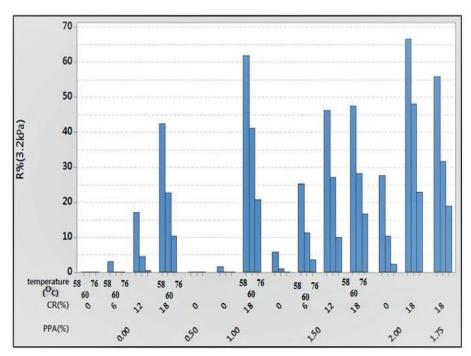


Figure 12 The effect of test variables on the R% parameter at a stress level of 3.2 kPa

of 18% CR plus 1.0% PPA. All examples are shown in Figure 10.

The non-recoverable creep compliance at a stress level of 0.1 kPa can be said to be significantly reduced by the addition of additives, and the highest level of CR (18 %), and the highest level of PPA (2.0%) have significantly reduced it. Since this value is directly related to the recovery rate, the best additive levels are the R% parameter. It is noteworthy that the base bitumen at 76 °C, is ultimately flowed, so it has been removed

from the comparison. All the points are illustrated in Figure 11. $\,$

At a stress level of 3.2 kPa, and for the percent recovery, it can also be said that by adding both bitumen modifiers, the bitumen behavior is improved, and CR seems to perform better than PPA. The sum of these two additives has been successful in increasing the bitumen recovery percentage, and it seems that the best example according to this parameter is the combination of 18% CR with 2.0% PPA, and the combination of

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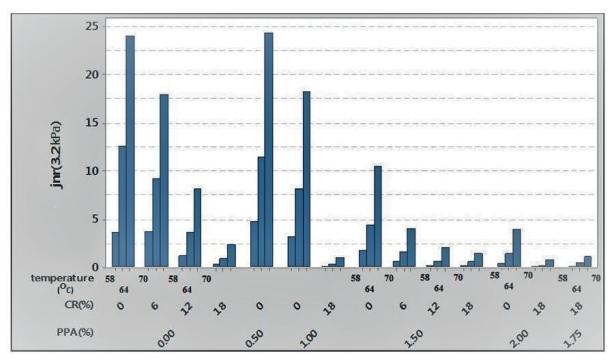


Figure 13 The effect of test variables on the j_{nr} parameter at a stress level of 3.2 kPa

18% CR plus 1.0% PPA, with a slight difference, is in second place. All the relevant points can be seen in Figure 12.

Finally, the essential parameter obtained from the MSCR test is the non-recoverable creep compliance at the stress level of 3.2 kPa, which has shown a high correlation with the result of rutting in field experiments [25]. A review of several studies in this regard shows that if the result of this parameter is reduced by half after modification, the result of ruts in the pavement will be almost halved [26]. Figure 13 shows that the base bitumen of this study, after the modification process, shows a remarkable improvement in performance.

3.2 Morphological properties of modified bitumen

The images presented in this study were obtained by electron microscopy (TESCAN VEGA 3) with magnifications of 1000 to 4000 times. These images can be seen in Figure 14. The largest size of waste powder particles used in this study is 600 microns, and also the smallest particle size is slightly less than 75 microns, which of course, includes a deficient percentage of particles. In the modified samples, no trace of CR particles of agglomerates is observed, and we see homogeneous, and uniform samples. In addition, in the unmodified sample (Figure 14, left) can be seen the presence of a series of filaments related to the asphalt particles in the bitumen. However, in all the modified samples (Figure 14, right), no trace of these particles

is found, what proves that the PPA has succeeded in dissolving the asphalt particles in the bitumen structure, apparently. In general, the combination of waste rubber powder, and PPA can be evaluated for bitumen modification, and from the structural point of view of bitumen, without any problems. However, for more accurate conclusions, more samples need to be evaluated.

4 Conclusions

The objective of this study was to investigate the effect of PPA, and CR on the properties, and performance of bitumen. For this purpose, the two materials were added to the bitumen with different percentages as additives. Then the modified bitumen was tested by classical bitumen tests, bitumen performance grades (PG), and Sharp supplementary grades (PG⁺). The results of this research are as follows:

The use of CR at the highest possible level (18% in this study) in the bitumen sample is allowed, and no adverse effect of this additive was observed. The determining condition for its maximum result is the integrity of the sample, and its proper mixing.

• PPA at the level of 1.0% showed positive effects without increasing the weaknesses of bitumen. Given the relatively high price of the product, it can be said that, both from a technical, and economic point of view, the use of 1.0% PPA seems to be suitable for bitumen modification, and of course, it is strongly recommended.

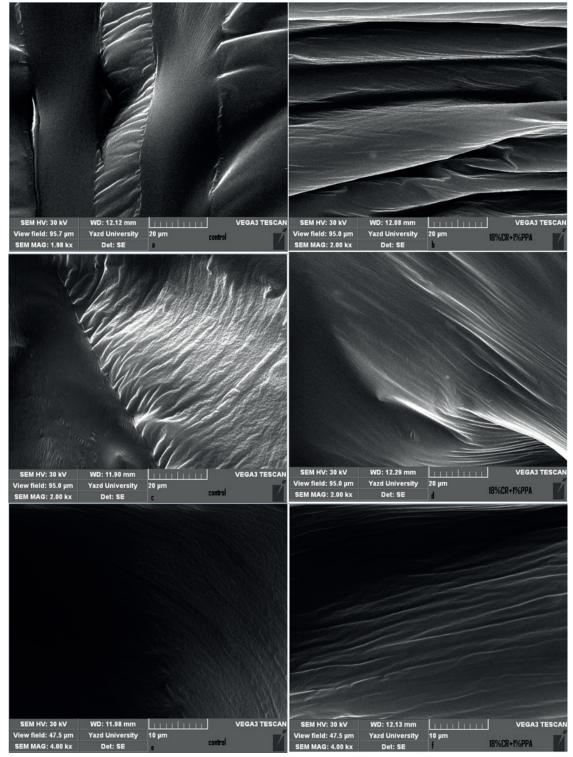


Figure 14 Scanning electron microscopy images of magnifications of 1000 to 4000 (left), control sample, and (right) of 18% CR+1.0% PPA sample

- Both additives in this study have succeeded in reducing the sensitivity of bitumen to temperature, and aging. The combination of these two additives is also synergistic, and has highly improved the performance of bitumen. The combination of these two additives has increased the performance class of bitumen at high temperatures up to 4 degrees.
- The samples (18% CR+2.0% PPA), and (18% CR+1.0% PPA) experienced substantial improvement in their rheological properties., and showed remarkable strength, and elasticity. These two samples remained in the range of elastic behavior of bitumen up to 56, and 52° C, respectively, and with further increase in temperature, they have experienced a decline in performance at a meager rate.

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- Only the sample containing 18% CR was able to improve the performance of bitumen at low temperatures by one rank, and the combination of bitumen with percentages of PPA content, such as 2.0, 1.75%, and even 1.5%, caused a decrease in performance at low temperatures. Of the samples containing both additives, only the sample (18% CR+1.0% PPA) had no adverse effect on the low-temperature performance of bitumen.
- The results of the LAS test showed that both additives increased the resistance of bitumen to cracking. The test results also revealed the need to pay special attention to the fatigue and cracking of bitumen at the moderate temperature, which is the most common failure related to pavement. The criterion of fatigue at medium temperatures, in addition to the high, and low temperatures of bitumen, should be considered in naming, and introducing the characteristics of bitumen.
- The MSCR test results also showed that the use of additives significantly reduces the non-recoverable creep compliance (j_{nr}) and also increases the bitumen recovery rate (percentage) at high temperatures.

 Examination of the morphological properties of the modified bitumen also showed that in the selected modified composition (18% CR+1.0% PPA), there is no trace of undissolved particles of CR, and this composition is uniform, homogeneous compared to the base bitumen, and is considered successful from this perspective.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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INVESTIGATING THE EFFECTS OF MICRO MONTMORILLONITE ON CEMENT MORTAR PHYSICAL PROPERTIES

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Resume

The effects of micro-sized montmorillonite clay (MMT) on Portland cement concrete were examined in this study, focusing on regular and calcined MMT as partial cement replacements. Key properties assessed include consistency, setting time, flexural strength, and compressive strength at 7 and 28 days. Regular MMT initially acts as an inert filler, potentially reducing compressive strength, while calcined MMT improves compatibility and strength. Both types extend the setting time, with regular MMT causing more delay. The study highlights that the regular MMT increases water demand and setting time, whereas calcined MMT enhances strength and mitigates these issues. The results emphasize the importance of carefully choosing MMT type and dosage.

