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Reliability and risk in the safe operation of a rail vehicle subsystem

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Highlights

- Reliability model of the pivot subsystem.
- Model for numerical experiment to calculate the reliability of the pivot subsystem.
- Reliability of the subsystem for different preventive maintenance periods.
- Safety integrity level SIL depending on the preventive maintenance period.

Abstract

This study highlights the problem of modernisation using a practical example of a rail vehicle pivot and constitutes an analysis of the impact of preventive renewals on the reliability of the upgraded structural node. The damage that occurs to the rubber vibration damper and, as a consequence, to the pivot itself, is a dependent failure. The developed model takes into account the random nature of the values of the operating times to failure of the pivot and the vibration damper cooperating with it, as well as the damage relationship between them. The model also includes preventive renewals of the vibration damper performed at fixed intervals of the vehicle's mileage, as well as information on its technical condition derived from inspections performed at shorter mileage intervals. As the analysis of the risk of damage to the pivot system has shown, changing the preventive renewal period of the vibration damper makes it possible to seek an acceptable risk value for the operator and to achieve the required safety integrity level (SIL).

Keywords
risk, safety, reliability, rail vehicle, preventive replacements.

1. Introduction

The safe operation of rail vehicles as means of mass transportation is a priority issue from a technical, as well as social point of view, and directly depends on the functional reliability of these objects. Operations related to ensuring the required level of reliability represent a wide spectrum of specialized technical issues, among which the problem of the rail vehicle's pivot subsystem has a significant role [11]. In [11], the authors analyze how changes in the technology of manufacturing of the element of rail vehicles may affect the reliability and safety of their operation. An algorithm for the design process of rail vehicle parts was also proposed.

The problem of assessing and ensuring the expected reliability of the above-mentioned components has arisen in connection with the modernisation of the manufacturing method of pivots involving the introduction of cast pivots in place of forged pivots. The change in the technology of their production resulted in a deterioration of the durability properties mainly in the aspect of resistance to fracture, which is important in the severe conditions of their operation, with the occurrence of variable and dynamic loads [2,11]. The research material from

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the cited paper [2] contains the results of a series of experiments conducted to model the relationship between the permissible parameters of important rail vehicle components and the predicted risk of vehicle safety loss. The cited paper does not

address the element directly discussed in this paper, but analyzes an element integrated into the same system and also having a significant impact on the operational safety of the rail vehicle. The method proposed in [2] involves the selection of predictors and a preliminary analysis of the ongoing processes based on information from published literature and adjusted by applicable standards. The obtained results are verified with data from operational condition monitoring through sampling. The

authors of the current paper used a different algorithm in which a generalized model of the ongoing damaging processes was developed based on experimental data, and further experiments were conducted using this model. The method proposed in this paper is characterized by shorter execution time and greater versatility.

This issue thematically falls within the scope of safety engineering, which is a set of activities carried out by specialists at the stage of design, manufacture and operation, as well as during decommissioning of technical objects in terms of minimising the effects of their operation on the negative impact on the environment. The problem of modernisation of structural elements of technical objects at the stage of their operation should be subject to procedures that determine the justification of the need for modernisation, the analysis of the economic benefits that will follow, as well as the assessment and assurance of reliability to provide safety, once they are put into operation [9,11]. An algorithm for the modernization of technical facilities when the aim is to achieve the assumed reliability of their operation was presented in [9].

An important aspect is the fact that in the pivot system under consideration, there are rubber components of the vibration damper that age and lose their damping properties over time [7,18,19], which can initiate the damage process and consequently lead to cracking and disintegration of the upgraded pivot. The cited studies describe the properties and applications of elastic components, as well as statistical studies on the durability of rubber components. A statistical analysis of the effect of rubber components on hardness is also proposed. Based on data from literature sources, statistical analyses were conducted using models such as linear regression and constrained linear regression. These analyses aim to determine which components of the rubber mixture have a decisive influence on the hardness of rubber components. The damage that occurs to the rubber vibration damper and, as a consequence, to the pivot itself, is a dependent failure, the modelling of which for computational purposes is often a significant problem. The issue of damage dependence was considered in [4,6,22]. The authors present failure mechanisms in non-repairable systems which have many kinds of correlation. One can see failure mechanism developing to a certain degree will trigger and very often accelerate another or many other failure mechanisms, some kind of failure mechanisms may have the same effect on the failure site, component or system. The character of the damage dependence occurring in the considered case (vibration damper - steering pivot) will be taken into account in the developed computational model for assessing the reliability of the pivot system.

One of the ways to ensure the required reliability of the structural nodes under consideration is to implement in service periodic preventive replacements of rubber components that directly interact with the pivot of the rail vehicle. Preventive replacements, together with periodic inspections, are used in the operation of this system and apply to the vibration damper. The reliability of the system and the risk of operation depend on the preventive replacement period of the system components used in practice [8].

Preventive replacement periods can be optimised taking into account a number of criteria and case-specific factors, resulting in the development of different types of renewal models [5,21]. Very often, these computational models include replacement costs and probability of failure as primary factors [3,16,23]. In some applications, due to current regulations and normative requirements, the criteria used to optimise the preventive replacement period are the risks associated with the operation of the object and the occurrence of failures [12,15,24] or the reaching and maintaining of the SIL safety integrity level required for the certain application [1,14].

This study highlights the problem of modernisation using a practical example of a rail vehicle pivot and constitutes an analysis of the impact of preventive renewals on the reliability of the upgraded structural node.

