University of Pardubice

MAINTENANCE MANAGEMENT OF ROLLING STOCK FOR DEPENDABILITY OPTIMIZATION

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1 The Current Situation in the Study Subject

The railway transportation system in the Czech Republic territory has been going through several changes during the recent years. Consequently, a major impact has the transport policy of the European Union [1] , which enforces a unified European market for the railway transportation of both cargo and personnel. Nowadays there are directives in place which decree the liberalisation of the interstate railway transportation of personnel. Starting in 2034 at the latest, railway transportation is supposed to be fully provided through public market competitions. The attempt to unify the security levels within the entire European Union is a second aspect of the efforts towards a unified railway market and transport infrastructure.

Therefore of the utmost importance to carriers are the attributes of the rolling stocks, which can be offered to their customers (respectively directly to the passengers, in the case of non-subsidiary transport routes).

As a general rule, the competitive environment increases the push towards increasing the internal process performance and the demand for the quality of the offered product. Transportation time is a decisive factor for most passengers and customers in public transport [2].

1.1 Dependability Standardisation

The latest edition of the *International Electrotechnical Commission* came into effect in 2015 [3]. The definitions in this document are further adopted by other norms. For the temporal attributes of the quality of the given object, the unified term ***dependability*** is used, which is why the dependability of rolling stocks is of crucial importance regarding the quality of railway transportation as perceived by the customers.

In general, the dependability of a given object can be either *inherent* or *operational*. *Inherent dependability* is the result of the quality of the project and vehicle manufacture and it does not change over time. Operational

dependability is partially influenced by the magnitude of inherent dependability, although it is dependent on a large number of other factors, which can be influenced mainly by maintenance and its provision.

In the railway industry, the EN 50126 norm (first issued in 1998) can be considered as the first international norm regarding the dependability on our territory. For vehicles of different modes of transport, there have been branch norms for quality and dependability in place for about 50 years already. As stated by Michal Vintr, *in the railway industry, dependability is understood as something slightly different than in other industrial branches*[4].

The prevailing model in passenger railway transportation in the Czech Republic is the following - the railway carrier owns the vehicles and directly provides the basic maintenance through their own employees, a higher degree of maintenance is then provided by external suppliers in some cases. Until recently, the carriers have not been required to track and evaluate the dependability of rolling stocks through standardised indicators and attributes, thus the importance of the standardised indicators has been growing over the recent past years. Due to the global changes regarding the field of company management, the model of *Integrated Management System* has been growing in popularity since standardised indicators have a much larger importance within this model. The regulatory decrees concerning safety now determine new requirements for the evaluation of safety in cases of alterations and modifications of vehicles already approved for operation. The vehicle construction alteration approval process is more rigorous and it can be assumed that with the employment of standardised indicators, the implementation of the required construction alterations can be markedly less difficult.

1.2 The Changes in the Management of the České Dráhy, a.s. Company

The České dráhy, a.s. (ČD) company has provided the data sources necessary for the composition of the dissertation. The research objective which has been reached using this data has thus been influenced by the current environment in the ČD company.

The maintenance of rolling stocks is directed by the internal V25 norm within the ČD company. The current issue of this norm is in effect since 2000. It sets down the dependability requirements only in a general manner and it does not determine any specific indicators through which the vehicle dependability would be systematically evaluated.

In July 2018, the original ČD management units have been abolished, i.e. the *Rolling stock depots*, which provided the operation and maintenance of the rolling stocks in a complex manner. The management changes in the ČD company resulted in the management units ensuring the operation of vehicles and the *Regional maintenance centres* (facilitating the management and maintenance of rolling stocks) to be expressly separated.

A new reinvented edition of the V25 norm is currently in preparation, which is supposed to not only take into account the inter-management alterations in vehicle maintenance but also to fulfil some of the legislative requirements regarding the provision of maintenance including all of the required documentation.

Although general standards and norms for dependability have already existed in the past, railway carriers have thus far not been required to evaluate vehicle dependability directly through the indicators gathered from the data regarding operation and maintenance.

1.3 Vehicle Management and Maintenance Information Systems

Following the technological advances, the requirements for the usage and evaluation of data and information are also increasing, which is concurrently a direct requirement of the quality management norms.

