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A novel methodology of risk assessment for railway freight wagons

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Abstract

This study proposes a new methodology for the accurate risk assessment of railway freight wagons that has real-world applications in the operation and maintenance of freight vehicles. The paper specifically focuses on the analysis of posterior reliability calculation methods using Weibull's reliability model to calculate reliability indicators by which the probability of occurrence of individual failures can be estimated. The consequences of failure are calculated through an existing system from the General contract used for freight wagons (AVV). The formula for calculating the risk value is based on a classical risk theory, where the risk is defined as a combination of the occurrence of a negative phenomenon and the severity of its consequence. The reasoning for this approach was in an effort to maintain simplicity and clarity for potential users in practice. This is based on the information gathered in examining the current state of risk management in the sector of railway vehicles in Slovakia. The data used for risk calculations were taken from a maintenance workshop in Slovakia to provide a realistic picture of the failure rates of freight wagons. The proposed methodology uses historical data for prediction of reliability for the next years. Based on the reliability being a function of time, the risk associated with it is variable, increasing with time. These findings have broader implications for the maintenance systems taken appropriate maintenance actions necessary with respect to increased risk.

Introduction

The issue of risks has been gathering significant research attention in recent years with the term mainly being associated with the field of occupational health and safety. The importance of risk management has spread to other industrial sectors across the world, especially in the field of mechanical engineering and in the automotive industry, where there have been efforts for risk identification and management. The concept of "Risk-Based Thinking" also appeared in the Quality management system standard ISO 9001:2015. Therefore, risk is a common parameter that affects several management systems. For example, by reducing risk, we can increase safety, but also reliability (Pačaiová, Markuliak & Nagyová, 2016).

Management systems associated with risk are commonly based on the ISO 31000:2009 standard, which provides principles and general guidance on risk management that can be applied to a wide range of activities in an organization. In this standard, risk management is defined as "coordinated activities for the management and governance of an organization with respect to risks" (Wawak et al., 2015). The legal requirements regarding railway transport safety in Europe are discussed in (Sitarz & Chruzik, 2019).

Dhillon (2011) provides a general overview on the reliability and safety in transport, where the author presents several examples and statistics of accidents in the field of railway, air, sea and road transport systems. Furthermore, the authors explain the basics of reliability and safety, and briefly describes selected methods of reliability and safety analysis, and deals with the basic distribution of errors in individual transport systems based on statistical evaluations. Moreover, the book presents mathematical models that can be used in the field of reliability of transport systems.

Maintenance plays an important role in the safe operation of railway vehicles (Consilvio et al., 2019), which is highlighted by the Commission Regulation (EU) No. 445/2011 of 10 May 2011 on a system of certification of the Entities in Charge of Maintenance (ECM) for freight wagons (Zvolenský et al., 2014). The European Union Agency for Railways (ERA), coordinates the process of certification of ECMs (Entities in Charge of Maintenance), under which ECMs have to provide evidence of responsibility and traceability of the maintenance undertaken on freight wagons in which they are responsible for maintenance. Risk management is required to be conducted within the entire maintenance functions, in particular in maintenance management, thus enhancing railway safety.

At present, each freight wagon must have a defined ECM that is responsible for its maintenance. From June 2020, the scope of vehicles was extended to other vehicles (passenger cars, locomotives, electric and diesel multiple units, track machines) with transition period to 2022, under the new Commission Implementing Regulation. In the regulation, the so called “safety critical components – SCC” are in focus as they require particular attention and priority in maintenance procedures. These components are primarily defined by the railway vehicles manufacturers, but should be continuously reviewed and updated according to the amount of time operated – operation and maintenance.

In the Slovak railway practice, risk assessment is carried out by various methodologies, which have been usually created by the individual companies operating the freight (Pačaiová, Sinay & Glatz, 2009). The main drawback of there being such a high number of methodologies is that it leads to inconsistencies; thus the inability to compare individual companies. Therefore, this study attempts to create a simplified methodology that would “objectively” use existing wagon operation, maintenance and failure data to calculate the probability of failure. Based on this probability the study also defines the risk levels.