The purpose of this study is to build a computational model to evaluate the reliability of an upgraded pivot system with a preventively renewed vibration damper and the occurring damage relationship between the vibration damper and the pivot. Furthermore, the aim is to determine the impact of changes in the applied preventive renewal period on the reliability of the system over its assumed operation period. An attempt is also made to determine the failure rate of the system and relate it to SIL safety integrity levels as one of the measures of the safety of technical systems.

2. The pivot subsystem

The task of the pivot subsystem is to connect the bogie of a rail vehicle to the body and transfer forces between these systems, as well as to enable the bogie to rotate relative to the body on curves of railroad tracks. The analyzed pivot subsystem is called a guideway.

It is a system of a pivot made of cast steel by casting technology and a guideway equipped with two flexible metal-rubber bushings, which act as a damper of force vibrations during the movement of a rail vehicle. Flexible metal-rubber bushings simultaneously allow a small angle of rotation and controlled displacement of the bogie relative to the body of the vehicle.

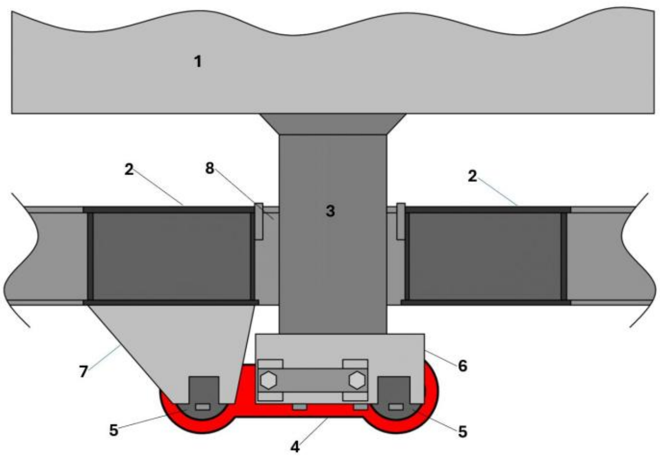

Figure 1. Pivot system: 1 - vehicle body, 2 - bogie frame crossmember, 3 - steering pivot, 4 - guideway, 5 - metal-rubber bushing of the guideway (vibration damper), 6 - bracket yoke, 7 - guideway bracket, 8 - through-window of the pivot in the bogie crossmember of the vehicle.

In the operating position, the pivot passes through a rectangular hole (window) made in the crossmember of the bogie frame (Fig. 1). Limitations on the displacement of the pivot are the dimensions of the through-window and the corresponding properties of the flexible metal-rubber bushings of the guideway (connector). The reliability and durability of these components is the basis for ensuring the safe operation of electric train units.

Damage to the pivot leads not only to the loss of the ability to transmit traction force, but in catastrophic failure in the form of a pivot fracture, it causes the loss of the main connection and the possibility of the bogie sliding out from under the body, leading to a train derailment. The determining factor in the breakage of the pivot in this system design is the damage to the metal and rubber elements of the guideway, which increases the freedom of movement of the pivot and its impact on the edge of the through window. In view of the direct dependence of vehicle operating safety on the reliability of the pivot system, the study determined the functional dependence of system reliability on the period of preventive replacement of vibration dampers [10].

Tables 1 and 2 present the results of tests and observations conducted in practice concerning the mileage to failure (expressed in kilometres) for the vibration damper and the steering pivot, as well as the inspection and replacement periods of the vibration damper used in operational practice, which will be used to perform the reliability analysis. The mileage to vibration damper failure values were defined as the number of kilometres from the last damper replacement until the moment the vibration damper failure was observed during one of its subsequent inspections. Due to space constraints, Table 1 presents only part of the data used to estimate the time to failure distributions. Kolmogorov goodness of fit tests performed in Statistica 13.1 at a significance level of 0.05 revealed no grounds for rejecting the null hypotheses that the empirical data were consistent with the theoretical probability distributions.

The mathematical models of the density function in the probability distributions used have the form:

$$f(t) = \frac{1}{\sigma \cdot \sqrt{2 \cdot \pi}} \cdot exp\left(-\frac{(t-m)^2}{2 \cdot \sigma^2}\right) \tag{1}$$

for vibration damper,

$$f(t) = \nu \cdot \left(\frac{1}{\beta}\right)^{\nu} \cdot t^{\nu-1} \cdot exp\left(-\left(\frac{t}{\beta}\right)^{\nu}\right) \tag{2}$$

for steering pivot working under conditions with a damaged vibration damper. The m, σ, ν and β parameters are as explained in Table 2.

Table 1. Mileage to vibration damper failure - part of data.

Mileage values to vibration damper failure [km]								
730994	731772	736250	753961	766539	770514	772772	776348	797183
830668	836446	846132	849411	864762	873524	887841	888179	889906
897122	908749	923372	924458	930697	931997	946670	950838	956563
973556	979817	980788	1030100	1041200	1053300	1057400	1077900	1142100

Table 2. Results of tests and practical observations regarding failures to the vibration damper and the steering pivot.

Parameter	Value
operating time to failure of damper	normal distribution (average value m = 897495 [km]; standard deviation σ = 109685 [km])
operating time to failure of a steering pivot working under conditions with a damaged damper	Weibull distribution (shape parameter ν = 1.9; scale parameter β = 8000 [km])
damper inspection interval	t_{kont} = 35000 [km]
damper preventive replacement interval	t_{pr} = 700000 [km]

3. Reliability assessment of the analysed subsystem

In order to assess the reliability of the considered subsystem of a rail vehicle pivot, an experiment developed for this purpose was used. The model takes into account the random nature of the values of the operating times to failure of the pivot and the vibration damper cooperating with it, as well as the damage relationship between them [4,6,21]. The model also includes preventive renewals of the vibration damper performed at fixed intervals of the vehicle's mileage, as well as information on its technical condition derived from inspections performed at shorter mileage intervals [20].