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1 Introduction

The incorporation of micro clay additives in cementitious materials has garnered significant attention due to their potential to enhance various properties of cement-based composites [1-3]. Micro clay, consisting of finely divided particles typically in the micrometer range, offers a sustainable and cost-effective means to improve the performance of cement mortar and concrete [4-6]. This introduction focuses on the effects of micro clay additives on the setting time of cement-based materials. Initial and final setting times are crucial parameters within the context of cement hydration, as they determine the workability and early strength development of concrete mixtures. Manipulating the setting times through the addition of micro clay can influence construction schedules, improve placement practices, and ultimately impact the mechanical properties and durability of hardened concrete structures. The present study investigates the influence of both virgin and calcined micro clay additives on the setting time of cement mortar. Virgin micro clay refers to untreated clay particles, while calcined micro clay undergoes a thermal treatment process to modify its properties. By comparing the effects of these two forms of micro clay at various dosages, insights into their respective contributions to setting time alterations can be gained. A study conducted by [7] explores alternative materials for replacing fine aggregate in building construction. Marine clay, combined with the microorganism Bacillus subtilis MTCC441, was investigated to enhance the mechanical properties of the mixture. In the study is found that the microbial marine clay mortar mix exhibited significant improvements in compressive strength and a reduction in water absorption compared to the control mix. However, the microbial excavated soil mixes did not demonstrate crack healing properties through bioprecipitation of calcium carbonate crystals, even after observing an induced crack of 0.5 mm width for 60 days at one-week intervals [8-10]. Alani (2020) [11] investigated the effects of incorporating nano-calcined montmorillonite clay (NCMC) into cement mortars on their mechanical strength and microstructure when exposed to high temperatures. NCMC, obtained through thermal activation of nano-clay, was added to mortars in varying proportions. The mortars were then tested at temperatures up to 900 °C. Analytical techniques including thermogravimetric analysis, X-ray diffraction, and scanning electron microscopy were used to assess the fire-resistant properties and microstructural changes. Results indicate that incorporating thermally

treated NCMC reduced density and microcrack widths, enhanced mass-loss behavior, decreased calcium hydroxide crystal content, and ultimately strengthened the matrix, leading to higher residual mechanical strengths in the mortars [11-12]. Khand and Nomana (2019) [13] evaluated Pakistani montmorillonite (Mmt) clay as a partial cement replacement in mortar, testing different temperatures and replacement levels. Calcined Mmt clay at 800 °C showed optimal strength performance, with a 25% replacement yielding strong compression results. Montmorillonite-modified mortars also exhibited better durability, particularly against mixed aggressive environments (SCS) compared to sulfate environments (SS) [13-15]. Chi and Huang (2012) [16] explored the effects of montmorillonite additives on cement paste and mortar properties. Different percentages of montmorillonite were added to mixes with varying water/cement ratios. Generally, montmorillonite enhances compressive strength, though not at 15% content after 28 days. Water absorption decreases in cement pastes but increases in mortars with montmorillonite. Both show higher adsorptiondesorption values compared to plain mixes, with denser cement paste observed under scanning electron microscopy. Hydration products include portlandite, hatrurite, and calcite in cement paste, and quartz and portlandite in cement mortar according to X-ray diffraction analysis [16-17]. The objective of this research is to investigate the effect of montmorillonite as a partial replacement for cement on the properties of cement paste and mortar. Mechanical tests, including compressive strength and flexural strength, have been used to determine the properties of cement paste with varying percentages of montmorillonite. Additionally, setting time tests and consistency investigations were performed.

2 Materials

2.1 Sand

In this investigation, the standard sand, obtained from the Iraqi Geological Survey (Ministry of Industry and Mining), is used. The gradation of the sand is presented in Table 1. Based on the grading results, it satisfies the required grading specifications as stated by the ASTM C778 [18] standard.

2.2 Cement

Ordinary Portland Cement Type I was used in all mixes throughout this research. It is manufactured in Iraq by Al-Mass Company type CEM I. The chemical composition and physical properties of the utilized cement are shown in Table 2 and 3, respectively. Test results indicate that the chosen cement complies with the Iraqi specifications IQS 5/2019 [19] and ASTM-C150-21 [20].

2.3 Clay (Montmorillonite)

Clay type Montmorillonite (MM) was used in this investigation, its source is the natural stone available

Table 1 Standard sand gradation

Sieve size	Percent passing (%)	Specification limits (%)
1.18 mm	100	100
600 μm	96.8	96-100
$425~\mu m$	71.1	65-75
300 μm	22.8	20-30
150	2.9	0-4

Table 2 Chemical composition of cement

Component	Results (%)	Specification limit (%)
MgO	1.25	max. 5
$\mathrm{Al_2O_3}$	5.46	
SiO_2	20.9	
CaO	62.3	
$\mathrm{C_3A}$	8.96	min 3.5
$\mathrm{SO}_{\scriptscriptstyle 3}$	2.48	max. 2.6
L.O.I.	3.56	max. 4
$\mathrm{Fe_2O_3}$	3.24	
I.R	0.9	max. 1.5

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Table 3 Physical properties of cement

Property	Results	Specification limit
Fineness (m²/kg)	291.4	230
Compressive strength at 3-days age, (MPa)	17.2	min. 15
Compressive strength at 7- days age, (MPa)	26.1	min. 23
Initial setting time (min)	144	min. 45
Final sitting time (min)	397	max. 600



Regular MM
Figure 1 Photographs for MM



Calcined MM
Figure 2 Photographs for calcined CMM

Table 4 Physical properties of Montmorillonite clay

Physical properties	Result	ASTM C618 class N specification limit
Retained No. 325 mesh (%)	11.2	max. 34%
Specific gravity	2.40	
Average particle size (µm)	4 to 5	

Table 5 Chemical properties of Montmorillonite clay

Chemical composition	Result (%)	ASTM C618 class N specification limit (%)
Sodium oxide (Na ₂ O)	1.36	max. 5
Magnesium oxide (MgO)	2.68	
Aluminum oxide (Al_2O_3)	18.24	
Silicon dioxide (SiO_2)	56.64	
Potassium oxide (K_2O)	0.66	
Calcium oxide (CaO)	3.10	
Titanium oxide (${ m TiO_2}$)	0.97	
Ferric oxide (Fe_2O_3)	6.1	
Sulphur tri oxide (SO_3)	0.18	max. 4
$(SiO_2) + (Al_2O_3) + (Fe_2O_3)$	80.98	min. 70
Loss on ignition (LOI)	7.3	max. 10

in the western part of Iraq. The stone was broken into small size pieces that is allowed to be ground by the pug mil to finer size passing sieve No. 200 (0.075 mm) to convert them to micro scale. Two types of MM were used; the first one, which is labeled as regular is the normal type without any processing. The second one is the calcined Montmorillonite (CMM). The calcination process consists of heating the Montmorillonite to 800

⁹C for two hours. Figure 1 and 2 shows both types of Montmorillonite used throughout this study. Tables 4 and 5 show the physical and chemical properties of both types of montmorillonite. For ease of reference, the following specimens' legend, as presented in Table 6, are adopted within the course of the experimental work. Besides, Table 7 lists the specimens legend and mix gradient. A comparison was made between the

Table 6 Chemical composition of tap water

Component	Results	Limits
Sulfites (mg/l)	20	max. 1000
Chlorides (mg/l)	10	max. 500
Carbonates and bicarbonates (mg/l)	65	max. 1000
Inorganic materials (mg/l)	420	total ions, max. 3000

Table 7 Specimens legend and mix gradient

Legend	Replacement rate (%)	Sand (g)	Cement (g)	Clay (g)	Water (ml)	No. of specimens (compressive)	No. of specimens (flexural)
RM	0	1375	500	-	242	6	3
MM1	0.25	1375	498.75	1.25	242	6	3
MM2	0.75	1375	496.25	3.75	242	6	3
MM3	1.25	1375	493.75	6.25	242	6	3
MM4	1.75	1375	491.25	8.75	242	6	3
CMM1	0.25	1375	498.75	1.25	242	6	3
CMM2	0.75	1375	496.25	3.75	242	6	3
CMM3	1.25	1375	493.75	6.25	242	6	3
CMM4	1.75	1375	491.25	8.75	242	6	3

Note: The amount of water added to the mortar mixtures was adjusted according to the findings of the consistency test.



Figure 3 Mortar mixing process

montmorillonite assay and the specified limit for ASTM C618 Class N, as stated in reference [21].

