RESEARCH INTO FAILURE RATES OF TRACTIVE ROLLING STOCKS

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Abstract: Failures of means of transport significantly affect the reliability and availability of the individual modes of transport. This paper presents a study of failure rates of powered railway vehicles. The frequency of failures in 69 powered locomotives was monitored. Bathtub curves were drawn for individual railway vehicles and the probabilities of their failure-free operation were identified. The most reliable powered locomotives, as well as locomotives with the highest failure rates, were identified based on the risk matrix by applying the Risk Based Inspection (RBI) method. The work brings new results from the point of view of the failure rate of tractive rolling stocks. The intensity of failures was determined to assess the reliability. Graphical dependences on the instantaneous values of the failure rate on time, i.e. the vehicle life indicators, were constructed. The contribution of this work is the research of the failure rate of rolling stock used in railway transport. Based on the risk matrix according to the RBI method, the most reliable electric locomotives were identified.

Keywords: Failure rate, locomotives, RBI, bathtub curve.

1 Introduction

In practice, reliability is typically evaluated based on a failure rate λ, which expresses the number of failures that occur over a time unit throughout the vehicle life cycle. Instantaneous values of failure rates may be calculated as a quotient of the value of the slope of the tangent line to the curve of probability of a failure F(t) and the respective value of probability of a trouble-free operation, i.e. reliability R(t) at a particular moment in time t_0 (Raschman & Pačaiová, 2002):

$$\lambda(t_0) = \frac{\left(\frac{dF}{dt}\right)t_0}{R(t_0)} \tag{1}$$

The failure rates of the railway rolling stock can be estimated using age values and the railway stock maintenance manual (Park et al., 2017).

A graphical representation of the correlation between the instantaneous values of failure rates and the time is a curve of the vehicle life indicators. The curve of the vehicle life indicators, i.e. the bathtub curve, is an analogue to the wear curve, which is comprised of three distinguishable phases (early use, normal use, wear-out). Since the failure rates are highest during the early life and at the wear-out, the bath curve (Figure 1) suggests 3 areas of failure rates (Roesch, 2012):

- I – early use phase;
- II – normal use phase;
- III – wear-out phase.

The period of early failures is referred to as the infant mortality period. Immediately after the vehicle is put in use, early failures may occur. Causes of such failures may be internal (faulty design, manufacture or assembly) or external (impermissible overloading of a vehicle, violation of rules for operation, maintenance or repair, etc.).

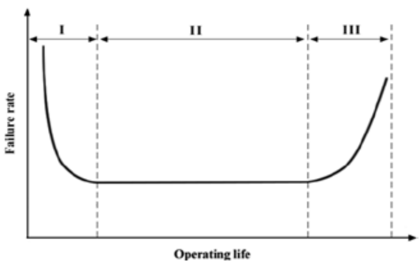


Figure 1. Curve of the vehicle life indicators (bathtub curve)

However, the curve is only typical for certain types of simple equipment and for certain more complex objects with a dominant mechanism of failures. The course of the failure period by wearing out is often affected by the wear, for example, by fatigue, corrosion and abrasion. In general, contemporary equipment is much more complex and the shapes of the curves of life indicators are therefore different. Fig. 2 shows the bathtub curves of various electric and mechanical components based on their use times (Raschman and Pačaiová, 2002; Moubray, 1997):

Pattern A (Figure 2a) represents a typical bathtub curve – it begins with a high failure rate period, which changes into the period of approximately a constant failure rate and ends with the wear-out zone.

Pattern B (Figure 2b) exhibits a prolonged period of a constant failure rate or a failure rate with a slowly increasing intensity, eventually followed by the wear-out zone.

Pattern C (Figure 2c) – the failure rate gradually and slowly increases, but the curve does not end with the wear-out zone.

Pattern D (Figure 2d) – typically low failure rates of new products, which shortly afterwards sharply increase to a constant level.

Pattern E (Figure 2e) represents a constant failure rate throughout the whole operating life.

Pattern F (Figure 2f) begins with a high failure rate, which later sharply decreases down to a constant value.

