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Modernization of Railway Wagons for Customer Satisfaction and Safety

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Abstract: This article focuses on the assessment of the efficiency of the modernization of railway wagons intended for passenger transport. The modernization of railway wagons is an important step towards ensuring the safer and more efficient operation of railways. However, this modernization is not without risks and, in addition to its many positive effects, it can also bring new challenges in the form of breakdowns and technical problems. Failures in passenger rail vehicles are a challenge facing manufacturers and transport operators, and identifying the relationships between these failures can help to improve the design, manufacture, and maintenance of these vehicles. Passenger rail vehicle failures can vary in nature, whether mechanical, electrical, or inside the vehicle. This paper attempts to provide a comprehensive view of the effectiveness of passenger rail car retrofitting based on the data collected and statistical analyses. The article further focuses on the description of selected rail passenger wagons, describes the analyses of the statistical data using the correlation between the selected rail wagon failures and their significance, in addition to whether the impact of modernization reduces the number of rail wagon failures. The results of this statistical analysis can be used to better understand the impact of modernization on different aspects of passenger transport and will help in making future investment and policy decisions in this area.

Keywords: railway passenger transport; modernization; wagons

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1. Introduction

Rail passenger wagons are a key part of rail operations, having an irreplaceable function in both national and international rail passenger transport. Wagons are designed to provide safety and comfort for passengers. However, regular inspection and maintenance may not prevent faults and defects arising from its operation. In the current era, where the emphasis is on sustainability, the modernization of passenger wagons is also a means of reducing emissions and increasing the energy efficiency of rail operations. The modernization of passenger wagons is a key factor in ensuring the competitiveness of rail transport. The aim of this paper is to provide an overview of the importance and benefits of passenger car fleet modernization and to stimulate debate on the future of rail transport in an era of rapid technological change and increasing passenger demands by testing statistical hypotheses and correlations. A variety of analyses and data collection can be performed to examine statistical correlations in the context of railcar modernization, which could provide valuable insights into the relationships between various variables and the effects of modernization measures [1,2].

To perform these analyses, relevant data and statistical tools such as correlation coefficients, regression analyses, and analysis of variance are needed. The results of these analyses could help to better understand the impact of railcar retrofitting on different aspects, which could lead to informed decisions on rail operations, finances, and sustainability. For the application of statistical correlation, two series of railcars were selected, a Bmz series wagon and a Bdteer series wagon. The Bdteer passenger coaches were manufactured and put into service between 1990 and 1992; thus, they have been in operation for almost 26 years. As part of the modernization of the passenger wagons, solutions are used as far as possible to help unify the transport operator's fleet [3–5]. Bmz wagons have been converted from Bmeer wagons. A major advance in technical specification compared to the old wagons has been made in the areas of the pipe brake accelerator, which has increased braking performance, the boarding doors and front doors, which ensure greater passenger safety, and the information system, which provides external diagnostics of the wagon [6].

2. Research Design

The data were collected between April 2018 and March 2023 by the staff of the transport company as well as by the authors of the present paper. By summarizing and stratifying the data, an extensive database was created, which is divided into three parts [7]. The first part—data from the field—consists of data regarding the date of the fault detection, the location of the fault detection, the number of the wagon on which the fault occurred, the transport company owning the wagon, the category of the wagon, the structural unit on which the fault occurred, and the description of the fault. The second part—modernization—contains the wagon number, wagon series, year of modernization, and year of manufacture of the wagon. The third part—summary operational statistics—contains summary statistics obtained from the statistical yearbook of the carrier, the Statistical Office of the Slovak Republic and the Ministry of Transport [8,9]. Statistical correlation is an analytical method used to measure and express the degree of mutual relationship or association between two variables. This method is valuable for identifying how changes in one variable may reflect changes in another variable. Statistical correlation is widely employed in science, economics, sociology, and various other disciplines to examine relationships between different data or variables.

2.1. Disorders

A total of 78 types of disturbances were identified and listed in the database. Based on the assessment of the significance of the statistical feature variations, nine were selected as having the greatest impact on customer satisfaction and wagon operability—I1: doors and CZD, I2: toilets, I3: blocks. I1. WC; I4: air conditioning; I5: interior issues; I6: heating, I7: train radio, I8: lighting, I9: power distribution issues [10].

2.2. Structural Units

The database lists a total of 19 distinct structural units on which a fault has manifested itself. In terms of the significance of the variables of the considered statistical feature, five structural units were selected on the basis of the most frequent failures: C1: WC and washroom, C2: heating and air conditioning, C3: electrical equipment and wiring, C4: wagon cabinet, C5: interior fittings [11].