The assumptions of the model for the experiment that is being built are as follows:

- damage to the pivot system, which consists of two parts (vibration damper, pivot), occurs only when the pivot is damaged in the form of disintegration (through fracture),
- if in the considered horizon of the vehicle's mileage there is no cooperation of the pivot with a defective damper, the pivot will not be damaged, which is due to the applied strength excesses in the design of the pivot and the conditions of its operation with a suitable damper,
- damage to the elastomeric component of the vibration damper does not prevent the operation of the system (does not cause damage to the pivot system), but changes the operating conditions of the pivot - impact loads and the initiation of pivot cracking takes place,
- elastomeric element of the damper has a much shorter lifespan than that of the pivot, and in practice an inspection of its technical condition is carried out at fixed intervals of mileage t_{kont} – the detection of damage to the muffler results in its immediate replacement with a new one (this inspection does not give information on the technical condition of the pivot),
- according to the preventive maintenance strategy implemented in the operating practice of the system under consideration, the vibration damper is replaced preventively at fixed intervals of the mileage t_{pr} (replacement of the damper does not give information on the technical condition of the pivot),
- in the developed model, two variants of the process of wear (cracking) of the pivot were considered. This process is always initiated by the pivot first occurring cooperation with a damaged vibration damper. The assumption that the cooperation of the pivot with a damaged damper always leads to the formation of a crack and its subsequent propagation is a pessimistic assumption adopted in the model and motivated by safety considerations. In the first variant, the initiated process of cracking of the pivot continues uninterrupted until its failure even if during the process damage to the damper is detected and it is replaced with a new one (Fig. 2). In the second variant, the initiated process of pivot cracking proceeds only at the time when the pivot cooperates with the damaged damper and its wear (cracking) to damage in the form of disintegration is cumulative (Fig. 3),
- the working time of the pivot to failure through fracture, which was initiated by cooperation with the damaged

damper, is a random variable described by a probability distribution,

– working time to failure of an elastomeric damper component is a random variable described by a probability distribution,

– determined random values of working time to failure of the pivot system in repeated experiment runs are the basis for determining the reliability of the pivot system according to the equation:

$$R(t) = 1 - \frac{n_{tucz}(t)}{n_s} \quad (3)$$

where:

n_{tucz} - the number of values of failure times of the pivot system less than or equal to t,

n_s - the number of repetitions of experiment runs.