The proposed methodology of risk assessment for railway freight wagons and its influence on maintenance systems is based on reliability analysis of operational and maintenance data obtained from the real-world applications. The data are mathematically processed using Weibull reliability model. From the theoretical results of reliability characteristics, the risk is calculated. In principal, risk is a multiplication of frequency (probability) of failure occurrence and severity of failure consequence. It was proposed to use existing categories listed in Annex 9 of the General Agreement for the Use of Freight Cars (AVV) as they are generally used throughout Europe. As the risk is obviously growing with time (operation of vehicles), this has been accounted for through a modification of corresponding maintenance system.

Maintenance data collection and processing

The most reliable results gained from reliability monitoring are those that are obtained by statistical methods when primary data are recorded directly for the purpose of establishing reliability indicators by statistical methods. However, this does not excluded data recorded for other purposes which may also be valuable as a source of information such as details of repairs done, faults found during regular maintenance interventions, etc. In this study, the authors have gathered the necessary information through fault reports.

Table 1. Failure input data processed in Excel (example)

Date of failure	Wagon No.	Failure code	Failure description
11.6.2016	23 56 073 3 003-4	6173	Tail sidesteps: damage causing injuries to body
26.7.2016	23 56 073 2 078-7	243	Connection between suspension, and axle box
17.8.2016	23 56 073 1 095-2	3311	Main brake air pipe
21.9.2016	23 56 073 2 517-4	334	Brake operational but not labelled
24.7.2016	23 56 073 2 445-8	312	Brake beam catch ineffective
28.11.2016	23 56 073 5 830-8	412	Side frame, end frame, and bolsters extensively stressed
16.12.2016	23 56 073 2 409-4	312	Brake beam catch ineffective

Table 2. Example of input and calculated values

Failure date	T_i (days)	i	$F_i(t)$	y	x
1.5.2013	486	1	0.011986301	−4.417967534	6.186208624
12.12.2013	711	2	0.029109589	−3.521953162	6.56667243
16.12.2013	715	3	0.046232877	−3.050489605	6.572282543
2.3.2014	791	4	0.063356164	−2.726435473	6.673297968
22.3.2014	811	5	0.080479452	−2.47809524	6.698268054
22.3.2014	811	6	0.09760274	−2.275938933	6.698268054
16.5.2014	866	7	0.114726027	−2.104897958	6.763884909
25.7.2014	936	8	0.131849315	−1.956233396	6.841615476
10.10.2014	1013	9	0.148972603	−1.824421368	6.920671504
7.12.2014	1071	10	0.16609589	−1.705745861	6.97634807

To allow for easier evaluation, it was necessary to process this information obtained from the fault records in the MS Excel program (Table 1).

Reliability analysis

Weibull's probability distribution was chosen as the most appropriate system to predict reliability because it was the investigation was technical in nature as it was exposed to mechanical wear and degradation mechanisms (Legát et al., 2007; Pačaiová, Sinay & Nagyová, 2017; Stuchlý et al., 2017).

For calculation of Weibull distribution parameters we used a linear regression that represents the approximation of recorded values by a least squares fitting method. Table 2 illustrates a portion of the aggregate input and calculates values for the failure code 334.

The first column of Table 2 contains the date of the failure, the second column (T_i) contains the number of days elapsed from the start of the test to the occurrence of the i-th failure. The third column (i) contains the sequence number of the failure.

In the fourth column the authors apply the Bernard's approximation in the form of (Legát et al., 2007):

$$F_i(t) = \frac{i - 0.3}{n + 0.4} \tag{1}$$

where:

$F_i(t)$ – estimation of mean value,
i – sequence number of a failure,
n – number of failures.

In the fifth column (y), the double natural logarithm is used to calculate the value; then in Formula 2.

$$y = \ln\left\{\ln\left[\frac{1}{1 - F_i(t)}\right]\right\} \tag{2}$$

In the last column (x), Formula 3 is used to calculate the value:

$$x = \ln(T_i) \tag{3}$$

In the graph on Figure 1 the values of the fifth and sixth columns are shown, where the blue points represent the real course and the dotted line represents the linear approximation; values for the x and y axes represent the values from Table 2 (columns x and y).