3. Results

Formulation of statistical hypotheses

From the point of view of the modernization of the units carried out on the passenger cars, it can be assumed that there is no statistical dependence between the individual failures and the cars. Based on the above, the statistical hypothesis H1 was formulated:

H1: *There is no significant statistical dependence between the individual failures.*

The structural units are upgraded based on the decision of the passenger wagon operator. This is mostly based on the frequency of failures. Therefore, repairing the most frequently failed unit should statistically significantly reduce the occurrence of a failure on that unit.

H2: *There is a significant statistical relationship between structural units and failures.*

The transport company regularly upgrades passenger wagons in order to increase passenger comfort but also to eliminate faults. By carrying out modernization it is possible to reduce the failure rate on passenger wagons.

H3: *The link between modernization and the reduction in breakdowns on passenger wagons is proven.*

3.1. There Is No Significant Statistical Dependence between the Different Disorders

A total of 275,895 failures were identified in the reporting period. From April to December 2018, 51,632 faults were identified. In 2019 and 2020, a total of 7027 and 42,178 faults were identified, respectively. Lastly, in 2021 and 2022, 44,433 and 56,640 failures were identified, respectively, and from January 2023 to March 2023, 10,739 failures were identified by the transport company's staff and employees. The following disorders subsequently led to the creation of a statistical correlation, the values of which are displayed in Table 1 [12,13].

Table 1. Correlation between selected passenger car failures.

	I1	I2	I3	I4	I5	I6	I7	I8	I9
I1	1								
I2	0.8569	1							
I3	0.1299	0.8934	1						
I4	0.0233	0.1093	0.0594	1					
I5	0.0834	0.1009	0.0837	0.2153	1				
I6	0.1573	0.2115	0.1080	0.7049	0.0655	1			
I7	0.0278	0.0819	0.4621	0.0255	0.0112	0.2115	1		
I8	0.3951	0.0482	0.3015	0.2145	0.2066	0.0985	0.1554	1	
I9	0.4587	0.2831	0.3591	0.1673	0.1862	0.2931	0.1576	0.9251	1

The correlation showed a statistical significance between parameters I1 and I2, I2 and I3, and I8 and I9. The results demonstrate statistical significance between the variations in the statistical feature of the disorder. A very strong correlation is shown between lighting and electrical wiring, strong between door and CZD and toilet, and between toilet and blocked vacuum toilet.

Statistically significant parameters need to be tested by a statistical significance test at alpha (0.05) level. Three pairs I1–I2, I2–I3, I8–I9 were tested.

For I1–I2, for the selected defining factor at the specified alpha confidence level, a p value of (0.0832) was obtained. Since the p value of the pair > p value is established, the dependence cannot be evaluated as reliable; i.e., we do not assume that dependence occurs in this pair.

For I2–I3, for the selected defining factor at the specified alpha confidence level, a p value of (0.1027) was obtained. Since the p value of the pair > p value is established, the dependence cannot be evaluated as reliable; i.e., we do not assume that dependence occurs in this pair.

For I8–I9, for the chosen defining factor at the established alpha confidence level, the p value reliability came out to be (0.0374). Since the p value of the pair < p value determined, it can be evaluated as reliable; i.e., we assume that dependence occurs in this pair [14–16].

The above hypothesis cannot be confirmed since a dependence between lighting and electrical wiring was found.

3.2. There Is a Significant Statistical Dependence between Structural Units and Failures

The carrier's dedicated passenger vehicles contain 19 structural units on which a failure was identified during the time period under review. By criterion selection of statistical feature variables, the structural units that are perceived by the customer—passenger the most were selected. These are five structural units: C1: toilet and washroom, C2:

heating and air conditioning, C3: electrical equipment and wiring, C4: wagon cabinet, C5: interior fittings.

Since the stated hypothesis is to find only those dependencies that are statistically significant, only dependencies where the coefficient of dependence $\beta > 0.85$ were considered. Based on the results presented in Table 2, a dependence between the following traits can be established:

- C1–I2;
- C2–(I4 + I6);
- C3–(I7 + I8 + I9);
- C4–I4;
- C5–I9.

Table 2. Correlation between selected passenger car failures and car structural units.

