Evaluation of Railway Vehicle Reliability Parameters

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Abstract: The subject of this paper is an analysis of the maintenance of the railway vehicles used in rail passenger transport. The analysis used data on the failure rates of engineless as well as driving vehicles, and it was carried out using reliability parameter indicators. The following parameters were determined for the individual vehicles: failure intensity, failure-free operation probability, failure probability, mean time between failures, mean maintenance time, maintenance intensity, equipment maintainability and technical readiness within the period of the two pre-pandemic years. Higher failure rate was confirmed of the operated railway engineless vehicles.

Keywords: railway vehicles; reliability; maintenance

1 Introduction

Maintenance is one of the key tools for ensuring the reliable operation of objects. The operational reliability assurance process continues throughout the technical life of any operated object [1, 2]. An increasing emphasis has been placed on the prevention of operational problems caused by technical failures. The development in the field of technical diagnostics proceeds from a simple search for the causes of proven failures, through regular preventive diagnostic inspections, controls or revisions, to the continuous automatic monitoring of the object's technical condition [3]. Due to a growing interest in increasing efficiency, reducing downtimes and costs, while increasing the operational reliability and safety, maintenance has become an essential process. Briefly, maintenance is a tool that increases the productivity, quality, overall efficiency and optimisation of the available objects, and that provides assurance of their operability and safety [2].

Reliability is a complex component of an object's quality, which is expressed, from a qualitative point of view, through partial properties, such as failure-free operation, maintainability and durability. These properties are expressed by individual indicators. A failure-free operation means that the required functions are continuously fulfilled in predefined modes and conditions. Conversely, a failure means the discontinuation of the object's operability. The calculation is, therefore, based on two mutually exclusive conditions, i.e. the failure-free operation and the downtime caused by failure, which randomly alternate during the object's technical life [4].

Railway transport is one of the main modes of transport throughout the world, as it is reliable, efficient, cost-effective and comfortable [5]. It requires minimal costs for fuel, it is very safe and, above all, it facilitates the transportation of large quantities of loads in an environment-friendly manner [6]. Over the years, the rail freight industry has witnessed a progressive increase in the quantities being transported, which has contributed to an increased number of trains in operation, with higher speeds and higher axle loads [7]. The basic unit of rail freight transport is the freight wagon. Depending on the type of transport, there are several types of freight wagons available, while the transport of fluids, especially those that are hazardous or combustible, is carried out using railway cisterns [8]. The maintenance work is focused not only on wagons but also on traction engine vehicles and railway tracks. The maintenance of the tracks isn't today fully implemented from different objective reasons, e.g. the absence of sufficient funding [9]. Furthermore, a reliable railway infrastructure is a crucial precondition for the growth and development of governments, companies and societies [10]. The primary purpose of maintenance is to keep the equipment operable and to prevent or minimise the outages caused by failures [11].

The basic function of the maintenance of railway vehicles is to maintain their safe and cost-efficient operation throughout their lifecycle. It is, therefore, necessary to take all necessary measures aimed at avoiding the failures that might lead to serious consequences, such as a train derailing [12]. Maintenance plays a crucial role in the reliability and availability of the rail transport [13], while achieving high-quality maintenance requires choosing the correct maintenance strategy. In recent years, a number of different maintenance approaches have been developed, each one of them representing a different generational approach based on the current level of progress [14]. Corrective maintenance is required after a failure, while condition-based maintenance (CBM) is the type of maintenance that is carried out proactively before a potential failure occurs. In addition, opportunistic maintenance is carried out in an opportunistic manner, by analysing the potential maintenance opportunities that result from the downtime of other equipment [15]. Preventive maintenance is effective in reducing the number of losses caused by degradation [16] and it has a remarkably good performance in reducing downtime and avoiding excessive maintenance work. Carrying out both preventive repairs and general repairs based on the maintenance staging also facilitates a more flexible and cost-efficient assignment of maintenance tasks when compared to the strategy focused on instant general repairs [17]. Within the rail transport field, the purpose of predictive maintenance planning is to maximise the reliability and availability of the transport vehicles, which makes scheduling the expected maintenance actions a vital part of operating a railway [18].

The service life of a traction vehicle is presumed to be approximately 30 years; however, in most cases the service lives of the individual components are not identical, as the body and the bogie will usually endure for longer [19, 20]. The costs of operation and maintenance increase as the vehicle ages. One of the options is to then replace these vehicles with new ones, which is, of course, very costly; while the other option is modernising them, which is both more acceptable and cheaper [12].