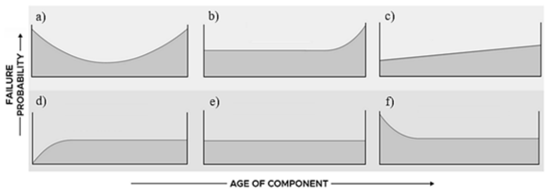


Figure 2. Curves of the vehicle life indicators, a) pattern A, b) pattern B, c) pattern C, d) pattern D, e) pattern E, f) pattern F (Christiansen, 2023)

Even though Patterns A, B and C can be monitored, it is impractical to monitor Patterns D, E and F as there is no or only a little change that could be used to justify the diagnosis of a maintenance need (Baglee, 2014).

Studies in the field of civil aviation have shown that Pattern A describes behaviour of approximately 4% of objects, while Pattern B describes 2%, C 5%, D 7%, E 14% and Pattern F describes 68% of objects (Pačaiová, 2006).

Despite the fact that relative proportions of objects with different behaviours (Patterns A to F) in the aviation sector and various industries are not identical, in general, the patterns of equipment failure rates increasingly approach the shapes of Patterns E and F as the complexity of the equipment increases (Pačaiová, 2011).

The bathtub curve model with a finite support can better conform the sharp change in the failure rate, which usually increases very fast in the wear-out phase (Jiang, 2013).

Increasing the proportion of railway transport is crucial for reducing the environmental pollution caused by road transport (Frisch et al., 2021). Maintenance of the railway infrastructure plays a key role in the railway transport sector. Its purpose is to ensure safety of operation and availability of railway lines, as well as related equipment, for the purpose of transport regulation. Competition on the transport market requires the improvement of vehicle maintenance with the aim of reducing the maintenance cost while maintaining the operation safety (Macchi et al., 2012) railway companies must comply with the determined safety regulations (Roberts et al., 2002) that define maintenance procedures, as well as frequencies of preventive measures, primarily aimed at providing high-level safety (Carretero et al., 2003). In the European Railway Transport, great efforts are exerted in the field of Condition-Based Maintenance (CBM) with the aim of collecting, processing and evaluating data using respective sensor systems for the online monitoring of the condition of lubricated components of locomotives and wagons in order to increase their safety and availability while reducing the maintenance costs and unplanned downtimes (Schneidhofer, Dubek & Dörr, 2023).

The paper (Ambriško, Šaderová & Antal, 2023) deals with the evaluation of parameters of reliability of railway transport vehicles and presents the methods for railway vehicle maintenance. Authors of the paper (Nedeliaková, Valla & Masár, 2024) assessed the efficiency of modernisation of wagons intended for the passenger transport; according to their opinion, modernisation is an important step towards safer and more efficient operation of railways. When idle, wagons are mostly kept in workshops and subjected to maintenance and repairs, and that increases the costs of, for example, lease and storage. Train fleets remain idle on average 70% of time; as a result, additional storage costs are incurred. Moreover, maintenance operations that are intended for larger train fleets become inefficient, while it is expected that they will be adjusted to the servicing and inspection of multiple idle wagons (Bigi et al., 2024). When organising maintenance of wagons, experts must take into consideration two main challenges: (i) which of the wagons of an arriving train must be parked for maintenance required under relevant regulations or which wagons must be replaced; (ii) how to implement a traffic schedule that will ensure traffic safety (Zagorskikh, Alsova & Gavrilov, 2020). The purpose of the paper (Bigi et al., 2024) was to investigate into long-term effects of mileage-based maintenance on the management of freight trains, as well as its impact on the fleet idle rate and management.

The challenges related to the support of required professional skills of staff performing the maintenance of railway wagons were discussed in the paper (Nikitin et al., 2020), authors of which designed a virtual-reality-based simulator for the purpose of testing the skills of maintenance staff according to the instructions.

The purpose of this paper was to investigate into failure rates of railway vehicles used in the railway transport. Bathtub curves were drawn for the monitored locomotives and the values of probability of their reliable operation were identified. The most reliable powered locomotives were identified based on the risk matrix by applying the RBI method.

2 Experimental part

The research described in this paper included the monitoring of failure rates of 69 electric tractive railway vehicles over the period of years 2018 and 2019: (i) Series 350 – 18 double-system electric locomotives; (ii) Series 361 – 26 double-system electric locomotives; and (iii) Series 757 – 25 engine-powered locomotives. The parameters of the locomotives of those three series are listed in Tab. 1.