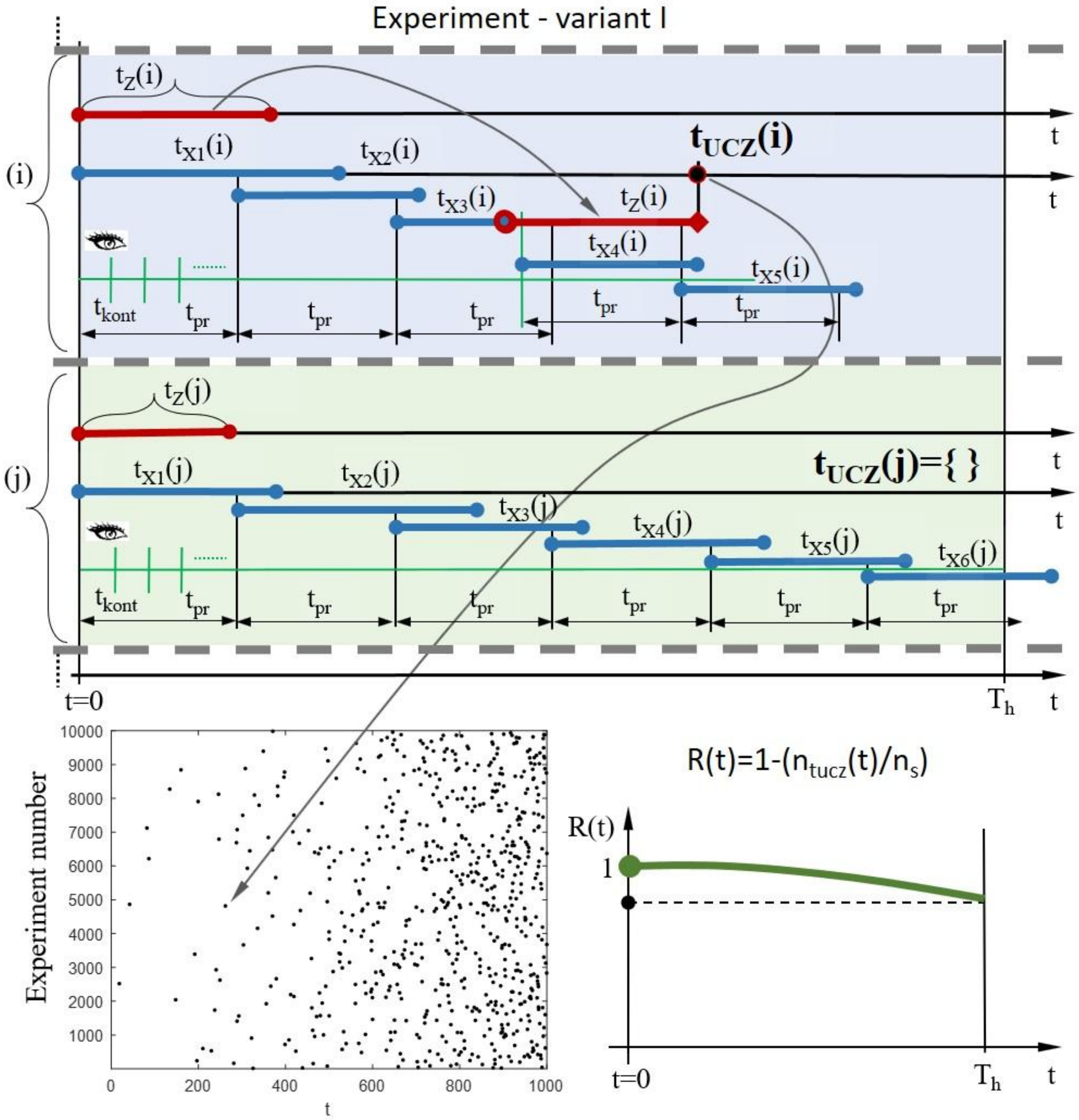

Figure 2. Graphical presentation of the experiment run in variant I - the initiated pivot cracking process proceeds uninterrupted to failure even after replacement of the damaged vibration damper: $t_{xi}(i)$ - values of working time to failure of the vibration damper in the i-th experiment run, $t_z(i)$ - working time to failure of the pivot after initiation of its cracking process in the i-th experiment run, $t_{ucz}(i)$ - moment of failure of the pivot in the i-th experiment run.

Figure 2 graphically shows two possible cases of the run and completion of the experiment of the working time to failure of the pivot system in variant I of the pivot wear process. Case (i) is the case in which, before reaching T_h working time, the system failed - the random variable of working time to failure of the vibration damper ($t_{x3}(i)$) was shorter than the value of the preventive replacement time (t_{pr}) and the process of pivot cracking was initiated.

The random variable of pivot cracking duration ($t_z(i)$) added then to the current time value determines the moment of system failure ($t_{ucz}(i)$) in this experiment. Although as a result of the closest after $t_{x3}(i)$ inspection (t_{kont}), damage to the damper was detected and it was replaced with a new one, this no longer affected the progressive process of pivot cracking. The only possibility when the system would not be damaged here is when the time value t_{ucz} would turn out to be greater than the calculation horizon (T_h). Case (j) represents the experiment run in which each successive random variable of the working time to failure of the vibration damper ($t_{xi}(j)$) was greater than the value of its preventive replacement time t_{pr}. This is the second possibility when the pivot system would not fail in the experiment run.