Regular maintenance is necessary in order to keep railway vehicles and their components in operation, as well as to eliminate failures and repairs. If maintenance actions are omitted or inadequate, this may cause delays, cancelled lines, dangerous situations and even fatal injuries. Such negative events are very important, as they clearly affect the competitiveness and profitability of a railway company. However, the complexity of maintenance processes is continuously increasing for several reasons. First, articulated trains are gradually replacing the trains consisting of a locomotive and passenger cars. This has led to more complex requirements for the scheduled maintenance. Furthermore, purely mechanical systems are gradually being replaced with complex mechatronic devices and systems that combine mechanical, electronic and information technologies with very different properties. Therefore, it is necessary to choose an optimal maintenance strategy and to assess its effectiveness in terms of the reliability, availability and cost of the system's durability. The evaluation of a maintenance strategy requires modelling the effects of potential alternative strategies on the system's performance and on the life cycle costs. However, due to the greater complexity of these systems and the increased performance requirements regarding the system's reliability, availability and safety, the complexity of a maintenance strategy evaluation has also increased. One of the methods of coping with this increased complexity and with the requirement for a higher availability of railway vehicles is through modular maintenance. The concept of the modular maintenance involves vehicles that are designed so that the replaceable units in the line may be replaced as a whole module, and can then be revised or repaired separately in a workshop in order to increase the availability of the vehicle. Nonetheless, despite the growing use of devices for monitoring the system's condition and the subsequent availability of the related data, the majority of the maintenance tasks in the railway industry are still carried out using the traditional maintenance concept [21].

In this paper, the maintenance methods of railway means of transport are discussed and its purpose is to evaluate the reliability parameters of engineless and driving railway vehicles.

2 Experimental Part

In this work, data from the operation and failure rates of engineless and driving railway vehicles were analysed using indicators of reliability parameters. These parameters were applied in railway transport for the purpose of identifying the complex component of quality from a qualitative point of view [4] using sub-features such as failure-free, maintainability and readiness, which were expressed through individual relationships of monitored indicators.

2.1 Maintenance of Wagons and Locomotives

Maintenance includes all activities whose role and purpose are to maintain railway rolling stock in operable condition. Readiness, failure-free and maintainability are related to maintenance. If we apply the given terms to railway passenger transport, we get to the regulation [22], which determines how to proceed with the maintenance of wagons and locomotives.

Safety is important for any type of transport, but it cannot be achieved without prescribed maintenance. During the maintenance of passenger cars, it is necessary to follow the legislative procedures that specify the requirements. Technology and technological procedures for the maintenance of railway rolling stock are in accordance with STN and EN standards, railway technical standards, laws and decrees of the Ministry of Transport of the Slovak Republic, regulations and documents of the transport company, its measures, directives and regulations, maintenance regulations as well as manufacturers' documentation, or repairmen. Technical inspections are carried out in accordance with the provisions of the Decree of the Ministry of Transport, Posts and Telecommunications of the Slovak Republic on the traffic regulations of railways No. 351/2010 Coll. In accordance with the decree, the intervals of technical inspections are shown in Table 1.

Table 1

Intervals of technical inspections of railway rolling stocks [22]

No.	Type of railway rolling stocks	Interval of technical inspections (years)
1	Driving vehicles	0.5
2	Motor, electric wagons and units, control wagons	1
3	Four-axle passenger wagons for domestic transport and electric and motor unit loaded wagons with speeds above 120 km.h^{-1}	1.5
4	Four-axle passenger wagons for domestic transport and electric and motor unit loaded wagons with speeds of up to 120 km.h^{-1}	2
5	Two-axle and narrow-gauge passenger cars	2

2.2 The Reliability Parameters

The reliability parameters were expressed for 69 driving vehicles (electric locomotives of two different product lines and engine locomotives of the same product line) and for approximately 900 railway engineless vehicles (used in rail passenger transport) while applying the exponential distribution of failures, in particular the Weibull distribution. The reliability parameters [23, 24] were expresses as follows:

(i) **Failure intensity** λ is determined by the number of failures that occur per unit time:

$$\lambda = \frac{a}{T} \tag{1}$$

wherein:

a is the number of failures (or repairs) over the whole operation period and

T is the total operation time (hours, months, years).

For a group of n units, λ is expressed as follows:

$$\lambda = \frac{\sum a}{nT} \tag{2}$$

wherein:

T is the total operation time for the group of units, either as the average operation time or as the sum of operation times of the individual monitored units (hours).