	I1	I2	I3	I4	I5	I6	I7	I8	I9
C1	0.7931	**0.8804**	0.0270	0.0057	0.3058	0.0991	0.0054	0.0040	0.0004
C2	0.2597	0.0434	0.1824	0.9053	0.1571	**0.9182**	0.1246	0.0806	0.7261
C3	0.2326	0.2775	0.2427	0.0330	0.7865	0.7770	**0.8649**	**0.9243**	**0.9535**
C4	0.1246	0.2191	0.0271	**0.9053**	0.1246	0.2144	0.0434	0.2053	0.0312
C5	0.0262	0.2155	0.2438	0.1747	0.1571	0.2675	0.2597	0.0259	**0.9254**

The above variations in the statistical features C and I that were strongly correlated with each other were tested by significance test at the chosen alpha level (0.05). Three pairs, one triplet, and one quadruplet were tested.

For C1–I2 (dependence of toilet and washroom design unit on the failure labeled toilet), for the selected defining factor at the specified alpha confidence level, a *p* value reliability value of (0.0332) was obtained. Since the *p* value of the pair < *p* value determined, the dependence can be evaluated as reliable, i.e., we assume that dependence occurs in this pair.

For C4–I4 (dependence of the car body structural unit on the fault labelled air conditioning), a reliability *p* value of (0.0499) was obtained for the selected defining factor at the established alpha confidence level.

Since the *p* value of the pair is <*p* value set, the dependence can be evaluated as reliable; i.e., we assume that dependence occurs in this pair.

For C5–I9 (dependence of the design unit interior furnishing on the fault labeled power distribution problems), for the selected defining factor at the established alpha confidence level, the reliability *p* value came out to be (0.0809). Since the *p* value of the pair > *p* value determined, the dependence can be evaluated as unreliable; i.e., we do not assume that dependence occurs in this pair.

For C2–(I4 + I6), it is necessary to split the analysis into two planes:

- C2–I4—dependence of the heating and air conditioning design unit on the fault labelled air conditioning—*p* value = 0.0409;
- C2–I6—dependence of the heating and air conditioning design.

For the chosen defining factor at the established alpha confidence level, the *p* value for both parameters came out < *p* value established, and the dependence can be evaluated as reliable; i.e., we assume that dependence occurs in this pair, despite the fact that both failures came out with only a medium level of dependence—i.e., it was not possible to statistically demonstrate dependence between the heating failure and the air conditioning failure. For C3–(I7 + I8 + I9), it is necessary to divide the analysis into three planes:

- C3–I7—dependence of the structural unit electrical equipment and wiring on the fault marked train radio—*p* value = 0.0750;
- C3–I8—dependence of the electrical equipment and wiring on the fault marked lighting—*p* value = 0.0231;

- C3–I9—dependence of the design unit electrical equipment and wiring on the fault labelled power distribution problems—p value = 0.0197.

For the chosen defining factor at the established alpha confidence level, the p value for both parameters (d,e) came out < p value established, and the dependence can be evaluated as reliable; i.e., we assume that dependence occurs in this pair. The dependence between failures referred to as power distribution and lighting problems was demonstrated, similar to the above design set.

3.3. There Is a Proven Correlation between Retrofitting and the Reduction in Breakdowns on Passenger Wagons

Due to the gradual modernization of the rolling stock, the following models were selected and compared in terms of their fault rates before and after modernization. Bdteer (18 wagons) and Bmz (26 wagons) were selected. The Bdteer passenger coaches were built and put into service between 1990 and 1992 and have been in service for almost 25 years. As part of the modernization of the passenger wagons, solutions are used to the greatest extent possible to facilitate the unification of the transport operator's fleet. Bmz wagons have been refurbished from Bmeer series wagons. A major shift in technical specification compared to the old wagons occurred in the area of the pipe brake accelerator, which has increased braking power, the boarding doors and front doors, which ensure greater passenger safety, and the information system, which provides external diagnostics of the wagon [17].

In terms of time series, the results were compared, as shown in Table 3.

Table 3. Comparative criteria.

Type of Wagon	Time Series before Modernization	Time Series after Modernization	Numbers of Wagons
Bmz	March 2018–September 2021	October 2021–March 2023	26
Bdteer	January 2020–April 2022	May 2022–March 2023	18

The modernization of both wagon rows was carried out by the same carrier and under the same conditions. During the modernization, several design changes were made, in particular an increase in the design speed, replacement of wiring, modernization of electrical elements such as wagon security, and the modification and replacement of toilets and other structural units. Based on Table 4, the retrofit for the Bdteer series cars has resulted in a reduction in the number of failures on several structural units. The highest benefit was brought by the upgrades to the WC and washroom structural units.

Table 4. Comparison of modernization efficiency on structural elements—Bdteer wagons.