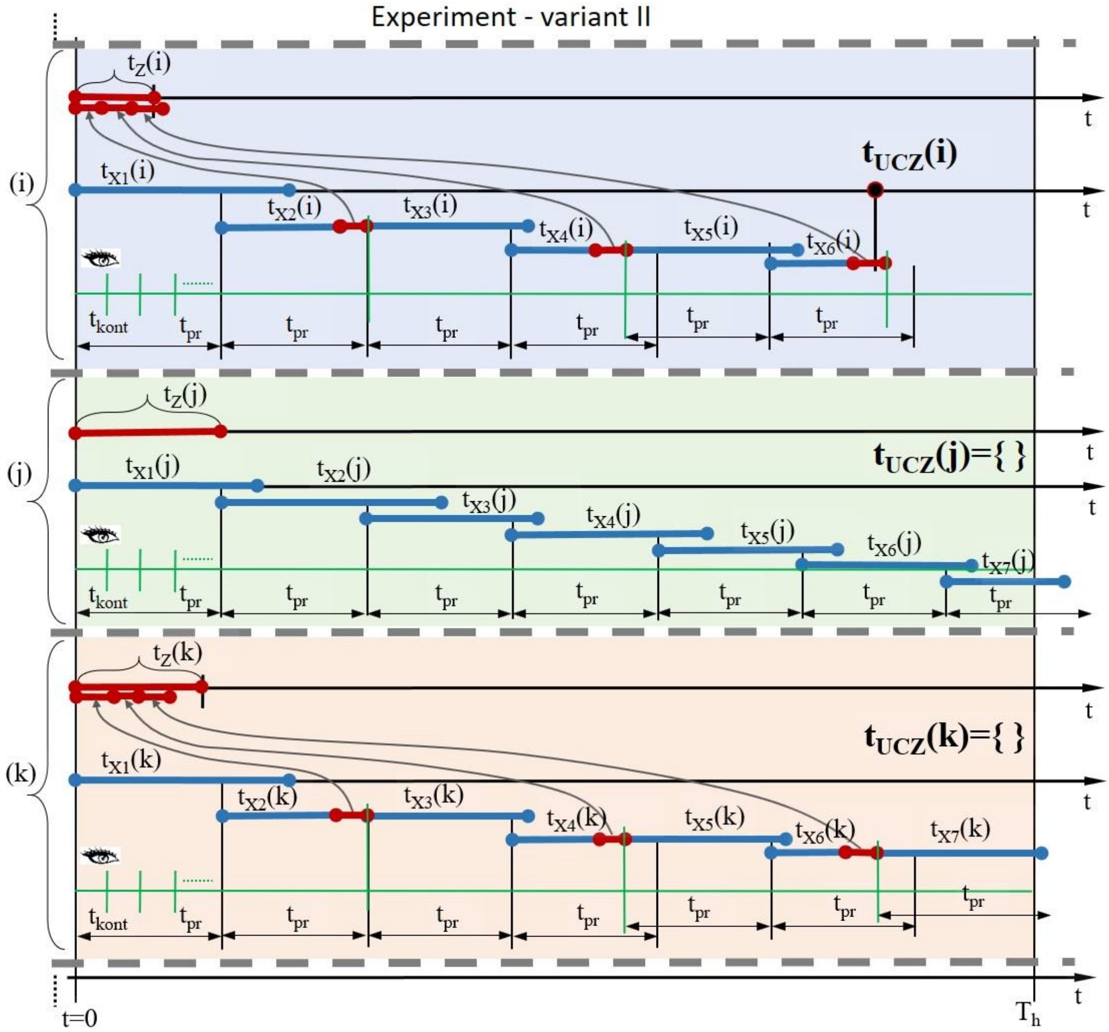

Figure 3. Graphical presentation of the experiment run in variant II - the initiated pivot cracking process progresses and accumulates only while it cooperates with the damaged vibration damper: $t_{xi}(i)$ - values of the working time until the vibration damper fails in the i-th experiment run, $t_z(i)$ - working time until the pivot fails after the initiation of its cracking process in the i-th experiment run, $t_{ucz}(i)$ - the moment the pivot fails in the i-th experiment run.

Figure 3 graphically illustrates three possible cases of the run and completion of the experiment of the working time until failure of the pivot system in variant II of the pivot wear process. In case (i), before reaching the working time horizon in the experiment (T_h), the system failed at time t_{ucz}. The random variable of working time to failure of the pivot in this experiment ($t_z(i)$) was achieved by accumulating shorter periods of cooperation of the pivot with the damaged vibration damper. For instance, random variable $t_{x4}(i)$ was smaller than the t_{pr} of the vibration damper, which resulted in the cooperation of the damaged damper with the pivot and an increment of its wear in the form of a crack but by a value that managed to grow only until the next inspection, when the detected damage to the damper resulted in its replacement with a new one and the operation of the pivot continued again under normal conditions with an undamaged damper - with no increment of wear.

Case (j) is the possibility of an experiment run when, throughout T_h, the successive random variables of working time until damper failure were greater than t_{pr} so the process of pivot cracking was not initiated and pivot failure did not occur.

Case (k) is the situation when in the experiment the pivot cracking was initiated and the process of its accumulation in successive periods of cooperation of the pivot with the damaged damper occurred, but before the end of the T_h horizon the accumulated time of cooperation of the pivot with the damaged damper did not reach the value of the random variable of working time until failure of the pivot $t_z(k)$ in this experiment run.

Both of the calculation variants developed should be regarded as pessimistic, with variant I more so than variant II. Both assume that once a pivot starts to cooperate with a damaged damper, the process of cracking always begins, which may not always occur in practice. However, adopting this approach results in a more conservative estimation of the reliability course and is appropriate in terms of operational safety.

4. Calculation results

In calculations performed according to the developed model, time is defined as vehicle mileage expressed in kilometres. In each case reliability estimates were made for calculation time horizon $T_h = 5 \cdot 10^6$ [km]. Figure 4 shows the course of the change in reliability of the pivot system for the assumed input data and a variable damper inspection interval (t_{kont} = 35000 [km], 20000 [km], 10000 [km]).

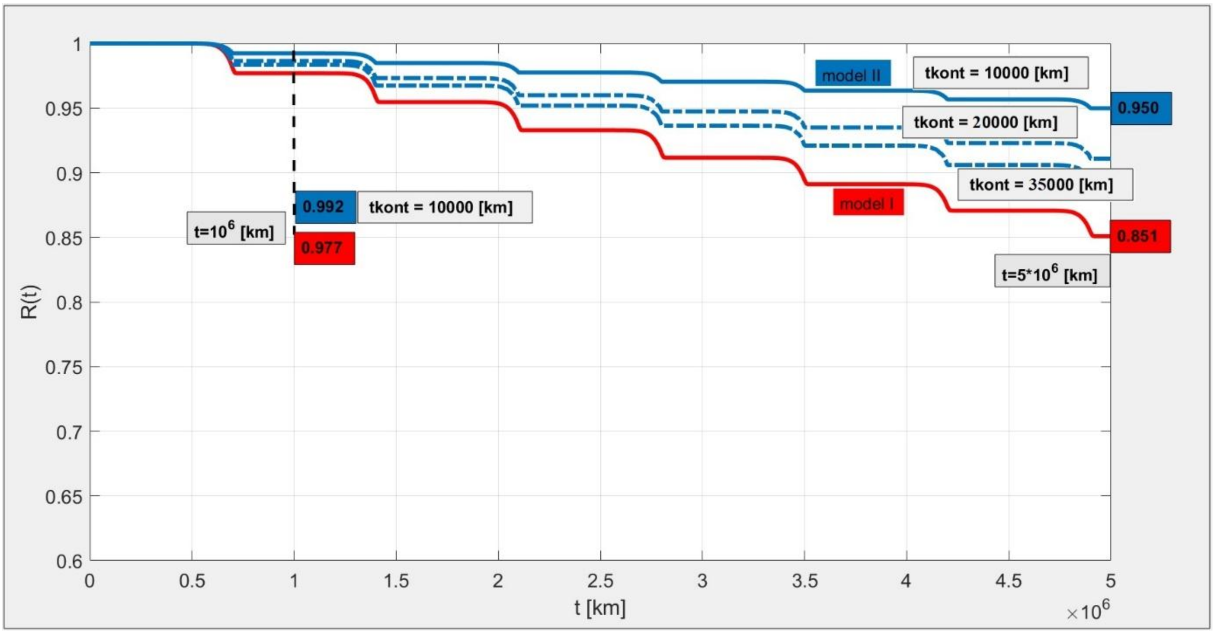

Figure 4. Reliability courses of the pivot system for both variants (I and II) with varying intervals of inspection (t_{kont}) of the condition of the vibration damper.