Tab. 1. Basic technical data of engine-powered locomotives (Series 350, 361, 757 locomotive)

Series	350	361	757
Gauge [mm]	1,435	1,435	1,435
Continuous horsepower [kW] (*total)	4,000	3,600	1,550*
Length over buffers [mm]	16,740	16,800	16,540
Total wheelbase [mm]	11,700	11,500	11,400
Bogie wheelbase [mm]	3,200	3,200	2,400
Max. speed [km.h^{-1}]	160	140	100
Locomotive weight [t]	87.6	86	75.4

2.1 Description of the methods used

During the use of a vehicle, the failure intensity λ is approximately constant; that means that the percentage of vehicles in which a failure occurs over the same time interval during the use period is the same. In such a case, the probability of a failure is distributed exponentially. For many real-world objects, such a result may be identified by calculating a mathematical equation, but also confirmed empirically in an analysis. The failure probability density for the operating time t is calculated using the following equation (Pačaiová, 2011):

$$f(t) = \lambda e^{-\lambda t}, \qquad t \geq 0 (\lambda = k = const.) \tag{2}$$

Failure probability in the (0, t) interval is determined by the probability density function F(t):

$$F(t) = 1 - e^{-\lambda t} \tag{3}$$

Reliability as the probability of reliable operation R(t) is then calculated using the following equation:

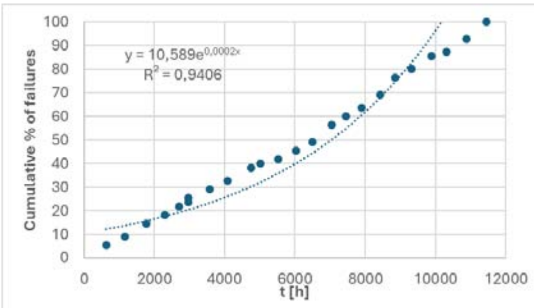
$$R(t) = 1 - F(t) = e^{-\lambda t} \tag{4}$$

The R(t) function expresses the probability that an object will withstand t hours of operation without a failure. For the reliability of railway transport vehicles with failure rates that change over time, the Weibull probability distribution was applied.

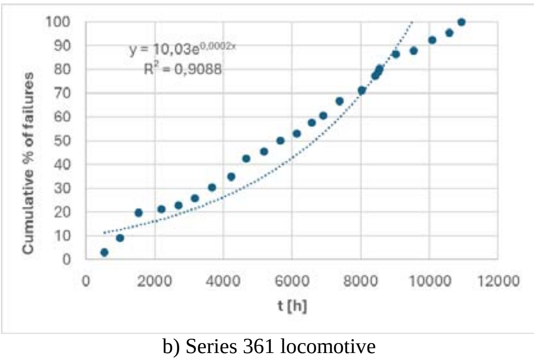
The Risk-Based Inspection (RBI) method is used to identify and understand the factors affecting the risks while considering the equipment lifespan (Petronic et al., 2024). RBI, i.e. the process of creating an inspection schedule based on the knowledge of the risk of equipment failure, is typically used in multiple industries (Mohamed. Hassan & Mahar, 2018). In this paper, the most reliable engine-powered railway transport vehicles, in particular locomotives, were identified based on the risk matrix (Čabaníková, Ambriško & Ďuriška, 2024).

3 Results

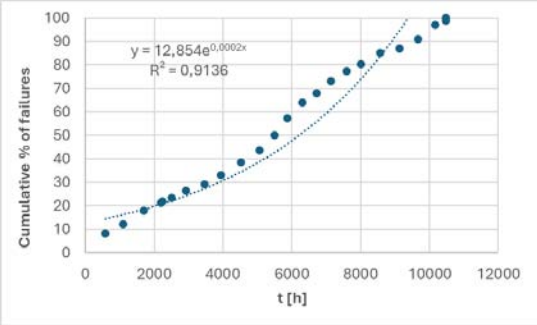
Failure probability distribution curves represent the correlations between the total number of locomotive failures in cumulative percentage and the operating time t. Figure 3 shows particular examples for the individual locomotive series. The least squares method was applied to approximate the curves using exponential functions. The values of the failure probability and of the probability of reliable operation (reliability) of the locomotives were identified (Figure 4). The sum of the failure probability F(t) and the reliability R(t) equals 1 in every moment in time (Ben-Daya et al., 2009).