2.4 Water

The tap water is used during the preparation of cement mortar. The chemical composition for the tap water is presented in Table 6.

3 Preparation of mortar specimens

According to ASTM C305 [22] in the mortar mixing process, the dry paddle and bowl are initially positioned in the electrical mixer. The materials for a batch are then introduced into the bowl following a specific sequence. First, all the mixing water is placed in the bowl. Next, the cement is added to the water, and the mixer is

started at a slow speed (140 \pm 5 r/min) for 30 seconds to ensure uniform mixing. Subsequently, the entire quantity of sand is added slowly over a 30 second period while continuing to mix at the slow speed. Afterward, the mixer is stopped, and the speed is changed to medium (285 \pm 10 r/min) for another 30 seconds of mixing. Finally, the mixer is stopped again, and the mortar is allowed to stand for 90 seconds. During the first 15 seconds of this interval, any mortar that may have collected on the side of the bowl is quickly scraped down into the batch to ensure uniformity. The mixing process is shown in Figure 3.

4 Specimen casting and curing

The specimen molding procedure, following ASTM C 109 [23] standards, requires initiating the molding within 2 minutes and 30 seconds after the mortar batch

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Figure 4 The casted specimens



Figure 5 Vicat apparatus

mixing is completed. Initially, a 25 mm layer of mortar is placed in the cube molds (50 x 50 x 50 mm). Each cube compartment is then tamped 32 times over four rounds, with each round perpendicular to the other, ensuring uniform filling. Once the first layer in all the compartments is tamped, the remaining mortar is added and tamped similarly. After the tamping, the cube tops slightly extend above the molds. Any excess mortar on top is smoothed with a trowel, and the cubes are leveled. Figure 4 illustrates this process. After 24 hours, samples are removed from the molds, marked, and immersed in tap water for 7 and 28-day curing. For flexural strength specimens, the same process is repeated with prisms measuring 40 x 40 x 160 mm as per the ASTM C 109 standards requirement. A 20 mm layer of mortar is evenly distributed in each mold, compacted with twelve tamper strokes in three rounds, and smoothed with a trowel. Excess mortar is removed, and the surfaces are made plane. Prisms are let to harden for one day in the molds and then removed for curing for 28 days.

5 Physical properties tests

5.1 Consistency

This test's significance lies in determining the water quantity required to achieve a consistent paste with standard consistency. A Vicat device, as per ASTM 187 specification [24], is employed for this purpose.

This device comprises a circular piston with a 10 mm diameter, as illustrated in Figure 5. Initially, 650 grams of cement are mixed with a calculated amount of water to form the paste. Subsequently, the mixture is agitated at various speeds in a mechanical mixer, following ASTM C305 specification, as previously mentioned. The paste, confined within a mold and resting on a plate, is positioned beneath the rod with the plunger's tip in contact with its surface, and the screw is tightened. The moving pointer is then aligned with the upper zero mark on the scale, and the initial reading is taken before promptly releasing the rod. This action must occur within 30 seconds of completing the mixing process. After 30 seconds, the screw is tightened once again to halt the piston's descent, and the distance it has descended below the original surface is recorded. The paste achieves standard consistency when the piston descends a distance of (10 ± 1 mm) below the original surface within 30 seconds of its release.

5.2 Setting time of blended cement

According to ASTM C191 [25], the initial and final setting times of the cement and MM pastes were assessed using Vicat's apparatus. The Vicat test, outlined in ASTM C191, is a widely employed method for determining the setting time of cement paste. In this examination, a water-to-cement ratio of 28% was utilized. Figure 6 shows the setting time testing device.



Figure 6 Vicat testing



Figure 7 Flexural strength testing



Figure 8 Compressive strength testing

5.3 Flexural strength

The flexural strength of cement mortar is determined using a flexural test conducted in accordance with ASTM C348 [26] standards. Specimens were tested immediately after removal from storage water at the age of 28 days. The testing setup involves carefully positioning the specimen on the testing device to ensure accurate alignment and load application. This setup includes centering the pedestal beneath the spherical head, placing the specimen on its side on the supports, and ensuring it aligns with the center of both supports. The load is then applied at a controlled rate of 2640 \pm 110 N, and the flexural strength is calculated using the formula:

$$\sigma_f = 3PL/2bd, \qquad (1)$$

where:

 σ_f = Flexure strength (MPa),

P = Maximum measured applied load (N),

L = Span's length (mm),

b = Width of the specimen (mm),

d = depth of the specimen (mm).

Photograph for specimen while testing is shown in Figure 7.

5.4 Compressive strength test

Compressive strength testing was performed on cubic specimens, following the guidelines of ASTM C109/C109M-21. The tests were conducted immediately after removing the specimens from the storage water at the predetermined ages of 7 and 28 days. During the testing process, the load was applied to the specimen faces that were in contact with the true plane surfaces of the mold. The load was applied at a controlled rate of movement between the upper and lower platens, ranging from 900 to 1800 N/s. The maximum load, indicated by the testing

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machine, was recorded, and the compressive strength was calculated using the following formula:

$$\sigma = P/A, \tag{2}$$

where:

 σ = compressive strength in (MPa),

P = total maximum load in (N),

 $A = \text{area of loaded surface in (mm}^2).$

Photograph for specimen while testing is shown in Figure 8.

6 Results and discussion

6.1 Consistency

The data presented in Table 8, as well as in Figures 9 and 10, illustrate the variations in consistency of the Portland cement paste resulting from the incorporation of montmorillonite in its regular and calcined forms. With regular montmorillonite, the proportion of water required to achieve the desired consistency increases as the replacement percentage rises, ranging from 0.25% to a maximum of 1.75% replacement. Similarly, with calcined montmorillonite, there is a consistent upward trend in water utilization with increasing replacement percentages, reaching a peak at the maximum replacement percentage. Comparing both types of montmorillonite to the reference mixture at 0% replacement, it becomes evident that calcined montmorillonite requires a greater amount of water to achieve the desired consistency compared to the regular type. Specifically, there is an approximate 10.71% increase in water requirement at its peak (1.75% replacement) compared to the reference mixture. This suggests that the calcination process results in water loss, necessitating a higher quantity of water than typically needed for montmorillonite.

6.2 Setting time

The data presented in Tables 9 and 10 and shown graphically in Figures 11 to 14 indicate that incorporating regular montmorillonite (MMT) into cement leads to a significant increase in both initial and final setting times. This escalation is directly proportional to the montmorillonite dosage, ranging from a 20% to a 93.33% increase compared to the control mix. The relationship between the dosage and its effect is pronounced, with the highest dose of 1.75% causing the most marked delay in the setting process. The likely cause of this delay is the increased water demand and the subsequent disruption of the hydration reactions. In contrast, cement containing calcined montmorillonite also exhibits longer initial and final setting times compared to the control mix; however, the increase is less marked than with regular montmorillonite, ranging from 13.33% to 60%. The activation of calcined montmorillonite is thought to elongate the setting time because it releases more heat during the reaction, facilitating the solidification process. On the other hand, regular montmorillonite does not produce such thermal energy, thus hindering the reaction and resulting in more extended setting times when compared to the calcined variant.

Table 8 Results of consistency test for micro clay samples

	Control	MM1	MM2	MM3	MM4	CMM1	CMM2	CMM3	CMM4
Consistency (%)	28	29	29	30	30	29	30	30	31
Percentage increase (%)	-	3.57	3.57	7.14	7.14	3.57	7.14	7.14	10.71

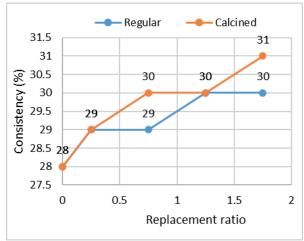


Figure 9 Consistency test for micro clay

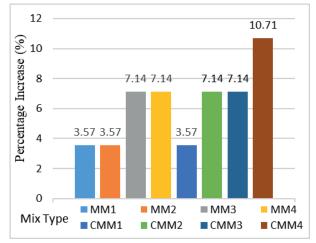


Figure 10 The percentage increase in the consistency

Table 9 Results of setting time (initial) test for micro clay samples

	Control	MM 1	MM 2	MM 3	MM 4	CMM 1	CMM 2	CMM 3	CMM 4
Initial (min)	75	90	110	125	145	85	95	115	120
Percentage increase (%)	-	20.0	46.66	66.66	93.33	13.33	26.66	53.33	60.0