As can be seen, the reliability courses of the pivot system only changed for variant II of the calculation (blue lines). In the case of variant I (red line), according to its assumptions, the frequency of inspections has no effect on the failure of the pivot because, once the damper has failed and pivot cracking has been initiated, it then occurs continuously until failure despite damper replacements.

However, in variant II, a reduction in the inspection interval results in a better reliability record of the system. The realisation of control inspections at intervals shorter than the base 35000 [km] would be possible in practice, but it would be associated with difficulties (more frequent vehicle stoppages) and additional costs for their realisation. It should be noted, however, that more frequent inspections will result in additional costs and complications in the established maintenance procedures in accordance with the vehicle's MSD (maintenance system documentation), but they enable earlier detection of vibration damper damage. This aspect can be analyzed in detail once the exact preventive inspection costs are known. The reliability values presented for time $t=10^6$ [km] show the reliability for the mileage followed by the inspection, during which the bogie is disconnected from the vehicle and at least a visual assessment of the technical condition of the pivot would be possible.

Figure 5 shows the course of changes in reliability of the pivot system for the assumed input data and variable interval between preventive damper replacements (t_{pr} = 700000 [km], 650000 [km]).

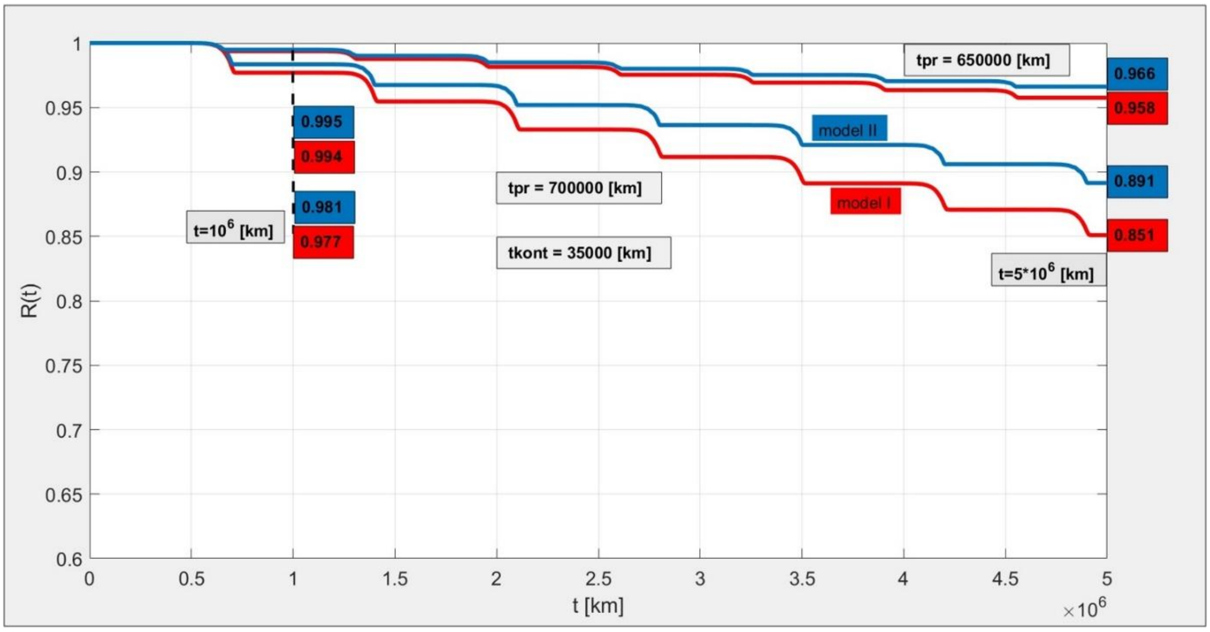

Figure 5. Reliability courses of the pivot system for both variants (I and II) with changing period of preventive renewal (t_{pr}) of the vibration damper.

It can be noticed that a reduction in the period between preventive renewals (t_{pr}) of the damper yields significant changes in reliability in both variants considered (I and II). In addition, a change in t_{pr} is easier to implement in practice and results in maintenance actions being required much less frequently than the visual inspections carried out on the condition of the damper. In this case, it can be concluded that changing the preventive renewal period (t_{pr}) of the damper is a better and more effective way of reducing the probability of damage to the pivot system than increasing the frequency of technical condition checks on the damper.

5. Assessment of the risk relating to damage to the pivot

The pivot analysed in a rail vehicle has the very important function of transferring the tractive force of the drive bogie to the wagon body. Failure of this element can result in the loss of the connection between the bogie and the body. This situation causes a loss of safety when using railway wagons of this design. Therefore, a risk assessment has been carried out concerning the failure of the pivot, which can be equated with the risk of a railway catastrophe. In order to ensure the safe operation of carriages, their critical components and systems should be assessed by quantitative methods [2].

The results of the assessment should be compared and verified with the standardised values of the risk indicators acceptable for the case. The problem is the lack of quantitative normative values for many technical objects in operation. Commonly used quantitative norms in the field of safety and risk assessment relate, among other things, to Safety Integrity Levels (SIL) [1,14]. The practical application of SIL guidelines refers to Safety-Related Systems – SRS.

These levels and the associated numerical ranges of quantitative indicators usually only apply to a selected group of objects - electrical, electronic and those with programmable electronics. There are groups of technical objects or their structural sub-components, as is the case with the pivot, whose failure can lead to a catastrophe that threatens the safety of their operation [13].