Structural Unit	Proportion of Disorders/1 Month	
	Before Modernization	After Modernization
WC Washroom	7.2143	5.2667
Wagon Cabinet	2.3571	2.2333
Electric Equipment	2.1786	0.9333
Interior Equipment	1.4643	1.0667
Heating/AC	1.1071	0.7667
Others	0.9286	0.3333
Chassis	0.3571	0.2333
Air Brake	0.1786	0.0667
Other Equipment	0.1429	0.0333
Low-Voltage locomotive current	0.0357	0.0333

The failures decreased from an overall average of 7.2 failures per month to 5.27 failures per month. In terms of failures, failures due to malfunctioning toilet equipment have significantly decreased; on the contrary, there have been a number of failures due to blockage of the vacuum toilet and lack of water in the storage tank.

The modernization also led to a significant reduction in faults caused by electrical wiring by almost two per month. Faults caused by insufficient recharging, train radio faults, and lighting problems were eliminated. After the upgrades, the most common fault identified as other faults occurred, which includes mainly broken seals or burnt tubes on lighting bulbs.

The Bmz series upgrades, like the previous series, have been successful. The results shown in Table 5 tell of a reduction in failures on the various passenger car structural units considered.

Table 5. Comparison of modernization efficiency on structural elements—Bmz type wagons.

Structural Unit	Proportion of Disorders/1 Month	
	Before Modernization	**After Modernization**
WC Washroom	8.5357	4.8667
Wagon Cabinet	3.1429	1.7667
Electric Equipment	2.4643	1.4333
Interior Equipment	2.3571	0.7333
Heating/AC	1.1786	0.5667
Others	0.8929	0.4333
Chassis	0.6429	0.2667
Air Brake	0.3214	0.1333
Other Equipment	0.2143	0.0667
Low-Voltage locomotive current	0.1071	0.033

As with the previous wagon type, there has been a significant reduction in failures on all structural units. In terms of the washbasin and toilet structural unit, there has been a reduction in failures of almost 50%. Failures due to non-functioning toilet equipment and lack of water were reduced. The defects that occurred most frequently after renovation were mainly stickers, interior soiling, and jammed doors.

A significant decrease in defects was also identified on the wagon box structure, where defects due to mechanical damage and soiling were reduced [18].

A decrease in defects was also observed on the structural unit interior equipment after retrofitting—the defects due to problems related to the interior equipment of the wagon were eliminated. After the retrofit, defects were rare, with only problems with wagon cleanliness being identified to a greater extent.

In conclusion, based on the results presented in Tables 4 and 5, the above hypothesis can be accepted, where based on the collected results, it can be stated that the modernization reduced the number of identified failures on the selected structural units of the passenger cars [19,20].

4. Discussion

The modernization of passenger railway wagons is a current topic with the potential to transform the face of railway transportation. It creates a better future for passengers as well as the environment. This discussion focuses on some of the key aspects of modernization and the questions that arise in this significant endeavor [21].

One of the primary objectives of modernization is to enhance passenger comfort. Modernizing the wagon interior can significantly contribute to increasing the number of passengers using rail passenger transport. The modernization of passenger railway wagons has the potential to reshape the way we travel and contribute to a more sustainable future.

Experience in the operation of passenger wagons shows that postponing their modernization and failing to fulfill the repair plan have adverse consequences [22,23]. The process of modernizing the wagons has a linear character; it is supposed to enable effective repairs in accordance with valid repair regulations, i.e., revision repair or intermediate repair. When carrying out general repairs or for specific requirements, equipped pit stations are usually already available in repair shops. Particular emphasis must be placed on the continuous modernization of diagnostic equipment for testing electrical equipment and brake systems to increase the operational reliability of wagons. A specific area in the process of repairing passenger cars is the issue of surface treatment. Particular attention must be paid to its quality. The problems of modernization of wagons and its financing include large-scale rebuilding of interiors, equipment of wagons, bridging of the emergency brake, and installation of fire detectors, central sources or air conditioning [24,25].