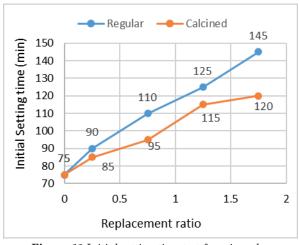


Figure 11 Initial setting time test for micro clay

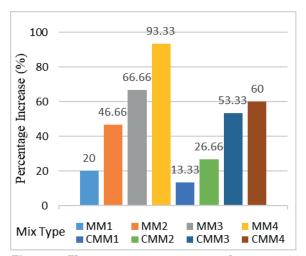


Figure 12 The percentage increase in initial sitting time

Table 10 Results of setting time (final) test for micro clay samples

	Control	MM 1	MM 2	MM 3	MM 4	CMM 1	CMM 2	CMM 3	CMM 4
Final (min)	285	315	350	395	425	315	325	355	380
Percentage increase (%)	-	10.52	22.81	38.59	49.12	10.52	14.03	24.56	33.33

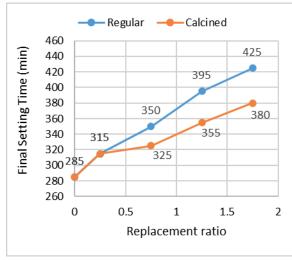


Figure 13 Final setting time test for micro clay

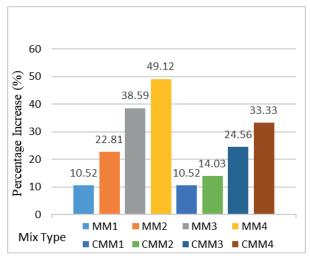


Figure 14 The percentage increase in final setting time

6.3 Flexural strength

The results of MMT and calcined MMT are presented in Table 11 and Figures 15 and 16. Initially, replacing montmorillonite in its regular form with a replacement ratio of 0.25% led to a 3% increase in flexural strength compared to the reference sample. However, replacing montmorillonite at higher ratios resulted in a decrease in resistance directly proportional

to the increased replacement rate. The initial increase at a low replacement ratio can be attributed to improved particle arrangement, void filling, and strengthening of the mortar structure. However, increasing the replacement ratio led to excessive particle accumulation, which caused the appearance of weak areas. On the other hand, flexural strength increased with calcined MMT up to a concentration of 1.25%. Calcination improved the dispersion and bonding of fine clay

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particles in the mortar, resulting in a more substantial strengthening effect. However, when the concentration increased to 1.75%, flexural strength decreased. This decrease can be attributed to excessive particle loading, which may cause particle agglomeration or restrict the movement of cement particles during hydration, thereby reducing the ability of calcined clay to improve flexural strength.

6.4 Compression strength

Tables 12 and 13 and Figures 17-20 present the results of the compressive strength test for mortar cubes aged 7 and 28 days. It was observed that adding MMT at all the replacement ratios resulted in a reduction in compressive strength. This decrease is likely attributed to the introduction of defects and brittle voids in

Table 11 Results of flexure strength test for micro clay samples

	Control	MM 1	MM 2	MM 3	MM 4	CMM 1	CMM 2	CMM 3	CMM 4
Flexural strength (MPa)	2.85	2.93	2.77	2.68	2.58	2.99	3.11	3.19	3.09
Percentage increase (%)	-	3.0	2.50-	5.73-	9.14-	5.18	9.13	12.08	8.50

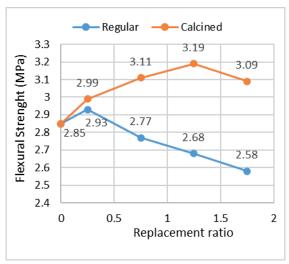


Figure 15 Flexural strength for micro clay

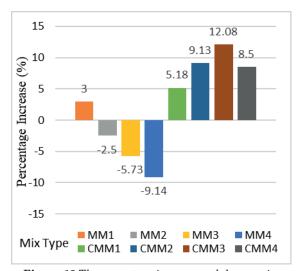


Figure 16 The percentage increase and decrease in flexural strength

Table 12 Results of compressive strength test for micro clay sample at 7 days

	Control	MM 1	MM 2	MM 3	MM 4	CMM 1	CMM 2	CMM 3	CMM 4
Compressive (MPa)	20.7	19.25	18.83	18.42	17.59	21.36	22.25	21.52	21.19
Percentage increase (%)	-	7.0-	9.03-	11.01-	15.03-	4.49	7.48	3.96	2.36

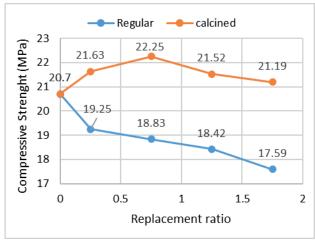


Figure 17 Compressive strength test at 7 days

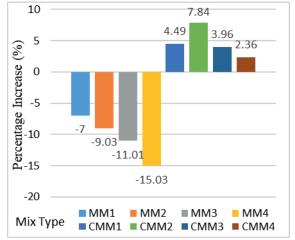


Figure 18 The percentage increase and decrease in compressive strength

Table 13 Results of compressive strength test for micro clay sample at 28 days

	Control	MM 1	MM 2	MM 3	MM 4	CMM 1	CMM 2	CMM 3	CMM 4
Compressive (MPa)	25.4	23.75	23.26	22.80	21.23	26.67	27.16	26.28	25.94
Percentage increase (%)	-	6.5-	8.40-	10.22-	16.40-	5.00	6.95	3.50	2.14

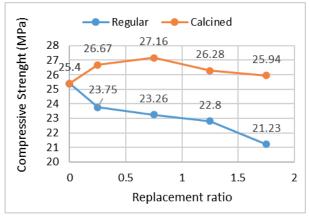


Figure 19 Compressive strength test at 28 days

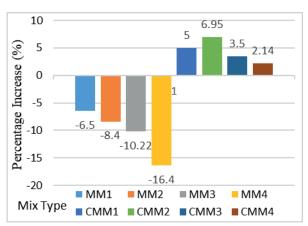


Figure 20 The Percentage increase and decrease in compressive strength

the arrangement of cement particles. In contrast, the addition of calcined MMT led to an increase in compressive strength, reaching its peak at a replacement ratio of 0.75%. At this ratio, the increase reached 7.84%, and then gradually decreased with each subsequent replacement ratio until reaching a compressive strength of 21.19 MPa. However, this value still exceeded the compressive strength of the reference sample by 2.36%. The increase in compressive strength, observed when adding calcined clay, is generally attributed to the heat treatment of the clay, which altered its properties such as surface area, shape, and interaction.

7 Conclusions

In the ambit of this study, the multifaceted impacts of micro montmorillonite (MM) on the physical properties of cement mortar have been investigated. Employing two types of MM; regular and calcined at varying percentages (0%, 0.25%, 0.75%, 1.25%, and 1.75% by weight of cement), the research delved into the core physical aspects through four fundamental tests: consistency, setting time, flexural strength, and compressive strength. The outcomes of these rigorous examinations are pivotal, providing nuanced insights into the interactions between the MMT and cement mortar. Based on the results of experimental work, the following conclusions can be drawn:

- Calcined MM, when added to cement, increased the water requirement for desired consistency, with the maximum replacement ratio showing a 10.71% hike in water demand.
- Both initial and final setting times of cement were extended by MM incorporation, with regular MM

- inducing up to a 93.33% increase in setting time at the highest replacement level, reflecting a direct dose-response relationship.
- 3. Introduction of regular MM at a 0.25% replacement ratio enhanced the flexural strength, which is attributable to optimized particle packing. Contrarily, excessive MM resulted in a decline in flexural strength due to the formation of weak zones.
- 4. The addition of calcined MM up to a 0.75% replacement ratio significantly improved compressive strength by 7.84%. However, any further increase in replacement ratio led to a decrease in benefits, although strengths remained higher than the control sample by 2.36% at 1.75% replacement.
- of regular and calcined MM on altering mortar properties within the constraints of the experimental conditions and material properties specific to this study. It suggests that while the findings are promising, they are preliminary and should be validated through the extensive field studies to confirm their applicability in real-world scenarios. Future research should continue to refine the application of MM, with a particular focus on the calcination process and precision in replacement ratios to fully realize the material's potential.
- 6. Swelling of montmorillonite refers to its ability to expand when hydrated or exposed to water. This clay mineral has a layered structure with a high surface area and negative charge, allowing it to absorb water molecules between its layers. This swelling property is significant in various applications, such as in