(ii) A correlation between the **probability of failure-free operation** P_{ff} and the failure probability P_{Pf} is important for predicting the operability of the units:

$$P_{ff} = 1 - P_{Pf} \tag{3}$$

wherein:

$P_{ff} = e^{-\lambda T}$ is the je probability of failure-free operation over time T.

(iii) **Mean time between failures** is expressed as the reciprocal of the failure intensity during the normal operation, when the failure intensity is constant:

$$T_m = \frac{1}{\lambda} = \frac{T}{a} \tag{4}$$

(iv) **Mean maintenance time** $\varnothing$ is the ratio of the total time of maintenance actions and repairs to their quantity:

$$\phi = \frac{\sum t}{a} \tag{5}$$

wherein:

Σt is the sum of times of all maintenance actions and repairs and

a is the number of all maintenance actions and repairs.

(v) **Maintenance intensity** μ is the reciprocal of the mean maintenance time:

$$\mu = \frac{1}{\emptyset} \tag{6}$$

(vi) **Maintainability** M is the property of the units which facilitates prevention or fast elimination of the wearing process consequences through maintenance and repairs. It is probabilistic in nature and described by the following equation:

$$M = 1 - e^{-\mu t} \tag{7}$$

wherein:

$e^{-\mu t}$ is the probability that in time t no maintenance action will be carried out.

(vii) **Technical readiness of the unit**, expressed by the coefficient of technical readiness C_{tr}, is the ability of the unit to fulfill the required function at any moment in time:

$$C_{tr} = \frac{\text{Probable failure−free operation}}{\text{Total monitored period}} \,.100\ [\%] \tag{8}$$

3 Results and Discussion

The evaluation of the reliability of railway rolling stock from the point of view of quality, and from the point of view of quantity, as well as the mathematical expression of the indicators of these properties is the subject of this work. The calculation of indicators is based on two mutually exclusive situations, i.e. from the state of fault-free operation and the state of fault downtime, which randomly alternate during operation [4]. The individual reliability parameters of railway engineless vehicles (cars) and driving vehicles (locomotives) were identified using equations (1) through (8) based on the data obtained during the use of these vehicles in years 2018 and 2019.

3.1 Car Reliability Parameters

Tables 2 and 3 contain the maximum and minimum average values of the individual parameters of cars in year 2018 and in year 2019.

Table 2

Car reliability parameters in 2018

2018	λ (days^{-1})	P_{ff}	P_{Pf}	T_m (days)	Ø (days)	μ (days^{-1})	M	C_{tr} (%)
Max.	5.0	1.0	1.0	359.0	111.0	1.0	1.0	100.0
Average	0.032	0.144	0.856	56.2	3.18	0.572	0.856	23.8

Table 3

Car reliability parameters in 2019

2019	λ (days^{-1})	P_{ff}	P_{Pf}	T_m (days)	Ø (days)	μ (days^{-1})	M	C_{tr} (%)
Max.	2.0	1.0	1.0	347.0	202.0	1.0	1.0	100.0
Average	0.059	0.083	0.917	24.8	4.85	0.526	0.917	11.4

Figures 1 through 12 show all the obtained reliability parameters for the group of 925 cars in year 2018 and for 892 cars in year 2019. Figure 1 shows a graphic representation of the failure intensity (λ) of all cars in year 2018. The values are expressed in days^{-1}. The highest failure intensity was observed for the car of a certain production line.

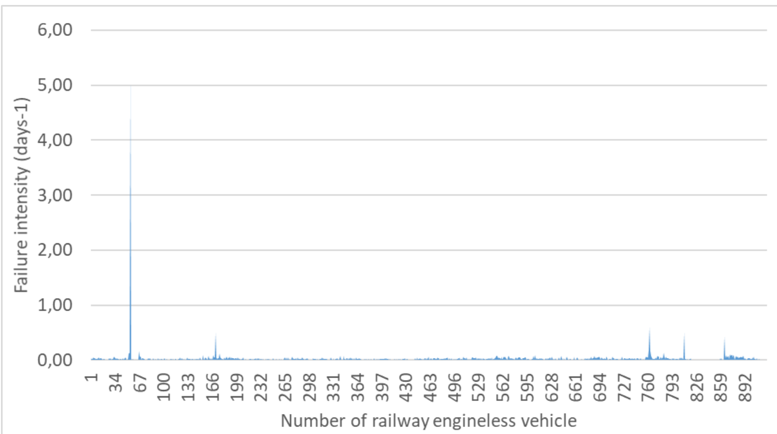

Figure 1

Failure intensity in 2018

The failure intensity (λ) of all cars in year 2019 is shown in Figure 2. The values are expressed in days^{-1}. The highest failure intensity was observed for the car of a product line different from the one with the highest value observed in 2018. The comparison clearly indicates that in 2019 the failure intensity was higher than in 2018.