a) Series 350 locomotive



b) Series 361 locomotive



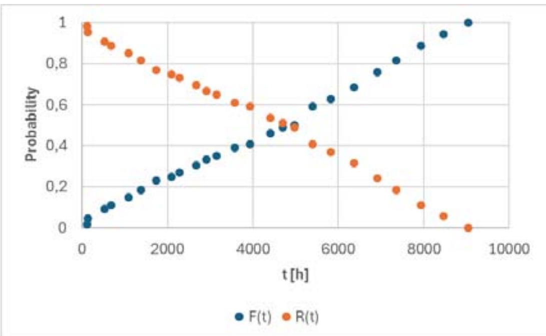
c) Series 757 locomotive
Figure 2. Failure probability distribution curves

The shapes of the curves of the F(t) functions for the 350 Series locomotives indicate that in the time interval of 0–3,500 hours, a failure may be expected in 35% of locomotives, while after 7,000 hours of operation, as much as 75% of them will exhibit a failure. The data shows that out of the locomotives that are put in use after 3,500 hours, 65 out of 100 will probably be functioning (i.e. 12 out of the monitored number), while after 7,000 hours, only 25 out of 100 will continue to be functioning (i.e. 4 locomotives of the 350 Series).

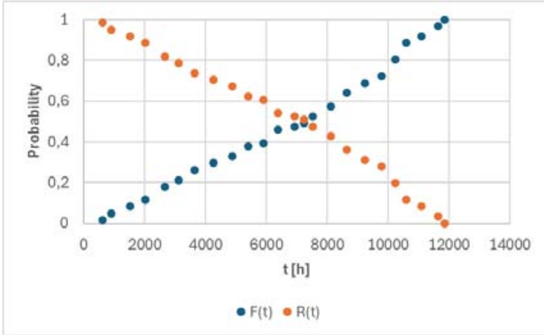
The shapes of the curves of the F(t) functions for the 361 Series locomotives indicate that in the time interval of 0–5,200 hours, a failure may be expected in 35% of locomotives, while after 11,000 hours of operation, 75% of locomotives will be malfunctioning. Out of the locomotives put in use after 5,200 hours, 17 out of the monitored locomotives will probably be functioning, while after 11,000 hours, only 6 locomotives of that series will continue to be functioning.

The shapes of the curves of the F(t) function for the locomotives of Series 757 clearly show that in the interval of 0–4,100 hours, a failure is likely to occur in 35% of locomotives, while after 8,100 hours of operation, 75% of locomotives will exhibit a failure. Based on the analysed data, after 4,100 hours of operation, 65 out of 100 locomotives will probably be functioning (i.e. 16 out of the monitored number), while after 8,100 hours, only 25 out of 100 locomotives will be functioning – 6 locomotives of the 757 Series.

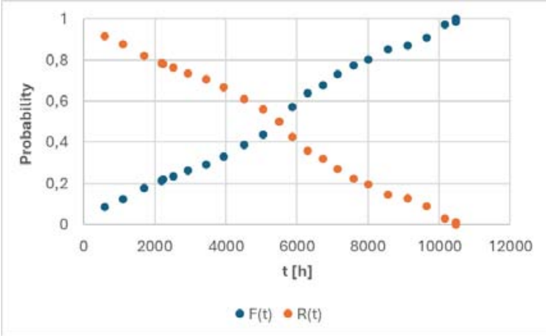
Data on failure probability may be used to determine reliability of an analysed object (Ben-Daya et al., 2009). The probability of reliable operation R(t) decreases over time. After 4,900; 7,250; and 5,500 hours of operation (Series 350; 361; and 757), the locomotive reliability value decreases to 0.5. The failure probability F(t) increases over the operating time: the initial value is 0 when the locomotive is put in use, then the value is 0.5 after approximately 5,880 hours of operation, and eventually 1 at the time of a failure occurrence.