After plotting the graph, you need to approximate the displayed data with the trend line and find the coefficients b and m of the equation in the form:

$$y = bx + m \tag{4}$$

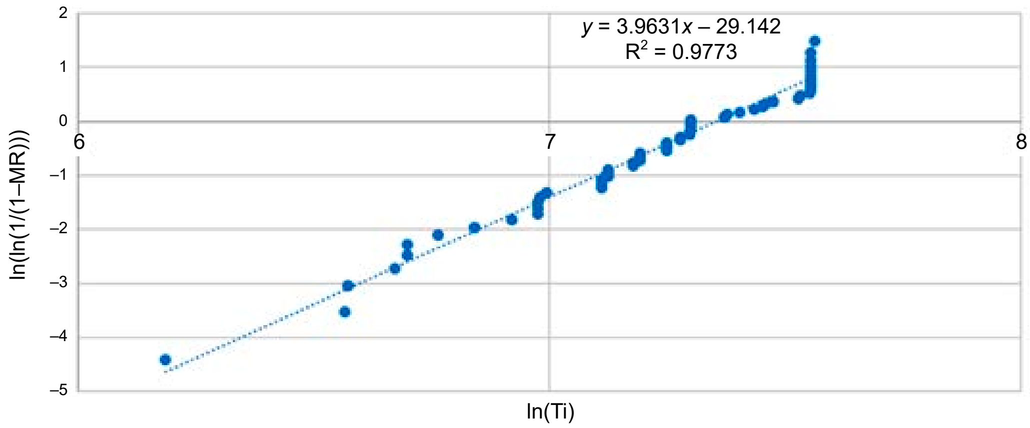

Figure 1. Weibull probability diagram for failure No. 334

Weibull distribution can be transformed into the equation:

$$F(x) = 1 - e^{-\left(\frac{x}{a}\right)^b} \quad (5)$$

where:
$F(x)$ – cumulative distribution function,
a – scale parameter,
b – shape parameter.

$$1 - F(x) = e^{-\left(\frac{x}{a}\right)^b}$$

$$\ln[1 - F(x)] = -\left(\frac{x}{a}\right)^b$$

$$\ln\left[\ln\left(\frac{1}{1 - F(x)}\right)\right] = b \cdot \ln\left(\frac{x}{a}\right)$$

$$\ln\left[\ln\left(\frac{1}{1 - F(x)}\right)\right] = b \cdot \ln(x) - b \cdot \ln(a)$$

By comparing this formula with a simple equation, we can see that the left side of the equation corresponds to y, $\ln(x)$ corresponds to x, b corresponds to b and $b \cdot \ln(a)$ corresponds to m. Therefore, to perform linear regression, it is necessary to determine the parameter estimation. The estimation of parameter b comes directly from the regression line. The estimation of parameter a is be calculated:

$$a = e^{-\left(\frac{m}{b}\right)} \quad (6)$$

From the linear equation: $y = 3.9631 - 29.142$ we get the shape parameter $b = 3.9631$, and we can calculate the scale parameter a:

$$a = e^{-\left(\frac{-29.142}{3.963}\right)} = 1561.41$$

Based on the Weibull model, the authors calculated values for graph that can be seen in Figure 2. There is a reliability function $R(x)$, probability of failure $Q(x)$, failure rate $\lambda(x)$ and probability density function $f(x)$.

Risks estimation

The consequence severity classes have been adopted form the AVV (AVV, 2014) agreement as this is generally used across Europe and they are also given in primary records on failures occurred in operation (Table 3).

Table 3. Consequence severity classes according to AVV (AVV, 2014)

Failure consequence severity class	Definition
1	Minor faults without effects on transport capability and operation safety
2	Faults with minor consequences on transport capability
3	Minor faults, faults with serious consequences on running capability and faults with consequences on operation of wagons (missing or erroneous marking with labels)
4	Major faults, faults at which operation capability is not ensured or which can lead to safety endangering, or faults which may lead to personnel injuries (operation personnel of freight wagons)
5	Critical faults, faults with serious consequences on operational safety and faults with consequences in acute transport endangering

The authors estimated the risk based on the above calculations, where the probability of reliability of operation $R(t)$ was calculated. This reliability indicator has been divided into five levels by transformation in accordance with Table 4.