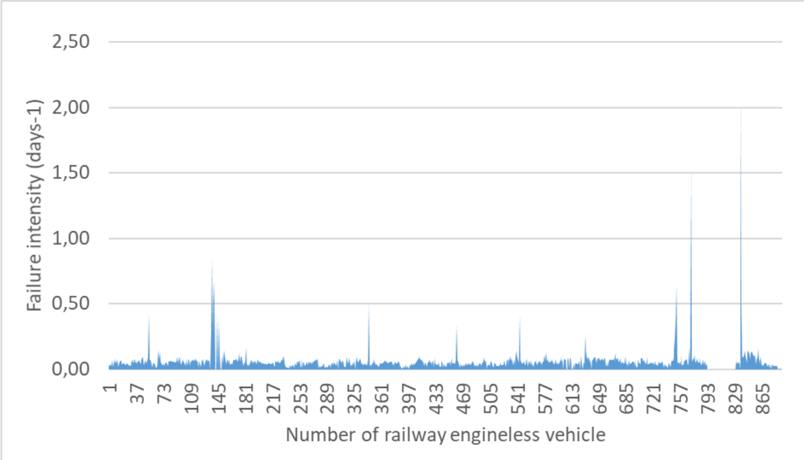

Figure 2
Failure intensity in 2019

Failure-free operation is a feature consisting in the continuous performance of the required function in prescribed modes and under specified conditions, which is quantified by the probability of failure-free operation. Figure 3 shows a graphic representation of the probability of failure-free operation (P_{ff}) in 2018 while Figure 4 shows the equivalent data for 2019. The average probability of failure-free operation was higher in 2018, corresponding to the observed lower failure intensity.

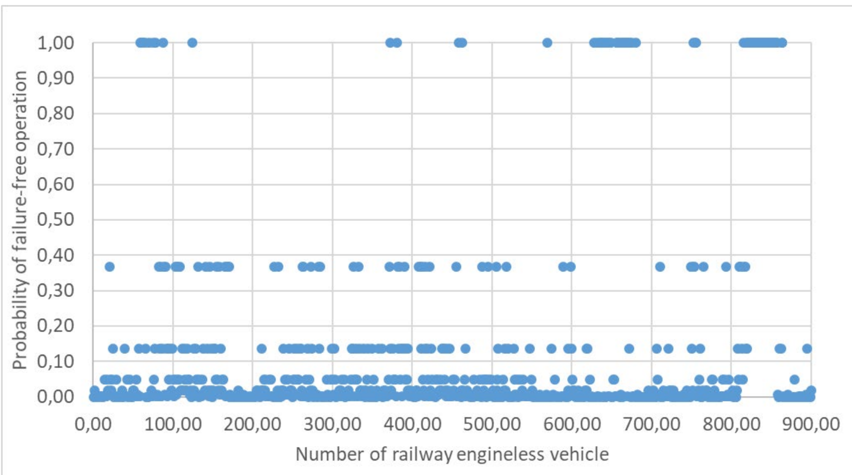

Figure 3
Probability of failure-free operation in 2018

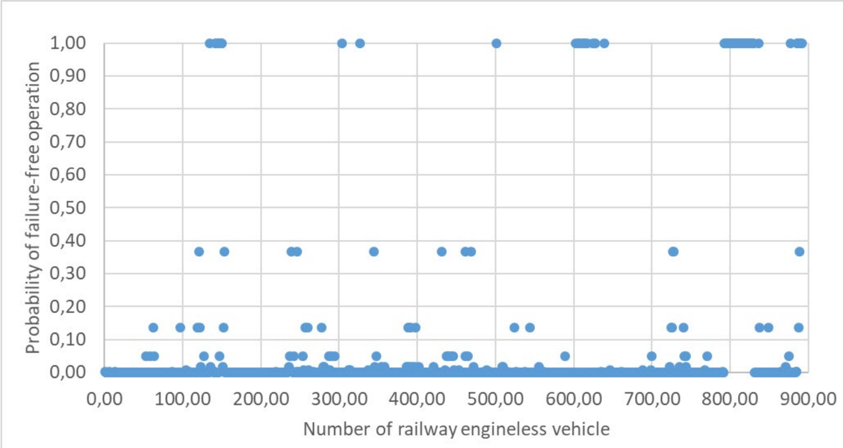

Figure 4

Probability of failure-free operation in 2019

Figure 5 shows the mean time between failures (T_m) in 2018, expressed in days. The highest observed value was 359 days; this is the probable period of the failure-free operation. Figure 6 shows the mean time between failures (T_m) in 2019 in days. The highest value (347 days) was observed for the car of the same product line as the one with the highest value observed in 2018.