The Enterprise Asset Management (EAM) information systems are used to facilitate the maintenance and management of technical devices.

Related to the „*Industry 4.0*" initiative, the integration and factual interoperability of information between individual systems and devices is taking place, the devices communicate with each other without any human involvement, and thus, the Internet of Things (IoT) phenomenon emerges. The coming of Industry 4.0 is associated with alterations to the maintenance of devices by some authors. With the term "preventive maintenance 4.0" they are referring to the maintenance strategy, which employs an extensive data and information analysis to direct the maintenance interventions, the data is gathered from the continuous data flow coming from the sensors of the maintained objects and the environment in which they operate.

The current EAM system inventors are attempting to integrate these resources directly into their products, and concurrently they create modules which adhere to the specific requirements for the management and maintenance of devices in the given industrial branch. All of the foremost EAM system invention enterprises provide extensions specifically for the management and maintenance of transportation vehicles, respectively specifically for railway vehicles, while at the same time providing the IoT functionality and other technologies. Thus, a single system can integrate the management and maintenance of rolling stocks with the workplace safety during maintenance and qualification plans of the maintenance personnel today.

1.4 Working with the Vehicle Maintenance Data

The Current Situation at ČD

The SAP company information system is integrated within the ČD environment. The *Plant Maintenance* module has been implemented in 2005. Currently, only the information about the daily mileage in kilometers is automatically loaded into the module, all of the other data (operation hours of certain combustion engines, the data gathered by the measurements intended for vehicle technical inspection etc.) is entered into the system manually. Even the contracts for vehicle maintenance and completed work reports are entered manually. The information system primarily serves the purpose of tracking the company finances and keeping records of the documents required by the legislative, including some of the values gathered by the measurements intended for vehicle technical inspection.

The ČD is preparing the upgrade of the system database to a new technology, the *SAP HANA*. This technology will make it possible to process large volumes of data and to immediately analyse it, thus in the future it will be possible to use new technologies from the data mining field concerning the technical condition of vehicles and their analysis. These tasks are currently performed by maintenance engineers separately from a unified information system.

Data Collection and Evaluation Abroad

The degree of evaluation and collection of data regarding the dependability of rolling stocks differs a lot abroad, one example in the field of transport vehicles is that the European Commission decreed the "holders of transport vehicles" to uphold several duties ensuring safety. Based on this decree Poland has implemented the methodology which implements the evaluation of dependability attributes stated in the 50126 European norm. This methodology is described in detail by the collective of authors led by professor Sitarz [5].

Several foreign enterprises, which operate with rolling stocks and which the author was able to gather the necessary information about, evaluate availability based on the tracking of the time intervals needed for maintenance and time periods over which the vehicles can fulfil the desired transportation functions. Further attributes, such as reliability, maintainability or maintenance support performance, are however not tracked by them. Furthermore, the enterprises do not track the causes of failures (which cause train delays) in much detail, neither do they track the reliability or maintenance support performance.

The degree of tracking and evaluation of partial attributes of dependability, the record keeping and evaluation of causes which diminish it, are seemingly all dependent on the size of the company and its resources regarding the ability to afford the corresponding information systems.

Large enterprises employ advanced systems which transfer the measured diagnostic values directly into EAM systems, in their vehicle diagnostics. The *Mainnovation* and *PwC* companies have performed a research effort aimed at the application of the Preventive maintenance 4.0 technology and the results show the companies in the railway industrial branch in Germany, Belgium and Netherlands are at the forefront in terms of implementing these new technologies [6].

2 Dissertation Objectives

Due to the changes in the market environment, the main motive behind the determination of the dissertation objective was the relation between the customer expectations and the conduction of rolling stock maintenance, and thus the formulation of the dissertation objectives and the procedures of the conducted research can be characterised with the following formula:

Customer expectations → QUALITY → DEPENDABILITY → MAINTENANCE of rolling stocks.

The first partial objective of the composed dissertation is thus to identify the customer expectations and to describe their requirements regarding the quality and dependability of rolling stocks. Processing this methodology was the starting point for further stages of research.