Risk assessment in groups of objects constituting a risk, other than those subject to SIL standards, are carried out by committees and expert teams on the basis of qualitative assessment most frequently. Such assessment is not very accurate and often insufficient to ensure the functional safety of the technical objects in operation. There is also a lack of quantitative standards for risk and safety performance for rail vehicle subsystems, on which human health and life also depend.

In view of the consequences of damage to the rail vehicle pivot, an attempt was made to verify the values of the risk index determined for the rail vehicle subsystem under consideration with the values of the index relating to SIL, i.e. PFH - average frequency of a dangerous failure [1/h]. The primary objective of the decision to use the numerical values derived from the SIL safety integrity ranges for the mechanical components of the rail vehicles was the common goal in both cases, which is to ensure the required operational safety.

A quantitative risk assessment was carried out on the basis of the failure rate of the pivot system determined using the damage data obtained in the experiment carried out earlier (variant II) over an operating horizon of $5 \cdot 10^6$ [km] of distance travelled. The $5 \cdot 10^6$ [km] mileage is referred to as the expected lifespan and is included in the manufacturer's order specifications for new trains [17]. The results of the analysis carried out are presented as a characteristic of the failure rate function. The determination of this characteristic makes it possible to quantify and observe the change in the risk of damage to the pivot system and the loss of transport safety, depending on the distance travelled and the applied period of preventive replacement of the vibration damper (t_{pr}) in the pivot system. The failure rate function obtained for the two example t_{pr} values is shown in Figure 6. In order to compare the results obtained with the PFH values for the SIL safety integrity levels, the mileage was converted into vehicle driving time expressed in hours, which for $5 \cdot 10^6$ [km] of travelled distance was 80645 [h].

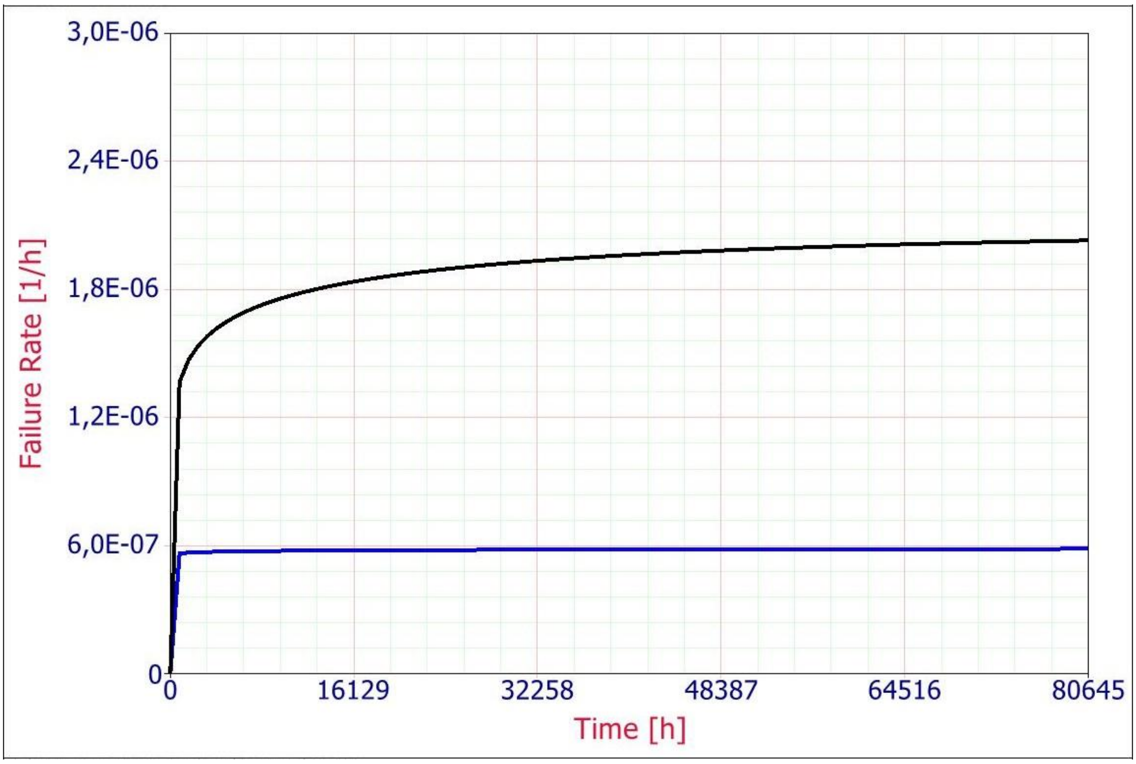

Figure 6. Characteristics of the course of changes in the intensity of damage to the system for two strategies of preventive replacement of the vibration damper in the rail vehicle pivot system - $t_{pr} = 7 \cdot 10^5$ [km] (11290 [h]) - black, $t_{pr} = 6.5 \cdot 10^5$ [km] (10484 [h]) - blue.

In the presented graphs obtained from the G. Gamma distribution adjusted to the data it can be observed that the failure rate function stabilises after an initial increase. This can be interpreted as an apparent effect of the preventive replacements performed on the vibration damper. A smaller value of time to preventive replacement (t_{pr}) results in an earlier stabilisation of the failure rate function and its smaller maximum value in the course than with a larger value of t_{pr}. By changing the value of the time of preventive replacement (t_{pr}) of the vibration damper, it is possible to have an influence on the value of the failure rate function and the risk occurring during the service life of the system.

Figure 7 shows (after calculations for different values of t_{pr}) the effect of the vibration damper preventive maintenance interval (t_{pr}) on the maximum value of the failure rate function over the analysed operating horizon of the rail vehicle.