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- drilling fluids, soil stabilization, and as an additive in materials like concrete to improve properties such as workability and strength.
- 7. Washing particles in concrete can negatively affect its strength and durability. These debris, usually clay or silt, can disrupt the cement matrix when excess water is applied during mixing or if segregation occurs. This can lead to decreased compressive strength, increased permeability, and durability issues along with cracking and decreased resistance to environmental elements.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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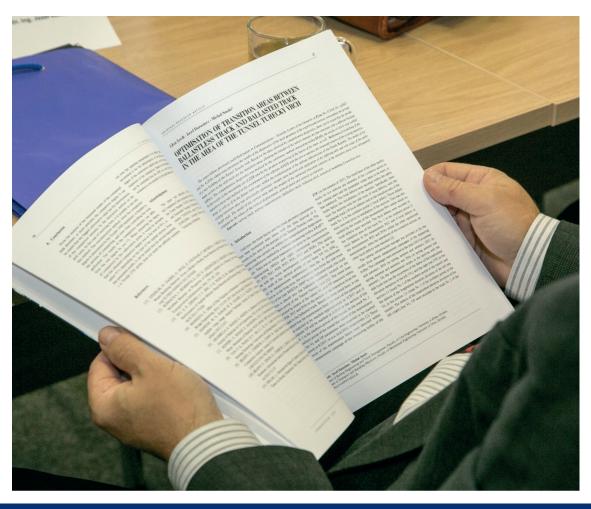
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VULNERABILITY ASSESSMENT OF TRANSPORT INFRASTRUCTURE ELEMENTS - CASE STUDY IN RAJEC

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Resume

The risk assessment of the area, with emphasis on the transport infrastructure, is dealt with in this paper. Disruption of some elements of transport infrastructure can lead to major negative impacts on the functioning of society, economies or states. The article therefore starts with presentation of the characteristics and importance of the road transport infrastructure with regard to its vulnerability. The core of the paper is the identification of vulnerable elements of road transport infrastructure and their parts and the subsequent vulnerability assessment of the selected element of the road transport infrastructure in the selected area. Therefore, the aim of the research, presented in this paper, was to propose a method for identifying and assessing the vulnerability of road transport infrastructure elements using the latest approaches in the field of vulnerability assessment. The proposed vulnerability assessment procedure is applied in the conditions of the city of Rajec in Slovakia.

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1 Introduction

The introductory part of the paper is focused on the definition of the basic theoretical background, with an emphasis on critical infrastructure and risk assessment. At the outset, it is necessary to emphasize the understanding of the concepts of a critical infrastructure and significant infrastructure elements.

The critical infrastructure in the Slovak Republic is defined in Act No. 45/2011 Coll. on Critical Infrastructure. This definition is based on the currently repealed Council Directive 2008/114/EC of 8 December 2008, which is replaced by Directive 2022/2557 of the European Parliament and of the Council of the European Union of 14 December 2022 on the resilience of critical entities. The critical infrastructure consists of system elements that are classified into sectors. By elements it is meant, in particular, engineering structures, services and information systems in the critical infrastructure sector that perform functions in the public interest and whose disruption or destruction, according to sectoral and cross-cutting criteria, would have a serious negative

impact on the performance of the economic and social functions of the State. At the same time, the population, property and the environment would be endangered [1].

Significant infrastructure elements are those elements whose disruption or destruction would have major consequences for the selected territory in which they are located, but which do not meet the criteria for inclusion in a national or European critical infrastructure.

Examples of such an approach include different methodologies for assessing the risks of an area. In these methodologies, significant infrastructure elements are treated differently. For example, these may be critical facilities or safety-critical objects, etc. [2-3]. This concept has also been addressed, for example, by Novotny et al. [4] or in the work of Kong et al. [5].

With respect to the road transport infrastructure, it is possible to identify engineering structures that have the potential to be classified as Critical Infrastructure Elements or Significant Road Infrastructure Elements. According to Act No. 50/1976 Coll. on spatial planning and building regulations, these include in particular,

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motorways, roads, local and special-purpose roads, bridges, overpasses, and tunnels [6].

In the Slovak Republic, the road transport is a separate sub-sector within the transport sector. The Ministry of Transport and Construction of the Slovak Republic oversees the transport sector [1]. The road transport is the most widespread type of transport in Slovakia. The importance of this type of transport lies in its ability to connect individual regions, districts, towns, and municipalities. The road transport is a crucial element for ensuring the international cooperation and trade, as well [7].

The importance of individual roads is also reflected in their classification. In the conditions of the Slovak Republic, this mainly involves the division into motorways, expressways and roads of the 1st, 2nd and 3rd classes. The road structures, such as bridges or tunnels, are built to ensure safe, smooth and economical traffic on the roads and to overcome various natural and man-made barriers [8].

The importance of the road infrastructure can also be highlighted regarding the protection of the population. The road infrastructure serves to supply the population with food and drinking water, even in the event of a crisis or extraordinary events. It is also used by the integrated rescue system for moving to the location of an extraordinary event.

The aforementioned roles of road infrastructure reflect its importance to society and the state. It is therefore necessary to protect individual elements of the critical road infrastructure and significant elements of road infrastructure. The importance of the road transport infrastructure elements can also be illustrated with examples from around the world. For instance, the collapse of the I-35W bridge in Minneapolis (USA) caused economic losses ranging from \$77,000 to \$220,000 per day [9]. Another example is the economic damage caused by landslides to road infrastructure in Scotland [10].

The protection of a critical infrastructure element involves ensuring its functionality, integrity and continuity of operation to prevent its disruption or destruction. Protection is ensured through mechanical barriers, technical safeguards, cybersecurity measures, physical protection, organizational measures, control measures or a combination of these [1].

The critical infrastructure protection is a process that considers all the risks and threats that could disrupt or destroy it. These risks, present in a particular area, may be natural or anthropogenic in nature, or may act in combination [11]. For protecting the road transport infrastructure elements, it is necessary to assess each risk, identify vulnerabilities and determine the possible consequences of its disruption or destruction [1]. By assessing all the road infrastructure elements in an area with respect to their vulnerability, it is also possible to determine the overall vulnerability of the area.

In the context of assessing both the vulnerability of the road transport infrastructure elements and the vulnerability of an area concerning these elements, it is necessary to define the concept of vulnerability. Hofreiter et al. (2013) defined the vulnerability as a characteristics of an object, technical facility or social entity that is expressed by a loss of ability to perform a natural or specified function. The loss of this capability is conditioned by the action of internal or external threats. Lovecek et al. further divided the vulnerability into three areas. These are physical vulnerability, technical vulnerability and operational vulnerability [12].

With respect to the impact of emergencies, it is also possible to characterize vulnerability in terms of a particular territory. In this case, vulnerability is expressed as a feature of the individual sub-elements of a particular territory. In general, vulnerability can be characterized as the susceptibility of a territory to the impacts of an extraordinary event, or the ability to react negatively to the consequences of crisis [13].

The vulnerability assessment of an object, territory or a society has recently received considerable attention. The vulnerability of the road transport infrastructure is not lagging behind in this respect. For example, the vulnerability assessment of the road infrastructure using territorial factors with the use of geographic information systems can be mentioned [14]. Another example is the road network vulnerability assessment model based on two factors considering seismic events [15].

Another interesting vulnerability assessment model from the transport sector is the railway key elements assessment model. The vulnerability assessment is based on main criteria that are identical for all the key elements and parameters set for each element separately. The advantage of the model is its simplicity, especially in terms of the data required for evaluation [16-17].

Considering the road infrastructure and its vulnerability, it is also necessary to identify the elements or parts of the infrastructure that are more susceptible or exposed to the effects of emergencies. For this purpose, a model for assessing the level of societal vulnerability, for example, can serve this purpose. This model uses indicators to determine the vulnerability of road and rail infrastructure [18].

Nowadays, the term resilience is also used to express the ability of the elements of a territory to cope with the impact of crisis phenomena. Resilience is the inverse of vulnerability. A higher level of resilience reduces vulnerability and vice versa [19]. Resilience can be characterized as the ability to absorb disruptive events, adapt to them, or quickly return to a desired state [20].