2.1 Evaluation of Vehicle Dependability Based on the Available Data

Through the fulfilment of the research objective (to describe customer requirements) were identified the primary attributes based on which the contractors of public railway transport evaluate its quality and dependability. Thus, the expected dependability of rolling stocks is de facto also determined.

The next objective of the dissertation was to create the indicators for the evaluation of vehicle dependability, which use routinely collected data by the carrier (ČD) and through which the degree of attribute fulfilment (which is of customer interest) can be periodically tracked. The basic requirement for the data usable for fulfiling this objective is its credibility.

2.2 Using Dependability Data to Manage Vehicle Maintenance

The indicators which were created based on the previous objective directly reflect the customer expectations through reliable data, however, they do not necessarily lead towards the determination of causes preventing the increase of vehicle dependability, and thus they cannot contribute to the changes in vehicle maintenance and the overall increase of the degree of railway transport quality.

Therefore, another objective of the dissertation was to determine the usable data structures and to propose indicators which can serve the maintenance managers and engineers in deciding for measures and changes in vehicle maintenance. The credibility of data necessary for fulfiling this objective is

however no longer guaranteed. An important step in this stage of research was to verify whether there are suitable data fields in the information systems, which would be usable after changing the data collection methodology along with certain other alterations, and the bridging of the inertial systems.

Determining the methodology which could be used to evaluate some of the dependability attributes from an operationally-economic perspective, was a specific objective in this stage of research.

3 Processing Methods and Manner of Solution

To perform a marketing research among the passengers, which could describe their expectations in transportation quality and dependability, would be above the scope of the dissertation - the identification of customer expectations has been performed in the form of research of the contracts between public transportation personnel clients and the carriers. Since the clients are either self-regulatory bodies or state authorities, and transportation for public benefit is financed by public budgets, thus also the contracts facilitating such transportation are publicly available. In total, 5 contracts and 1 transportation provision supply competition documentation have been analysed.

3.1 Train Delay and Kilometre Mileage Data Analysis

There are three perspectives from which transport clients evaluate vehicle dependability from:

- train delays,
- adhering to the planned ordering of train units (adhering to planned quality norms for train units),
- the dependability of onboard devices in train units.

The third perspective employs evaluation using spot checks; however, the data regarding them was not available to be processed in the dissertation.

Train Delays

Investigations into train delays within the ČD environment used to exist in the form of *dispatcher orders and admonitions*. To make the routine analysis of the data from these documents possible, the dissertation author created his own software using the *Visual Basic* programming language functionality in the Microsoft Word software - the data collection was standardised using this custom software. Based on this the author created his own methodology for data collection and train delay evaluation. The train delay data research method was the conduction of a range of analyses which differ in their purpose and usage of specific values, which have been gathered for the purpose of train delay evaluation.

The Evaluation of Vehicle Deployment Based on Kilometre Mileage

It is not possible to obtain data that would be immediately usable for the evaluation of the adherence to the planned ordering of train units from the current information systems used for vehicle maintenance - this is caused by the absence of an information link between the operation and maintenance systems. One of the credible quantitative data sources regarding vehicle operation is their mileage, which is entered into the system daily.

For the evaluation of vehicle dependability based on kilometre mileage, the comparison of the statistic files representing different vehicles or vehicle groups is included in the dissertation. For such comparisons, "box plots" can be used for our advantage.

The method of comparison between the empirical mileage of vehicle fleets designated for the given transport route and the created theoretical operation model is included in the dissertation for the purpose of periodical evaluation of the adherence to the deployment of vehicles in trains. From

this comparison of daily values, time series have been prepared. As one out of the available methods for their analysis, the application of the Box-Jenkins methodology "ARIMA models“ is included in the dissertation.

Then, from their application coupled with the analysis of the time series, several conclusions can be reached regarding the fulfilment of the anticipated operation concept at the given route and the actual operation security attained by the given vehicle groups.

3.2 Investigations of Data Structures for Dependability Management

Due to the fact that from the evaluation of kilometre mileage no conclusions can be drawn within the ČD environment regarding the causes of operation failures for specific vehicles, it is necessary to specify other indicators for the management of maintenance and de facto also the dependability of vehicles. In order to create the possibility of determining the causes of the decrease in the degree of vehicle *availability*, it is appropriate to evaluate the following attributes - *reliability*, *maintainability* and *maintenance support performance*.