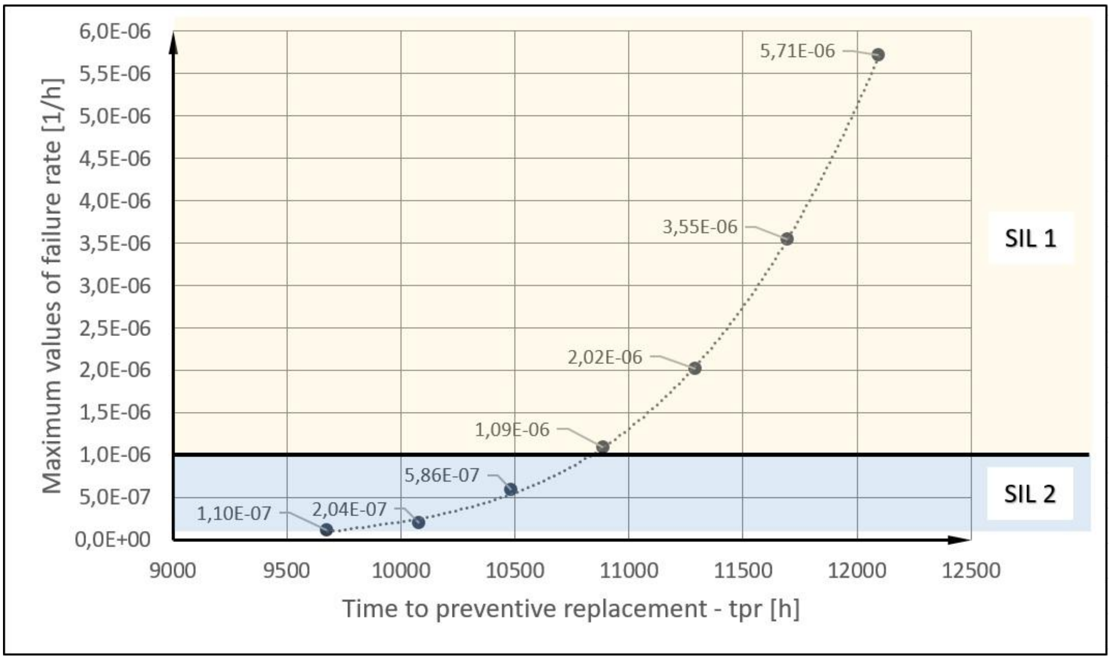

Figure 7. Dependence of the maximum failure rate value over the service life of the pivot system (80645 [h]) on the vibration damper preventive renewal period (t_{pr}).

It can be noted that decreasing the value of t_{pr} has a clear effect on the maximum value of the failure rate function reached over the analysed fixed operating period (80645 [h]). On the basis of the obtained course of changes, it is possible to determine what the vibration damper preventive renewal period (t_{pr}) should be in order not to exceed the risk value (failure rate function) set by the operator or to enable the required SIL to be achieved.

In the case under consideration, performing preventive maintenance of the damper at least every 10800 [h] (669500 [km]) of driving should ensure that the pivot system meets safety integrity level SIL2. On the other hand, preventive replacements less frequently than every 10800 [h] of travel will result in the system meeting a lower safety integrity level SIL1.

6. Conclusions

The issue of reliability of modernized rail vehicle components is little addressed in current publications, despite the frequent occurrence of vehicle modernization projects. The innovative aspect of this work is the development of a model for reliability testing and risk assessment for variable maintenance intervals. This study is particularly significant because it addresses safety-critical rail vehicle design components. The main scientific achievements of the article include: development of two variants of the computational model for assessing the reliability of the rail vehicle pivot system, taking into account the dependence of damages of the system components – the pivot and the vibration damper – in the model, determining the influence of preventive maintenance and preventive inspections of the damper on the reliability of the system and on the maximum value of the failure rate during the considered period of operation of the system.

The computational model developed made it possible to assess the reliability of the rail vehicle pivot system, taking into account the relationship of damage occurring between the parts of this system and preventive renewal for a selected practical case. The experiments carried out determined the effect of both the inspection period (t_{kont}) on the reliability of the system and the effect of the vibration damper preventive renewal period (t_{pr}) on the reliability of the system. The baseline values of t_{pr} (11290 [h] driving) and t_{kont} (565 [h]) were adopted according to the inspections scheduled in the maintenance system documentation (MSD) of the vehicle under study.

Changing these values would certainly involve additional problems associated with the vehicle downtime and the cost of additional inspection activities. However, as the analysis of the risk of damage to the pivot system has shown, changing the preventive renewal period of the vibration damper makes it possible to seek an acceptable risk value for the operator and to achieve the required SIL safety integrity level. These aspects, with a view to ensuring operational safety, should be prioritised in operational practice and should form the basis for determining, in particular, the preventive replacement periods for components.

The analysis presented in this article, using the example of a pivot system, draws attention to the problems of maintaining the safety of vehicle operation following an in-service upgrade of a structural component. There are many similar situations in the operation of technical objects.

Relevant structural components after modernisation should undergo adequate strength testing and preliminary verification of performance characteristics, including in-service reliability. A measure of safety is, among other things, the reliability of the object in service, which in safety engineering plays an important role and its determinant can be the SIL. The influence of the applied preventive maintenance strategy on vehicle reliability, which can be seen in the analysis, testifies to the great practical importance of this type of actions and takes place in the majority of technical objects in service.

The main directions of further work on improving the computational model may primarily concern the introduction of probabilistic initiation of journal cracking after the start of cooperation with a damaged vibration damper. A second research direction, which would increase the model's applicability, would be to perform a detailed economic analysis of the use of preventive inspections and replacements of vibration dampers.

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