In the context of resilience and vulnerability, the notion of preparedness emerges. In crisis management issues, preparedness is one of the phases of the crisis management cycle. According to the authors in "Vulnerability and disaster preparedness", preparedness

Table 1 Criteria for determining the susceptibility of road infrastructure elements to the effects of crisis events (processed by [18])

Element type	Description of the risk			
Element is located near the river	is at risk of being washed away, flooded or is directly in a flood risk area (flood maps).			
Element is located below the slope	danger of rockslide, landslide, etc.			
Element is located in a forest area	danger of falling trees and forest fires.			
Element is located in a location threatened by strong wind	fall of trees, etc			
Element is located in mountainous areas	risk of avalanche or calamity.			
Element is located in another area that has the potential to cause negative impacts	other risks based on actual condition			

Table 2 Detour route criterion and its parameters

	Detour rout	te (K1)		,				
	Increase	of the detour rou	te by a percenta	age of the origin	al one [%]			
	1-20	21-40	41-60	61-80	81-100			
Length of detour route	Detour length							
	to 1.2x	1.21x-1.40x	1.41x-1.6x	1.61x-1.80x	1.81x-2x			
Compliance with the vulnerability criterion [%]	20	40	60	80	100			
Number of detour routes	0	1	2	3	4 and more			
Compliance with the vulnerability criterion [%]	100	75	50	25	0			
7. N. J.		According t	o normal load c	apacity [%]				
Full-value compensation	81-100	61-80	41-60	21-40	0-20			
Compliance with the vulnerability criterion [%]	20	40	60	80	100			

integrates the previous phases of the cycle. It includes established crisis plans, knowledge of the causes and the course of individual emergencies. It also includes the anticipation and recognition of impending hazards. Preparedness also means having ready organizational, personnel, management, technical, material and other measures in the case of a crisis event [21].

Preparedness is also a risk reduction measure [13]. Rehak et al. described resilience as the intrinsic readiness of subsystems for an adverse event [19]. Preparedness is often considered to some extent in vulnerability assessment in the context of risk assessment of territorial units [3, 13, 18, 22]. Thus, preparedness can be seen as a component of resilience that helps to increase it and at the same time reduce vulnerability.

The process of vulnerability assessment of the critical transport infrastructure elements and major road infrastructure elements is then itself a way of preparing for crisis events. The importance of assessing the vulnerability of the road transport infrastructure is based on the significance of these infrastructure elements and the need for planning and responding to emerging crisis phenomena. That is why the modification and use of vulnerability assessment models focused on transport infrastructure are discussed in the next part of the paper.

The choice of appropriate models is often influenced by the availability of data. Therefore, for the purposes of this paper, models that are relatively data-light have been selected. The proposed procedure in the following sections of the paper allows for assessing the vulnerability of the road transport infrastructure, which represents a significant part of the overall set of elements that determine the level of vulnerability of an area. At the same time, the selected and modified models are applied to the chosen territory.

2 Materials and methods

The authors focus in the article on the description and application of the selected models to a specific area, to identify and assess vulnerable parts of the road infrastructure elements. For this purpose, two vulnerability assessment models have been selected. Specifically, these are: Societal Vulnerability Level Assessment Model and the Model for the Assessment of the Key Railway Transport Elements [16-18].

The principles used in [17] were used to determine the criteria and evaluation parameters, which were adapted to the needs of the road transport infrastructure. ${
m F26}$

Table 3 Criterion construction characteristics and their parameters

Construction characteristics (K2)										
Bridge length to [m]:	102	203	304	405	506	607	708	809	910	1008
Compliance with the vulnerability criterion [%]	10	20	30	40	50	60	70	80	90	100
Material of bridge		Material used stone steel						reinforce	l concret	te
Compliance with the vulnerability criterion [%]		100			66			3	3	
Age of bridge	up to 2	5 years	26 - 5	2 years	53 - 7	7 years	78 - 108	3 years		years over
Compliance with the vulnerability criterion [%]	2	20	4	40	6	30	80)	10	00

Table 4 Criterion element significance and parameters

;	Significance of element (K3)		
D / CMENIM	The brid	ge is located on a TEN	N-T road
Part of TEN-T	Yes		No
Compliance with the vulnerability criterion [%]	100		0
D. A. CENDAR	The bridge lie	s on a road that is par	rt of the TEM
Part of TEM	Yes		No
Compliance with the vulnerability criterion [%]	100		0
	The bridge	lies on a road that is	part of "E"
Part of the international road network "E"	Yes		No
Compliance with the vulnerability criterion [%]	100		0
	Main category	Subcategory	Compliance with the criterion [%]
	Motorways and 1st class	Motorways and express roads	100
The economic significance of transport	roads	1st class roads 80	
		2nd class roads	60
	Other roads	3rd class roads	40
		Local roads	20

2.1 Identification of vulnerable elements

The Societal Vulnerability Assessment Model integrates the factors that determine a society's vulnerability. Those factors are categorized according to vulnerability drivers, which are mainly exposure and susceptibility factors. Within these factors, the indicators of the road network density (exposure), vulnerable parts of the road network (susceptibility) and vulnerability of road network objects are established [18].

The indicators under the exposure factor are based on the assumption that a higher density of the road network in an area represents a greater exposure to the effects of crisis events. The susceptibility indicators are used to select elements and parts of the road infrastructure that are more susceptible

to crisis events. Criteria are developed within the model to identify these elements or parts of elements. Those criteria have been selected to identify the more susceptible (vulnerable) road infrastructure elements in the selected area [18]. These criteria are described in Table 1.

2.2 Vulnerability assessment of the road transport infrastructure

The vulnerability assessment of the identified vulnerable road infrastructure elements and their parts is based on the Model for the Assessment of the Key Railway Transport Elements [16-17]. As this model is primarily intended for the vulnerability assessment of

Table 5 Criterion transport capacity and its parameters

Transport capacity (K4)								
m cc - 1 1 [c/]	Traffic load per population							
Traffic load [%]	to 50	to 90	to 100	to 150	over 150			
Compliance with the vulnerability criterion [%]	20	40	60	80	100			

Table 6 Territory risk criterion and its parameters

		Te	erritory ri	sk (K5)				
		Charac	cteristics	of the area			nce with the ty criterion [%]	
Slope movements and	Hig	gh rate of occ	currence o	f slope deformation			100	
deformations	Mea	an rate of occ	urrence o	f slope deformation	S		50	
	Lov	w rate of occu	irrence of	slope deformations		1		
		Charac	cteristics	of the area			nce with the ty criterion [%]	
			Lo	w range, low water	level		10	
	Low p	robability	Med	ium range, medium level	water		20	
			Ext	ensive flooding with water levels		30		
			Lo	w range, low water	level	40		
Floods		probability 00 years)	Med	ium range, medium level	water		50	
		, ,	Ext	ensive flooding with water levels	n high		60	
			Lo	w range, low water	level		70	
	High p	orobability	Med	ium range, medium level	water		80	
			Ext	ensive flooding with water levels	n high	90		
		Flood with	disastrou	s consequences			100	
		Course	of the thr	eat	Compl	iance with th criterion	e vulnerability [%]	
Torrential rains	Slight incr		not enda ne bridge	ngering the statics		1		
	Br	idge damage	d by wate	r overflow		50		
	Bridge d	estroyed by e		100				
Toological condition of the			C	ondition of the dilat	ation unit			
Technical condition of the dilatation unit	Perfect	Very good	Good	Satisfactory	Wrong	Very bad	Emergency	
Compliance with the vulnerability criterion [%]	10	20	30	50	70	90	100	

railway infrastructure elements, its adaptation to road infrastructure elements was necessary. The elements of railway infrastructure that are the focus of the model are the bridge, tunnel, broad gauge and marshalling yard [17]. For application of the model, the parameters of the main criteria for the bridge element were extracted from the model and modified.

The main assessment criteria and the modified parameters of these criteria, together with the scales for determining the vulnerability, based on the criteria, are included in Tables 2-6.

The parameters "Length of detour route" and "Number of detour routes" have remained unchanged, as they are also suitable for assessment of the road bridge. Parameter P3 will be assessed according to the normal load capacity of the bridges located on the detour route, taking into account the bridge with the lowest load capacity on the selected shortest detour route. If a bridge is not located on the detour route, the parameter will be assigned the lowest vulnerability value.

The "Bridge length" parameter for criterion K2 has been adjusted according to the length of road bridges.