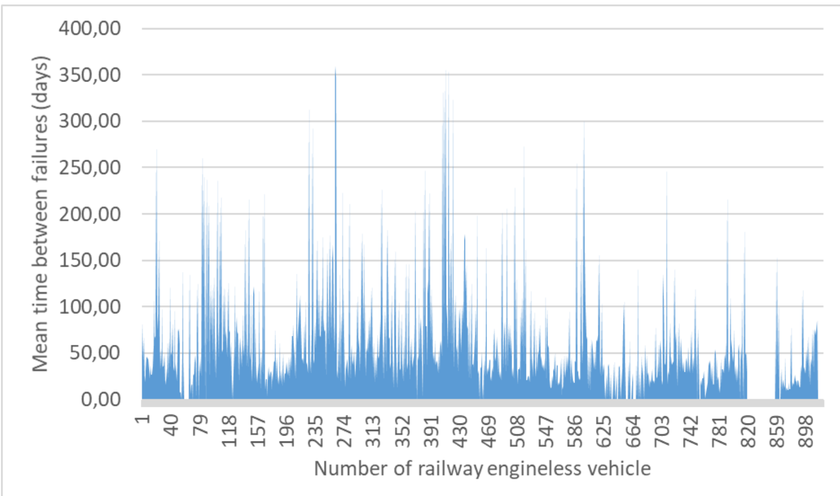

Figure 5

Mean time between failures in 2018

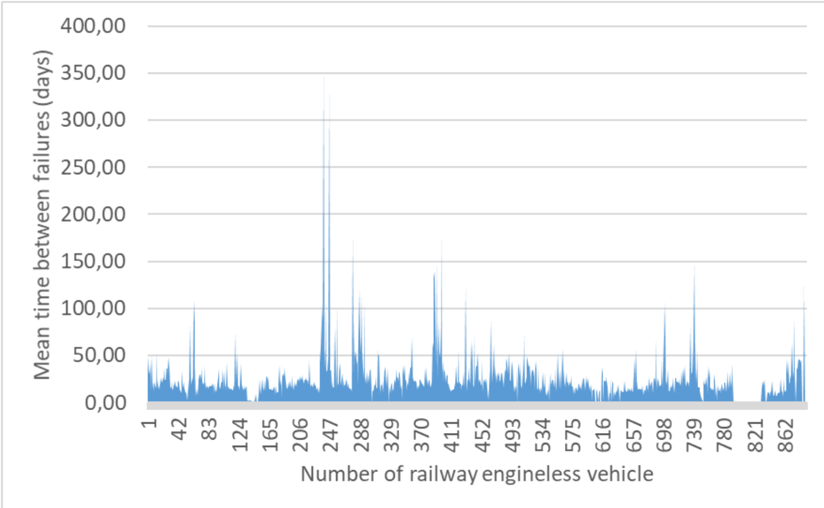

Figure 6
Mean time between failures in 2019

The exponential correlation between the mean maintenance time (φ) and maintenance intensity (μ) is presented in Figures 7 and 8 for years 2018 and 2019, accordingly. Longer mean maintenance time with lower maintenance intensity was observed in 2019.

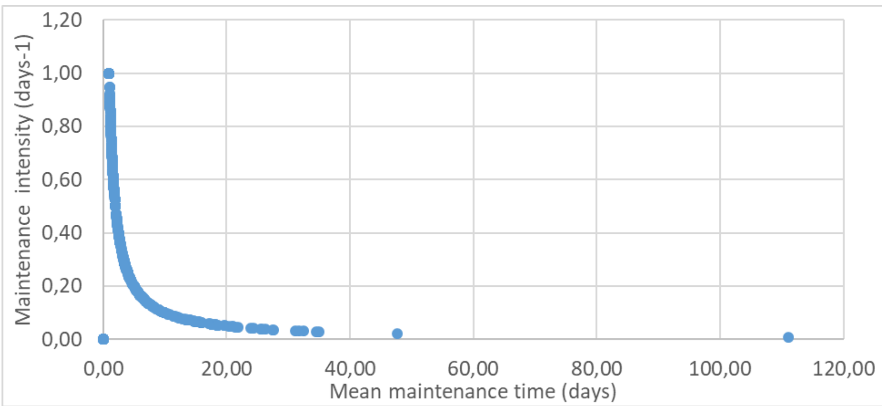

Figure 7
Exponential correlation between the mean maintenance time and maintenance intensity in 2018