a) Series 350 locomotive

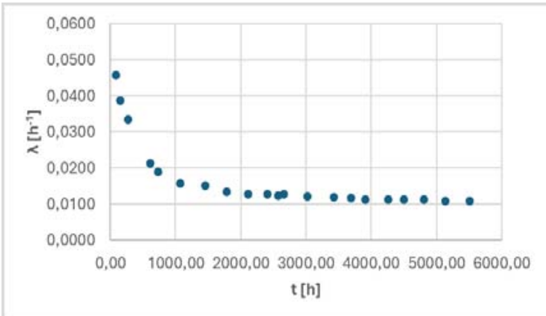


b) Series 361 locomotive

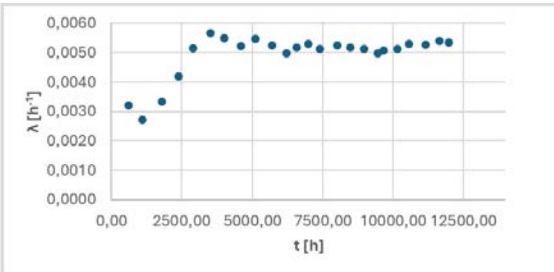


c) Series 757 locomotive
Figure 3. Curves of the failure probability F(t) and the reliable operation R(t)

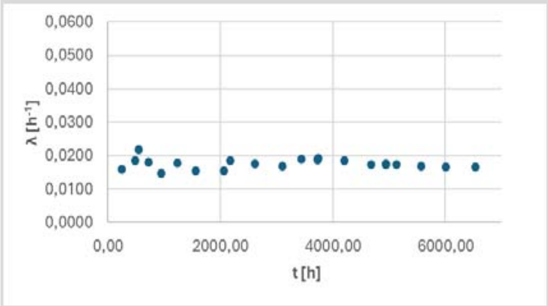
A graphical representation of the correlation between the instantaneous values of a failure rate λ and time t represents the curve of the locomotive life indicators – a bathtub curve (Figure 5). Immediately after the beginning of operation, early failures occur. After a certain time of operation, the period of low and approximately constant failure rates follows. Even though this period of standard operation is designated on the bathtub curve with a horizontal line, it is actually of a slightly bent shape (Pačaiová, 2006).



a) Pattern F for the Series 350 locomotive



b) Pattern D for the Series 361 locomotive



c) Pattern E for the Series 757 locomotive
Figure 4. Bathtub curves

Analysis of the bathtub curves for the analysed locomotives showed that Pattern D describes behaviour of 30.3% of locomotives, while Pattern E of 39.4% of locomotives and Pattern F of 30.3% of locomotives. Although relative proportions of the individual locomotives are not identical, the shapes of the curves of failure rates of the locomotives of the Series 350 are similar to Patterns E and F, while the shapes of the curves for the locomotives of Series 361 and 757 are similar to Patterns D and E.

The input data required for creating the risk matrix was the data on failure rates of the locomotives (in particular the duration and number of failures). Based on the performed analysis and subsequent data categorisation into 3 levels (I, II, III), the locomotives with short-lasting failures and of low failure frequency were identified, i.e. the locomotives with a lower risk of failure. By contrast, locomotives with long-lasting failures and of a high failure frequency were identified as the locomotives with a significantly higher risk of failure. The risk matrix (Figure 6) facilitated the identification of the locomotives that are excellent or problematic, as well as those that require the following:

- Applying the TPM (Total Productive Maintenance) in order to improve their efficiency and reduce the maintenance costs and losses caused by downtimes (Sharma, Chandra & Singh, 2019), based on good communication between the operator and the maintenance staff – the key principle of the TPM strategy (Valenčík and Stejskal, 2009) which emphasises active engagement of employees in maintenance;
- Applying the Reliability-Centred Maintenance (RCM) – a methodical approach to the creation of a planned maintenance programme consisting of cost-effective tasks while ensuring the performance of the critical functions of the equipment (Roberts et al., 2002); RCM is aimed at the identification of critical components of locomotives and creates maintenance plans based on the risks related to those components and their importance;
- Preventive repairs, i.e. a set of activities of various natures that are performed as the prevention against failures;
- Trainings for maintenance staff or equipment operators are aimed to ensure that the employees engaged in the operation and maintenance of locomotives posses the knowledge, skills and information required for the efficient and safe performance of their tasks;
- General repairs and improvements, i.e. extensive adjustments and renovation of locomotives that will improve their reliability, performance and safety, and will extend their lifespan.