Based on the results of the research, it is essential that the wagons currently meet the following conditions. Wagons should be designed for the Central European climate zone, with air-conditioning with cold air streaming from the wagon ceiling and heating and cooling regulation [26]. The next very important condition is windows with tinted athermal windowpanes. After the modernization, to make customers happy, the wagon entrance corridor should be redesigned with modern folding seats and bicycle storage brackets, new easy cleaning floors, an enclosed vacuum toilet system and spacious toilet for wheelchair users, electro-pneumatic plug doors with an integrated system of selective opening to station platform side, electro-pneumatic sliding connecting doors, and sliding interior doors. All doors system should comply with the applicable TSI requirements. An upgraded lighting system and cabling, a new system of sockets for laptops, an upgraded water supply system, and an emergency brake overriding system are needed. There should be a fully air-conditioned interior, 230 V sockets, high performance WiFi for passengers, with all the entrance doors located in the low-floor area. The control system must enable the multiple control of the units. An integral part includes ergonomic seats and a well-arranged information system. An external and internal camera system with remote data transmission is important, and a smart information system is needed [27–29].

Due to rising prices and the energy crisis, repairs and modernization of wagons are taking longer, and the level of quality of rail travel is also decreasing. The level of quality of maintenance provided by suppliers is directly proportional to their technology and innovation. Railway undertakings have set requirements that individual suppliers must meet. The breakdown rate of vehicles is significantly affected by their age, and in this area, the undertakings must try to increase reliability by modernizing the vehicle fleet. Ensuring repairs of railway rolling stock must be approached in a standardized manner and in terms of internal processes with an emphasis on the quality and safety of railway operations. It is necessary to approach individual suppliers in the same way and communicate with them intensively, regardless of whether they are domestic or foreign. Extending repair deadlines naturally has a negative impact on the planning and implementation of traffic services. Contractors must communicate with carriers when dealing with complicated situations and specific requirements in the field of rolling stock repairs. If suppliers do not fulfill their obligations or have a non-standard approach, the solution is to apply contractual fines and sanctions enshrined in individual contracts [30,31].

Based on the previous conclusions of the research, regular and high-quality modernization is part of eliminating the failure rate of wagons. This can only be ensured in the case of a systemic approach aimed at customer orientation and service quality [32].

The methods of the applied statistical analysis have demonstrated that regular maintenance and modernization of railcars are primarily associated with increased passenger safety. Specific technological and structural elements have been identified, and the effectiveness of railcar modernization has reduced the number of malfunctions, thereby minimizing risks and accidents within the operation of passenger rail transportation. The efficiency of modernization is primarily contingent on the level of financial resources provided. Investments in railcar modernization prove to be cost-effective, contributing not only to safer and more efficient operations but also yielding long-term financial benefits for operators of passenger rail transportation. Based on the obtained results, we have identified areas that require further research, particularly in the optimization of specific technological solutions and a deeper understanding of passenger satisfaction with modernized railcars. The results of the statistical correlation confirm that the modernization of passenger railcars brings significant benefits in terms of safety, efficiency, and passenger satisfaction. These findings can serve as a foundation for further innovations in the field of railway transportation and provide support for investments in railcar modernization in the future.

5. Conclusions

The correlation between selected malfunctions in passenger railcars in railway transportation has been thoroughly analyzed and assessed in this study. Based on a wide range of collected data and a detailed examination, mutual relationships between various types of malfunctions and their potential causes have been identified. Statistical correlation has demonstrated a dependence among the selected types of malfunctions, some of which may be caused by similar factors. The theoretical contributions of establishing this correlation enable a better understanding of the interconnection between individual malfunctions, leading to more effective diagnostic procedures and faster fault resolution. Simultaneously, the results of the correlation allow a focus on specific areas where actions for improvement are necessary. Correlations between selected malfunctions in passenger railcars were also identified in the article, with their statistical significance being assessed. The collected data were analyzed using statistical methods, aiming to confirm whether the identified relationships were random or indeed significant. Statistical methods were applied in the research section of the contribution to evaluate the significance of the identified correlations. This approach confirmed that the relationships between malfunctions and the structural components of railway passenger cars were not random but possessed statistical significance. The result of the research also includes a comparative table of railway passenger cars, specifically examining the types of cars Bdteer and Bmz. This table recorded data on the failure rates of the cars for the past month both before and after modernization, considering a selected number of examined vehicles. Following a thorough statistical analysis, a positive impact of the modernization on the operation and failure rates of the cars was indeed observed. For the first series of the Bdteer railway car, the average failure rate was reduced by more than 55% based on the selected indicators. Similarly, for the second type of railway car in the Bmz series, the failure rate decreased by more than 39% under the same statistical parameters. The conclusion of the research emphasizes that understanding and systematically monitoring the structural components of railcars can significantly contribute to preventing malfunctions and improving the overall reliability of the railcar fleet. The findings offer a substantial contribution to more efficient railcar maintenance and can serve as a foundation for future innovations in the construction of passenger railcars, aiming to optimize their performance and ensure safe and reliable railway transportation for passengers.

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