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Table 7 Scale for determining the vulnerability of the element under consideration (processed by [15])

Rating scale for bridge vulnerability								
Minimum	Low	Medium	High	Maximum				
11.78	11.79-39.78	39.79-67.78	67.79-95.99	96				

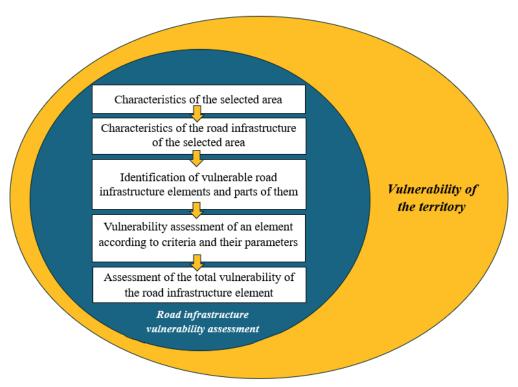


Figure 1 Vulnerability assessment procedure for a road infrastructure element

According to the technical data available on the website of the Slovak Road Administration, the longest road bridge M6437- Estakada nad zeleznicou in Zilina is 1007.76 metres long [23]. The Sturges' rule principle was used to create the intervals. Parameter P4 from the baseline model was not included in evaluation.

The parameters of the element importance criterion (K3) have been adjusted for the needs of road transport infrastructure in the Slovak Republic.

For this criterion, the original model parameter had to be replaced as it was not suitable for the road transport needs. The traffic load parameter is based on the traffic load data. The traffic load parameter is calculated as the ratio of the average number of motor vehicles that pass through the section closest to the bridge structure to the population living in the given municipality or city.

For the purpose of assessing the road bridge structures, it was necessary to modify the last parameter. For this purpose, a scale for evaluation of the expansion joints of bridge structures was used [24].

Criteria-based vulnerability according to these parameters is calculated through the following relation [17]:

$$Ki = \frac{\sum P_i}{number\ of\ parameters},\tag{1}$$

where:

Ki is one of the criteria,

 P_i is the value of the parameters of the criterion.

The total vulnerability of the road infrastructure element under consideration shall be calculated according to Equation (2) [17]:

$$Ve = \frac{\sum K_i}{5},\tag{2}$$

where:

Ve is the total vulnerability of the element under consideration

Ki are the evaluation criteria.

For the purpose of assessing the vulnerability of the element under consideration, the authors of the model prepared a vulnerability scale. This scale is included in Table 7.

The vulnerability evaluation process for the selected road infrastructure element consists of five steps and is illustrated in Figure 1. In the context of a site-specific vulnerability assessment, this is constitute of the overall vulnerability. The overall vulnerability can only be fully assessed after evaluating the other elements of the territory, including various types of infrastructure, services, society and the natural conditions of the territory.

The preliminary assessment procedure, developed based on two established models and modified for the needs of the road transport infrastructure, is suitable for determining the vulnerability of individual elements. The advantage of this procedure lies in the relatively low complexity of obtaining the necessary data, combined with the application of criteria and parameters that characterize the individual elements of road transport infrastructure in a detailed manner. This can be advantageous compared to other models that require more extensive data collection and processing for assessment.

In the following section, the modified model for assessing the road infrastructure vulnerability is applied to the cadastral territory of the town of Rajec.

3 Implementation of the models in the selected territory

To identify potentially significant elements of the road infrastructure in the territory of Rajec, the criteria for determining susceptibility (sensitivity) from the model presented in Section 2.1 were used. For the vulnerability assessment of the selected transport infrastructure element, the modified model presented in Section 2.2, was used.

3.1 Characteristics of the selected area

The characteristics of the selected area are based on the document "Analysis of the area in terms of the occurrence of possible emergencies", processed at all levels of government under Act No. 42/1994 Coll. on Civil Protection of the Population. Territory characteristics consist of geographical, demographic and economic aspect specific to the area [25-26].

According to the administrative division of the Slovak Republic, the town of Rajec is located in the

Zilina self-governing region within the Zilina district. The total area of Rajec's cadastral territory is 31.46 km², comprising 11.19 km² of agricultural land, 17.45 km² of forest land, and 2.82 km² of other nonagricultural land. The town lies in the Rajecka basin, a subdivision of the Zilina basin, and is part of the Vah River basin hydrologically. The Rajcianka River flows through the town, draining the entire area of interest with its right and left side tributaries. The left-hand tributary Ciernanka and the right-hand Porubsky brook contribute to the river's flow. The region's rainfall runoff is influenced by soil types, and precipitation levels typically exceed evaporation over the year. Stream flow follows a mid-mountain snow-rain regime, with peak levels occurring from March to May [27].

According to the Statistical Office of the Slovak Republic, the population of Rajec in 2022 was 5,818, which represents 3.61% of the Zilina district's total population. The town's population comprises 2,907 males (49.97%) and 2,911 females (50.03%) [28].

Rajec serves as an economic centre for surrounding municipalities, specializing in manufacturing agricultural machinery parts and carpets, alongside electrical and woodworking industries [29]. It holds regional significance and serves as the hub for the recreational Rajecka kotlina area. Rajec possesses substantial regional resources and spatial potential for creating employment opportunities in the secondary and tertiary sectors [27].

3.2 Characteristics of the road infrastructure in Rajec

The town of Rajec is connected to the main routes leading through the Slovak Republic via the I class road I/64 on the section Prievidza-Zilina. Rajec is also connected to Povazska Bystrica via the II class road II/517. Class I road I/64 is of supra-regional importance. The first-class road I/64 and the second-class road

Table 8 Traffic characteristics of class I and II roads in Rajec (processed by [30])

Section	Route	Trucks and buses	Passenger vehicles	Motorcycles	Total
91381	I/64	1384	8282	87	9753
91391	I/64	1123	5886	116	7125
91392	I/64	1031	5765	53	6849
92409	II/517	427	2111	25	2563

Table 9 Significant elements of the road transport infrastructure of Rajec (processed by [23, 27, 31])

Road transport infrastructure element	Length in the study area	
Route I/64	3.21km	
Route II/517	$3.72\mathrm{km}$	
Bridge M995 (I/64)	17.45 m	
Bridge M5745 (II/517)	9 m	
Bridge M3698 (II/517)	4.05 m	

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Table 10 Technical	characteristics of t	ha MOO5 bridge	(processed by [23])
Table 10 Technical	characiensucs of i	ne maaa oriage	Unrocessed by (251)

, , ,	V	
Characteristics	Description	
Bridging	Rajcianka watercourse	
Year of building	1963	
Length of bridging	17.45 m	
Type of construction	Beam	
Material	Precast prestressed concrete	
Normal load ability	16 t	
Exclusive load ability	48 t	
Exceptional load ability	88 t	
Building-technical condition	Poor	

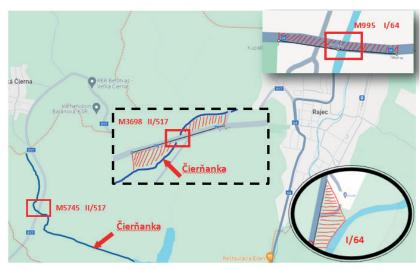


Figure 2 Representation of parts of the elements near the river (processed by [31])

II/517 serve to connect the town with the surrounding villages and towns. The significance of the I/64 road also expends to freight transport and supply [27]. The daily traffic characteristics of I/64 and II/517 are shown in Table 8.

There are also road bridges with identification numbers M995, M5745 and M3698. Bridge M995 is located on the I/64 road and bridges the Rajcianka River. Bridges M5745 and M3698 are located on the II/517 road and span Ciernanka watercourse. In addition to the bridges mentioned above, there are two other motor vehicle bridges in the town. However, these are located on local special purpose roads. Table 9 shows all the significant elements of Rajec's transport infrastructure. An example of the characteristics of a selected road infrastructure element required for vulnerability assessment is provided in Table 10.

3.3 Identification of vulnerable road infrastructure elements and parts of them

The criteria in Section 2.1 are used to identify the parts of the road transport infrastructure that are susceptible to the impact of individual events. The assessment of the potential impact of extraordinary events on the territory of the town of Rajec is based on the documents "Analysis of the territory from the point of view of the occurrence of possible extraordinary events of the District Office of the Zilina Region" (hereinafter referred to as the "Territory Analysis") [29], "Zoning Plan of the town of Rajec" [27] and other relevant textual and map documents.

According to the model presented in Section 2.1, the first criterion evaluates the length of the road and the number of road structures located close to the watercourse [18]. For this criterion, a distance of 50 meters or less the watercourse was considered. Flood maps for this area are not available. The representation of the elements near the river is shown in Figure 2.

According to the statistical data of the Ministry of Interior of the Slovak Republic, no flood has been recorded in the territory of Rajec [32]. However, according to the Territory Analysis, the town of Rajec is classified as flood-prone areas. A flood occurred here on the Rajcianka watercourse in 2011 [29].