The usage of standardised indicators for dependability evaluation carries many advantages, however, for them to be applied, it is necessary to identify the individual time periods and intervals in which the rolling stock can find itself in.

As a part of composing the dissertation, the time intervals in which a given rolling stock can find itself in over the duration of its *operational and maintenance* life cycle have been identified. They have been identified through the general period description (stated in [3]), for some of these intervals the description of their current records in the ČD environment is included in the attachment of the dissertation.

For the purposes of analysing the usability of the data which has been determined by the previous study, we have merged the data from the

databases: *Operation performance data archive* (using the *PARIS* task) and the *SAP Plant Maintenance module* information system.

The data usability analysis itself was conducted according to an unified methodology through experiments. The experiment has been evaluated as successful if for the randomly chosen attributes, Weibull distribution parameters have been found that would not necessitate the refusal of the data distribution approximation hypothesis based on a χ^2 *Pearson's chi-squared test*. 8 experiments using different statistical files are presented in the dissertation, the files are mutually related and they have been created using the maintenance and operation data regarding vehicles designated for specific transport routes in both regional and long-distance transport.

To demonstrate the importance of tracking the time intervals, the dissertation includes the application of the *multivariate random variable*. It is possible to determine the need for a backup vehicle using a random attribute determined by the previous step using the method published in [7] with minor alterations.

4 Achieved Results

The contract research shows that the expectations of the majority of transport clients regarding vehicle dependability can be described through two main attributes: *accuracy indicator* and *adherence to the ordering plan* (Figuere 1).

The accuracy indicator is a form of a certain expression of the relation of train delays to the total ordered transport performance. The threshold value for train delays which the clients are normally willing to tolerate is approximately between 5 to 10 minutes, and the threshold value for delays in case of which the clients are no longer willing to compensate for the train operation expenses is approximately between 30 to 60 minutes.

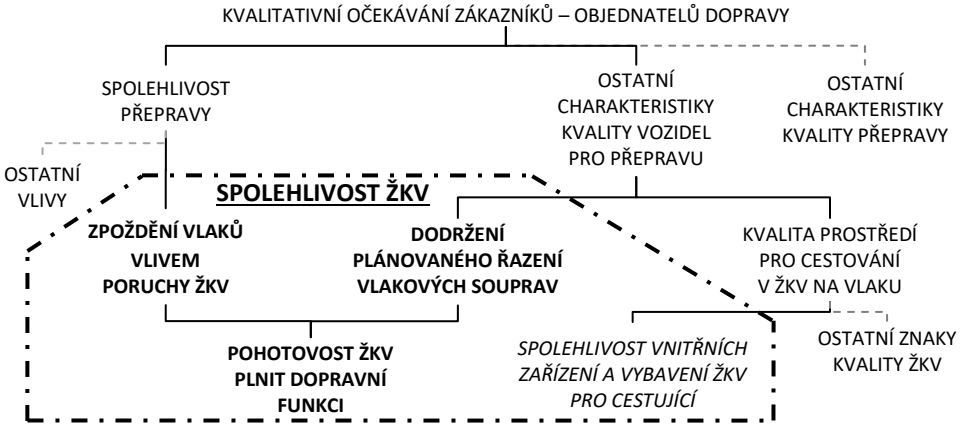

Figure 1 – Dependence of the public transport customers' expectations and the dependability of rolling stock

The indicator of the adherence to the ordering plan is an expression of the relation between the number of trains which are formed by planned vehicles, to the amount of all ordered transport performances. For clients, the acceptable value of this attribute is approximately between 90 to 98 %.

4.1 The Possibilities Regarding Train Delay Analysis

As a part of the research necessary for the composition of the dissertation, a new comprehensive methodology for collecting data regarding train delays has been employed. The data which was successfully gathered over the duration of the application of this methodology can be processed into analyses and indicators, which can then be used to identify the real causes of vehicle malfunctions that cause the delays. An example of the analysis is depicted in Figure 2.

To achieve a blanket application of the stated methodology, it is appropriate to integrate the information and to minimise manual data entry - a proposal for the integration of information through the linking of several data sources is described in the dissertation.