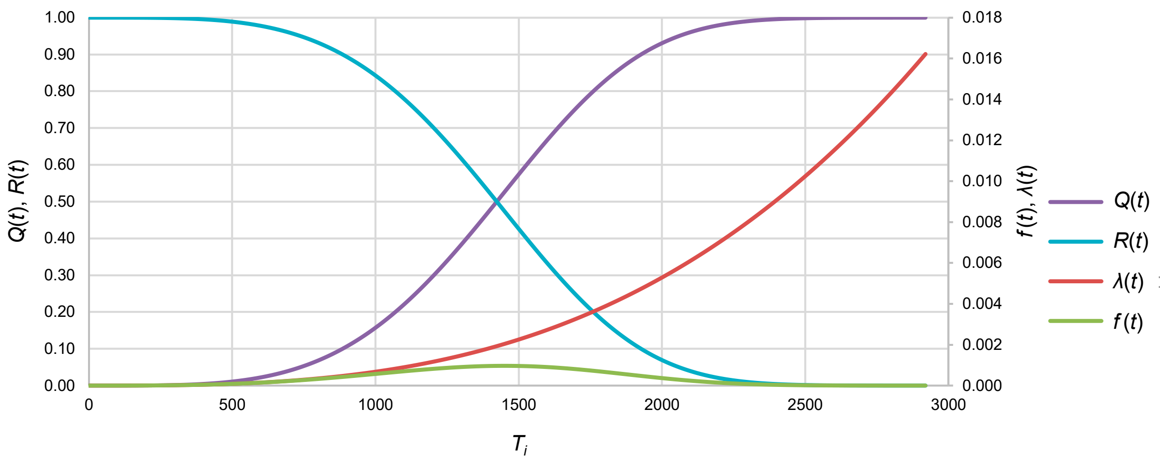

Figure 2. Calculated reliability indicators for fault No. 334

Table 4. Conversion between probability of operational reliability and estimation of risk

P	5	4	3	2	1
$R(t)$	⟨0–0.5)	⟨0.5–0.65)	⟨0.65–0.95)	⟨0.95–0.99)	⟨0.99–1⟩

Calculation of risk value

The authors used the following formula to calculate the risk value (Pacaiova & Nagyova, 2015):

$$R = P \cdot S \tag{7}$$

where:
R – risk value,
P – failure probability,
S – failure consequence severity degree (class).

Table 5 shows the total risk estimation values for the selected failures with five-level color distribution: insignificant (lowest), low, small, major and critical (largest).

The acceptable area includes risks that achieve insignificant (1–2) and low (3–4) values. Their level is negligible and no further action is required (Nagyova et al., 2018).

Acceptable area includes risks that achieve small (5–10) and major (12–16) values. Such risk is tolerable only if future mitigations are impractical or the costs incurred are inadequate to improvement.

Unacceptable areas of risk are those that achieve critical (20–25) values. Such a risk cannot be accepted under any conditions.

Conclusions

The methodology proposed has calculated the reliability indicators by means of the Weibull distribution analysis of the failures, where the authors "objectively" estimated the probability of occurrence of individual failures. To estimate the consequences, it was necessary to use existing categories listed in Annex 9 of the General Agreement for the Use of Freight Cars (AVV). The risk calculation formula is based on the classical risk theory, where risk is defined by a combination of the occurrence (probability) of a negative phenomenon and the severity of its consequences. The reasoning for this approach was to maintain simplicity and clarity for potential users. From the results obtained, a model was subsequently created to optimize the process calculations to perform the scheduled maintenance interventions. Such maintenance optimization is considered critical to reducing vehicles life cycle costs, maintaining high operational availability and reducing the consequences of failures.

It is envisioned that the future development of this methodology will incorporate the detectability component into the risk value calculation formula and explore the possibility of incorporating. Therefore enabling the methodology to be potentially used in information systems, thus improve maintenance managements system.

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Table 5. Evolution of risk in time for given failures (codes)

	T_i	$R(t)334$	$R(t)321$	$R(t)561$	$R(t)312$	$R(t)314$	$R(t)6171$	$R(t)6122$	$R(t)3311$	$R(t)412$
Days	S	3	3	3	4	3	4	3	4	4
365	P	3	3	2	2	2	2	1	3	2
	R	9	9	6	8	6	8	3	12	8
547	P	3	3	3	2	3	3	1	3	3
	R	9	9	9	8	9	12	3	12	12
730	P	3	3	3	3	3	3	1	4	3
	R	9	9	9	12	9	12	3	16	12
912	P	4	5	3	3	4	3	1	5	5
	R	12	15	9	12	12	12	3	20	20
1095	P	5	5	5	4	5	5	2	5	5
	R	15	15	15	16	15	20	6	20	20

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