The matrix contains colour-coded locomotives of three different series (350, 361 and 757), divided into 9 cells. The risk matrix clearly shows that the majority of locomotives of the Series 757 were identified as those with the highest risk. In order to increase reliability of those locomotives, TPM and RCM methods should be applied, and general repairs should be performed on the locomotives with the highest failure rates. Three colour-coded cells contain the locomotives that require radical repairs.

Frequency of failures	Time of failure: I Low	Time of failure: II Medium	Time of failure: III High
I Low	*Excellent locomotives* 19, 20, 27, 30, 31, 35, 36, 41, 44	*TPM* 9, 10, 21, 23, 24, 25, 37, 38, 40, 43	*Problematic locomotives* 47, 49, 51, 52
II Medium	*Preventive repair* 5, 22, 26, 28, 29, 34, 39, 42	*TPM* 1, 6, 8, 11, 16, 32, 33, 50	*TPM, RCM* 45, 53, 54, 55, 56, 57, 58
III High	*Trainings* 2, 3, 13, 14, 15, 18	*TPM, RCM* 4, 7, 12, 17, 65	*General repair, improvements* 46, 48, 59, 60, 61, 62, 63, 64, 66, 67, 68, 69

Series 350, Series 361, Series 757 — Radical repair

Figure 6. Risk matrix for engine-powered locomotives

4 Conclusion

Research into failure rates of tractive rolling stock provides the options how to improve the management of maintenance in railway transport. Shapes of the bathtub curves drawn for the monitored engine-powered locomotives approach the shapes of Patterns D, E and F.

The failure probability distribution curves for the ribution were approximated using exponential functions. The curves of failure probability clearly show that the locomotive of Series 361 exhibited the longest operation times to failure occurs in 35% and 75% of locomotives. Their reliability, i.e. probability of reliable operation, for the value of 0.5 reaches the maximum operation time out of all 3 locomotive series. The risk matrix confirmed the lowest risk of failures, particularly for the series 361.

Literature:

1. Ambriško, Ľ., Šaderová, J., Antal, R.: *Evaluation of Railway Vehicle Reliability Parameters*. Acta Polytechnica Hungarica. 20(4). 2023. pp. 27-43. ISSN 1785-8860.
2. Baglee, D., Jantunen, E.: *Can Equipment Failure Modes Support the use of a Condition Based Maintenance Strategy?* 3rd International Conference on Through-life Engineering Services. Procedia CIRP 22. 2014. pp. 87-91. ISSN 2212-8271.
3. Ben-Daya, M., et al.: *Handbook of Maintenance Management and Engineering*. New York: Springer, 2009. 768 p. ISBN 978-1-84882-471-3.
4. Bigi, F., et al.: *Long-Term Fleet Management for Freight Trains: Assessing the Impact of Wagon Maintenance Through Simulation of Shunting Policies*. Journal of Rail Transport Planning & Management. 29. 2024. pp. 1-21. ISSN 2210-9714.
5. Carretero, J., et al.: *Applying RCM in Large Scale Systems: a Case Study with Railway Networks*. Reliability Engineering & System Safety. 82(3). 2003. pp. 257-273. ISSN 1879-0836.
6. Čabaníková, L., Ambriško, Ľ., Ďuriška, M.:. *Assessment of Wagon Failures by the RBI Method*. Acta Logistica Moravica. 14(1). 2024. pp. 1-8. ISSN 1804-8315.
7. Christiansen, B.: *An Introduction to Equipment Failure Patterns*. Available at: https://limblecmms.com/blog/equipment-failure-patterns (Accessed on 20 August 2023).
8. Frisch, S., et al.: *Solving a Real-World Locomotive Scheduling Problem with Maintenance Constraints*. Transportation Research Part B. 150. 2021. pp. 386-409. ISSN 1879-2367.
9. Jiang, R.: *A New Bathtub Curve Model with a Finite Support*. Reliability Engineering & System Safety. 119. 2013. pp. 44-51. ISSN 1879-0836.
10. Macchi, M., et al.: *Maintenance Management of Railway Infrastructures Based on Reliability Analysis*. Reliability Engineering and System Safety. 104. 2012. pp. 71-83. ISSN 1879-0836.
11. Mohamed, R. B., Hassan, C. R., Mahar, D. H.: *Developing a Risk-Based Inspection Practices Maturity Model for Malaysian Industries*. Journal of Loss Prevention in the Process Industries 56, 2018. pp. 217-230. ISSN: 1873-3352.