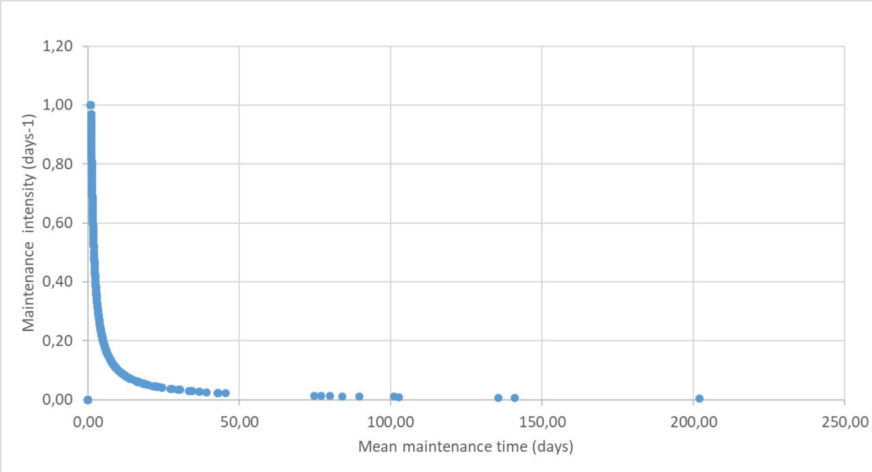

Figure 8

Exponential correlation between the mean maintenance time and maintenance intensity in 2019

Maintainability (*M*), i.e. the ability that consists in the ability to prevent breakdowns in the form of prescribed maintenance, in years 2018 and 2019 is shown in Figures 9 and 10. Higher average maintainability was observed in 2019.