According to the second criterion, which assesses the features based on their proximity to slopes, contourbased mapping or slope stability maps can by utilized. According to these maps, a 0.75 km section of the II/517 road, constituting 20.16% of the total length in the

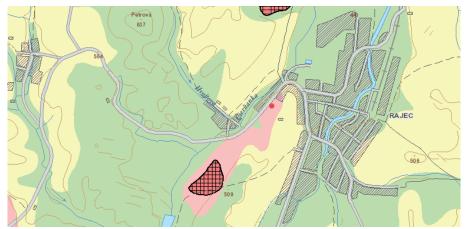


Figure 3 Map of slope stability in the cadastral area of Rajec [33]

Table 11 Resulting vulnerability values by parameter

Criterion	Parameter	Compliance with the vulnerability criterion
	Length of detour route	20 %
K1	Number of detour routes	25%
	Full-value compensation	60%
	Bridge length	10%
K2	Material of bridge	33%
	Age of bridge	60%
	Part of TEN-T	0 %
170	Part of TEM	0 %
K3	Part of the international road network "E"	0 %
	The economic significance of transport	80 %
K4	Traffic load	100%
	Slope movements and deformations	1%
175	Floods	10%
K5	Torrential rains	1%
	Technical condition of the dilatation unit	70%

study area, is particularly susceptible to landslides. An example of a slope stability map of the study area is shown in Figure 3.

For the purposes of assessing the third criterion, mapping documents or geographic information systems can once again be utilized. Among the selected features, the most common in the forested area is the II/517 road. Based on statistical data, no forest fires have occurred in the study area in the recent period [32]. In assessing the criterion for the impact of wind on the road infrastructure, mapping documents from Dlubal Software were employed. According to the map documentation supported by calculations based on technical standards, the territory of the town of Rajec is not located in an area threatened by wind. The same method was used to evaluate the threat of snow calamity. The territory of the town of Rajec falls under Snow Load Area 2, indicating a low risk [34]. These findings are supported by statistical data. No windstorms or snow calamities have been recorded in Rajec from 2013 to 2023 [32].

Since the data on the transport of hazardous substances on the selected routes are not available, the technical condition of the selected bridges M995, M5745, and M3698 were assessed based on the last criterion. These bridges are reported to be in poor technical condition according to available technical data [23].

To illustrate the process of vulnerability assessment of road infrastructure elements, the M995 bridge located on the first-class road I/64 was selected.

3.4 Vulnerability assessment of an element according to criteria and their parameters

Based on the previous characteristics, a vulnerability assessment of the major road infrastructure elements could have been conducted. For the purpose of applying

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Table 12 Lengths of possible detour routes (processed by [31])

Detour route	Length of the detour route
Povazska Bystrica - Rajec (II/517)	23.5 km
Zilina - Kamenna Poruba - Rajec (I/64-III/2108)	$23.2\mathrm{km}$
Prievidza - Rajec (I/64)	40.9km

Table 13 Resulting values of criteria and overall vulnerability of bridge M995

	F	Results of individual crite	ria	
K1	K2	K3	K4	K5
35%	34.33%	20 %	100%	20.5 %
		Resulting vulnerability	,	
		V=41.97%		

the modified parameters of the element vulnerability assessment criteria, the M995 bridge was selected. The values of each parameter are shown in Table 11. The individual parameters were calculated according to Equation (1).

From the above evaluations of the individual parameters, it is necessary to describe the parameter "Length of detour route". This parameter considers the significance of the bridge as a means to cross the Rajcianka River for the purpose of travelling to the surrounding area (especially to the city of Zilina) for work. Rajec hosts state forces such as the Police of the Slovak Republic and the Fire and Rescue Corps of the Slovak Republic, along with a polyclinic [31]. Therefore, in the case of damage to the M995 bridge, the basic functionality of emergency services (IZS) would be ensured. Another critical factor is the town's supply of foodstuffs, industrial materials, and fuel for petrol stations. It is assumed that this supply is primarily routed via the I/64 road from nearby Zilina. In assessing the "Length of detour route", parameter Rajec serves as the starting point. Table 12 below shows the detour routes and their respective lengths.

For the purpose of evaluation, the detour route Povazska Bystrica-Rajec (II/517) was chosen as it is a class II road and Povazska Bystrica is a district town. Cars can also use the route via Kamenna Poruba, which however runs along the Class II. road and local special purpose roads.

3.5 Assessment of the total vulnerability of the road infrastructure element

The values of each criterion and the resulting vulnerability of the road infrastructure element are shown in Table 13. The resulting vulnerability of the element was calculated according to the relation 2.

The resulting vulnerability of bridge structure M995 is 41.97%. To determine the vulnerability of the area, based on the road transport infrastructure elements, it would be necessary to calculate the vulnerabilities

of the remaining elements. This process would enable identification of the most vulnerable element of the transport infrastructure in Rajec. However, the assessment process itself provides valuable information about the element and its significance, which can serve as a basis for implementing measures.

4 Discussion

Road infrastructure plays a crucial role in functioning of a society and the economy, underscored by its classification as a sub-sector within critical infrastructure. The classification of the road infrastructure element is governed by specific sectoral and cross-cutting criteria. The disruption or destruction of the element would result in widespread negative consequences affecting the operations of the state or a significant part of its territory. However, at the county, city and town levels, there exist several road infrastructure elements that hold social or economic significance for those specific areas.

The aim of this study was to propose an approach for assessing the vulnerability of the road infrastructure elements using validated models. The authors consider the vulnerability assessment of the road transport infrastructure as an integral part of the overall vulnerability assessment of a territory. The overall vulnerability of an area is derived from the vulnerabilities of its constituent elements such as buildings, environment, population, etc. This study presents a potential approach to vulnerability assessment of the road transport infrastructure, using a modified model originally developed for assessing key elements of the railway transport at the Faculty of Security Engineering, University of Zilina.

The presented procedure enables the assessment of vulnerability in individual road infrastructure elements based on freely available data. By employing approaches that are not overly demanding in terms of data collection and availability, it allows for rapid and reasonably accurate results. These results can be informative for

the decision-making and further planning in territorial development and crisis management. The criteria and their parameters are well-suited for identifying significant elements of the transport infrastructure. By integrating those criteria into indicators for assessing vulnerability in the road infrastructure elements and their components, based on a societal vulnerability assessment model, it becomes feasible to pinpoint elements more susceptible to emergencies.

The diverse parameters, indicators, criteria, and assessment factors serve as a solid example of how to approach vulnerability or resilience assessments in specific areas. The criteria developed within the models, as adapted in this work, enable swift determination of transport infrastructure vulnerability. Identified vulnerable elements and their parts can subsequently influence the investment decisions, primarily benefiting crisis planning. Outputs from the assessment can facilitate development of evacuation route scenarios that account for the vulnerability of specific transport infrastructure elements. Moreover, they can guide emergency supply planning and the coordination of integrated rescue system components.

This assessment procedure is also applicable within a broader framework of territory risk assessment. Here, the vulnerability of the road transport infrastructure elements contributes to overall area vulnerability, which is a fundamental characteristics of the territory. Together with resilience determination, preparedness, and other features, this approach can comprehensively describe the state of the territory concerning the crisis impacts.

Many variables used to assess the vulnerability of area parts or elements can be expressed or analysed using the spatial data and geographic information systems. In the future research, aimed at comprehensive risk assessments and territory characteristics, like vulnerability or resilience, this approach could prove to be a suitable and valuable tool.

5 Conclusion

The effective models, aimed at identifying and assessing the vulnerability of transport infrastructure

were introduced and validated in this paper, and specifically applied and verified within the city of Rajec. By doing so, it was aimed to enhance the general understanding of vulnerability assessment within the road transport infrastructure and underscores its significance in bolstering the territorial resilience. This comprehensive approach not only evaluates the current vulnerabilities but prepares the communities for future challenges, as well. Moreover, the paper introduces the concept of resilience, increasingly acknowledged and applied by researchers to gauge the readiness of regions and individual stakeholders in facing crises. Resilience, as a concept, emphasizes adaptive capacities and the ability to recover swiftly from disruptions, thereby ensuring continuity and minimizing adverse impacts on communities. Through the models presented, the paper provides the readers with valuable insights into utilizing diverse indicators and criteria for assessing the vulnerability of transport infrastructure. Those assessments serve as pivotal components within the broader framework of resilience, contributing to informed decision-making processes and strategic planning for sustainable development. The integration of these models not only enhances the understanding of vulnerability within the transport infrastructure but also lays the groundwork for proactive measures that enhance resilience and ensure the long-term sustainability of urban and regional environments.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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