12. Moubray, J.: *RCM: Reliability Centered Maintenance*. South Norwalk: Industrial Press, 1997. 448 p. ISBN 9780831131463.
13. Nedeliaková, E., Valla, M., Masár, M.: *Modernization of Railway Wagons for Customer Satisfaction and Safety.* Vehicles. 6. 2024. pp. 374-383. ISSN 2624-8921.
14. Nikitin, A., et al.: *VR Training for Railway Wagons Maintenance: Architecture and Implementation.* 24th International Conference on Knowledge-Based and Intelligent Information & Engineering Systems. Procedia Computer Science 176. 2020. pp. 622-631. ISSN 1877-0509.
15. Pačaiová, H.: *Maintenance Management* (In Slovak). Košice: SjF TUKE, 2007. 127 p. ISBN 978-80-8073-751-1.
16. Pačaiová, H.: *Maintenance Management II., Efficiency and Safety in Maintenance* (In Slovak). Košice: SjF TUKE, 2011. 111 p. ISBN 978-80-553-0856-2.
17. Park, S. C., Kim, Y. J., Won, J. U.: *Application of IoT for the Maintaining Rolling Stocks.* Quality Innovation Prosperity. 21(2). 2017. pp. 71-83. ISSN 1338-984X.
18. Petronic, S., et al.: *Analysis of Remaining Life Assessment of Three-Phase Gravity Separator for Oil Rectification with the Simultaneous usean RBI Matrix.* International Journal of Pressure Vessels and Piping. 209. 2024. pp. 1-15. ISSN 1879-3541.
19. Raschman, P., Pačaiová, H.: *Specific Module II* (*Reliability, Risk and Strategy Maintenance)* (In Slovak). Košice: IMVOCED, 2002. 92 p.
20. Roberts, C., et al.: *Distributed Quantitative and Qualitative Fault Diagnosis: Railway Junction Case Study.* Control Engineering Practice. 10. 2002. pp. 419-429. ISSN 1873-6939.
21. Roesch, J. W.: *Using a New Bathtub Curve to Correlate Quality and Reliability*. Microelectronics Reliability. 52. 2012. pp. 2864-2869. ISSN 1872-941X.
22. Schneidhofer, C., Dubek, K., Dörr, N.: *Robust Sensors Enabling Condition-Based Maintenance of Lubricated Components in Locomotives and Wagon*. Transport Research Arena (TRA) Conference. Transportation Research Procedia. 72. 2023. pp. 3236-3243. ISSN 2352-1465.
23. *Series 350 locomotive.* Available online: https://www.rail.sk/arp/slovakia/ rolstock/350.htm (Accessed on 11 June 2024).
24. *Series 361 locomotive*. Available online: https://www.zos-vrutky.sk/rusen_ 361_sk.html (Accessed on 11 June 2024).
25. *Series 757 locomotive.* Available online: https://fpedas.uniza.sk/~gasparik/SR1013%20zmeny%201-12.pdf (Accessed on 11 June 2024).
26. Sharma, S. K., Chandra, S., Singh, K. A.: *Total Productive Maintenance using Cosine Maximization Multi Attribute Method*. AD ALTA: Journal of Interdisciplinary Research. 9(2, special issue IX.). 2019. pp. 110-117. ISSN 2464-6733.
27. Valenčík, Š., Stejskal, T.: *Basics of Machine Operation and Maintenance* (In Slovak). Košice: TU, 2009. 105 p. ISBN 978-80-553-0252-2.
28. Zagorskikh, A. A., Alsova, O. K., Gavrilov, A. V.: *A Simulation Model of the Process of Organizing the Movement and Maintenance of Trains at a Railway Station*. Journal of Physics Conference. 1661. 2020. pp. 1-6. ISSN 1742-6596.

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