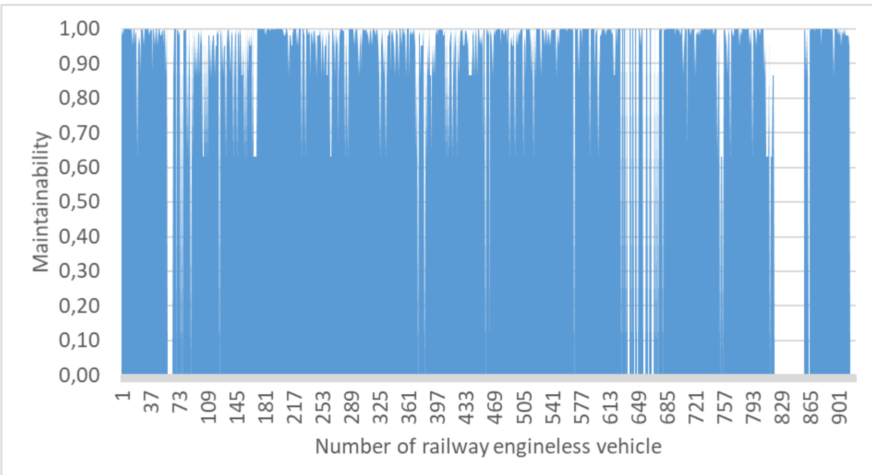

Figure 9

Maintainability in 2018

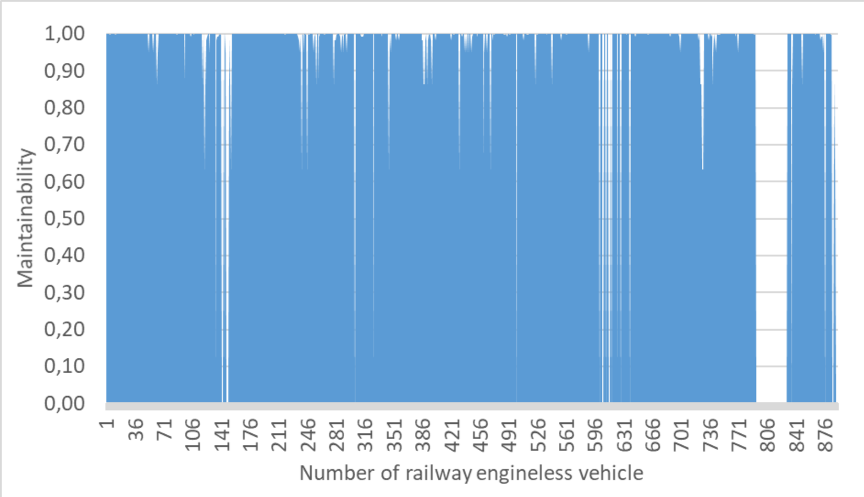

Figure 10
Maintainability in 2019

Figures 11 and 12 show the coefficient of technical readiness (C_{tr}) in years 2018 and 2019. A higher coefficient of technical readiness was confirmed for year 2018. The coefficient considers not only the time of trouble-free operation, but also the time required for repair and maintenance, but it does not allow assessing the size of continuous trouble-free operation.

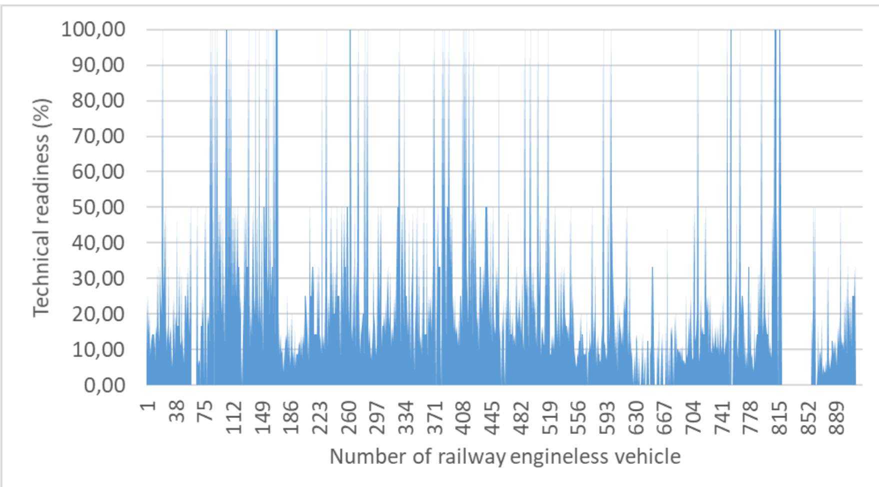

Figure 11
Coefficient of technical readiness in 2018

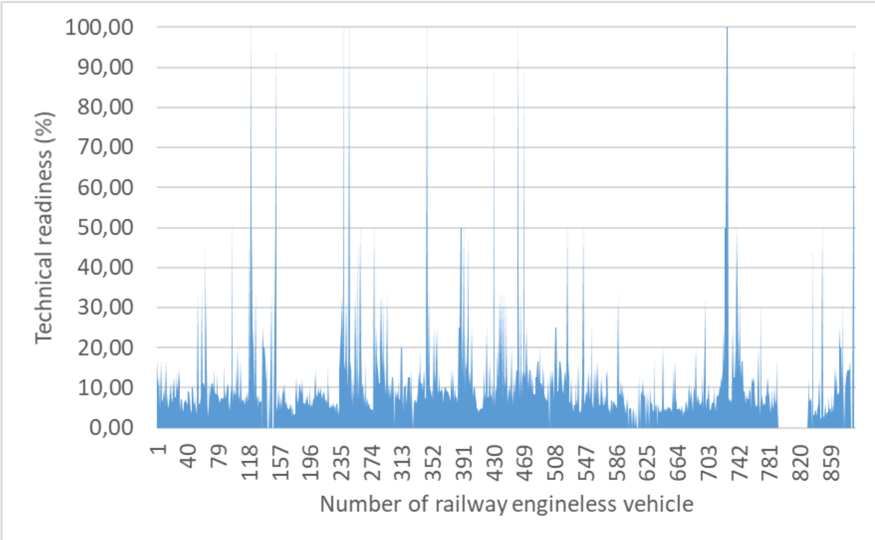

Figure 12
Coefficient of technical readiness in 2019

3.2 Locomotive Reliability Parameters

Tables 4 and 5 contain the average monthly values of indicators for locomotives in years 2018 and 2019 (bold figures are the maximum values). The calculations were made for 69 locomotives of three product lines.

Table 4
Locomotive reliability parameters in 2018

Average values in individual months (2018)								
Month	λ (h^{-1})	P_{ff}	P_{Pf}	T_m (h)	$Ø$ (h)	μ (h^{-1})	M	C_{tr} (%)
I.	0.212	0.877	0.123	0.788	6.042	0.941	0.867	3.886
II.	0.246	0.872	0.129	0.755	6.237	1.027	0.846	**4.825**
III.	0.372	0.861	0.139	0.628	6.120	1.203	**0.899**	2.234
IV.	0.270	0.862	0.138	0.730	7.134	1.060	0.860	4.124
V.	0.278	0.855	**0.145**	0.723	6.462	0.837	0.862	3.774
VI.	0.329	0.855	**0.145**	0.672	5.171	1.084	0.881	4.216
VII.	**0.396**	0.870	0.130	0.604	5.596	1.166	0.875	4.133
VIII.	0.258	0.869	0.131	0.742	6.239	0.964	0.861	4.226
IX.	0.265	0.858	0.142	0.735	6.063	1.263	0.886	4.037
X.	0.242	0.855	**0.145**	0.758	6.442	**1.301**	0.859	3.940

XI.	0.199	0.877	0.123	**0.802**	6.954	1.009	0.842	3.651
XII.	0.320	**0.879**	0.121	0.680	**7.690**	1.046	0.845	3.396
Yearly average	0.282	0.866	0.134	0.718	6.346	1.075	0.865	3.870

Table 5
Locomotive reliability parameters in 2019

Average values in individual months (2019)								
Month	λ (h^{-1})	P_{ff}	P_{Pf}	T_m (h)	$Ø$ (h)	μ (h^{-1})	M	C_{tr} (%)
I.	0.243	**0.896**	0.104	0.757	**7.466**	0.903	0.838	3.590
II.	**0.531**	**0.896**	0.104	0.469	6.775	0.918	0.827	4.398
III.	0.378	0.865	**0.135**	0.622	6.157	1.320	**0.874**	2.950
IV.	0.202	0.878	0.122	0.798	5.750	**1.374**	0.860	3.823
V.	0.235	0.869	0.131	0.765	4.973	1.101	0.870	4.292
VI.	0.219	0.885	0.115	0.781	5.197	1.118	0.849	**4.681**
VII.	0.202	0.881	0.119	0.798	6.703	1.023	0.855	4.037
VIII.	0.234	0.886	0.114	0.766	6.342	1.185	0.836	3.353
IX.	0.207	0.891	0.109	0.794	5.162	1.101	0.855	3.674
X.	0.200	0.878	0.122	0.800	6.035	1.296	0.852	3.137
XI.	0.199	0.888	0.112	**0.801**	5.682	1.351	0.861	3.120
XII.	0.203	0.879	0.121	0.797	5.138	1.157	0.873	2.910
Yearly average	0.254	0.883	0.117	0.746	5.948	1.154	0.854	3.664

In 2018, the failure intensity of the monitored locomotives reached a higher value than the value observed in 2019. A comparison of the individual calendar months didn't reveal any evident trend or a period that would indicate a higher failure rate caused by weather conditions. In 2019, the probability of the failure-free operation exhibited higher values. In the same year, the failure probability remained above 1.10 in all of the months, while in 2018 its values were higher. The mean time between failures and the mean maintenance time exhibited certain fluctuations during the monitored period, but the average values observed in the individual years did not exhibit any statistically significant differences. In 2018, the mean maintenance time was the highest in month XII, while in 2019 it was in month I. In both years, the mean time between failures reached the peak in month XI The intensity of locomotive maintenance was higher in 2019 than in 2018, while the minimum values correspond to the maximum values of the mean maintenance time. The maximum maintenance intensity was observed in month IV of 2019 and in month X of 2018. Higher average maintainability and a higher average coefficient of technical readiness were observed in 2018.

Conclusion

In recent years, the rail transport industry has witnessed increased quantities of transported loads. This has resulted in the deployment of more vehicles and in the necessity to maintain the vehicles' operability with a minimum occurrence of downtime. This paper presented the reliability parameters of railway engineless and driving vehicles observed in years 2018 and 2019, i.e. in the period before the COVID-19 pandemic. In the following year, i.e. in 2019, the observed values of these reliability parameters indicated higher failure rates of the operated railway engineless vehicles. This may have been caused by the fact that despite the availability of the data on the condition of rail cars, the prevailing type of maintenance was the conventional maintenance concept. A solution to this is to increase the proportion of preventive maintenance, which is efficient in reducing the losses caused by mechanical as well as chemical wear that leads to gradual degradation.

As for the engine railway vehicles, it is evident that the prevention of operational problems caused by technical failures resulted in a lower failure rate in 2019. Preventive diagnostic inspections have led to higher operational reliability of the traction vehicles.

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