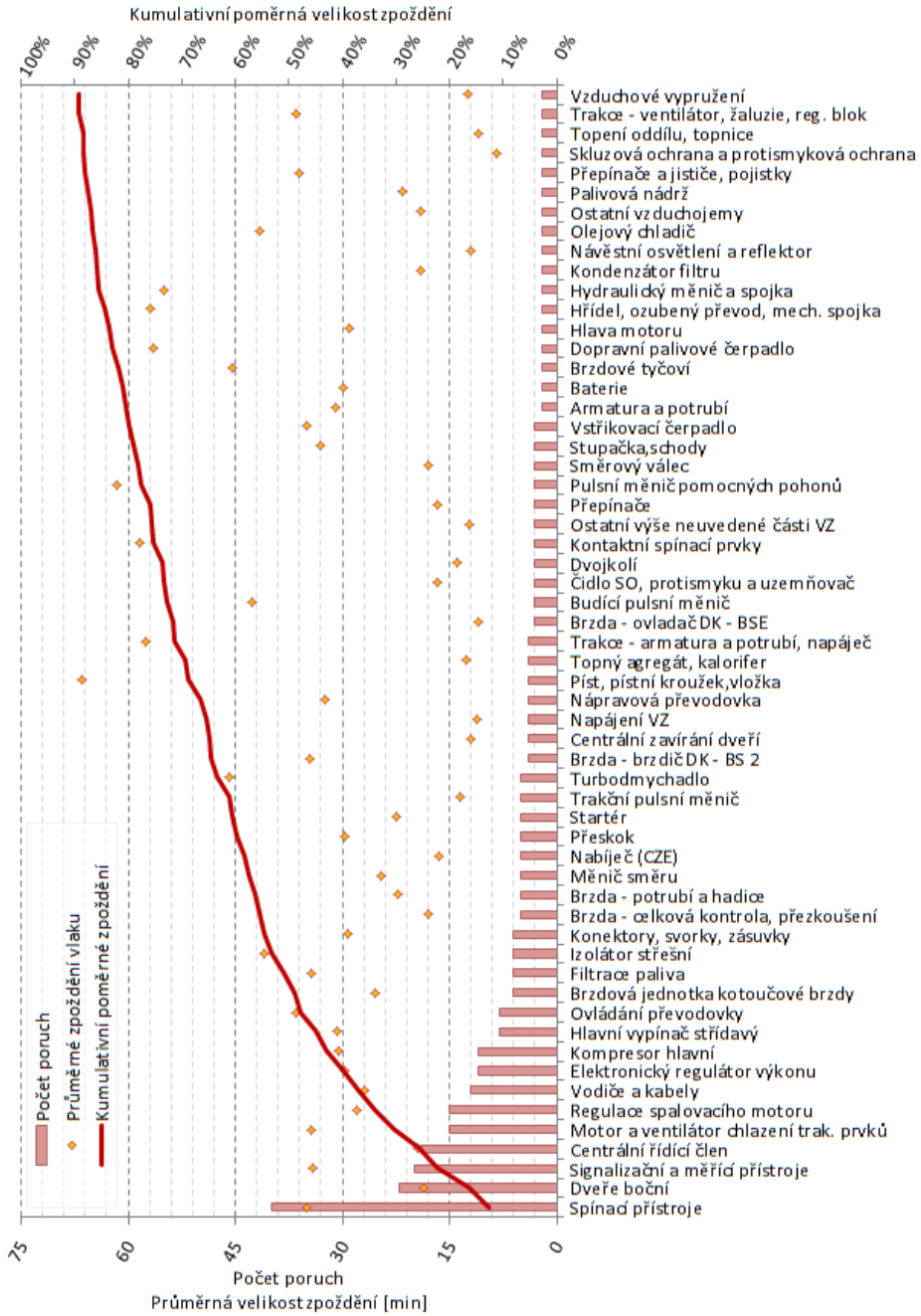

Figure 2 – Pareto analysis of the causes of train delays due to vehicle failure

4.2 The Evaluation of Rolling Stock Availability

Even though no exact statements regarding the standard dependability attributes can be found in the contracts between the clients and the carriers, it is clear that one of the dominant vehicle attributes in relation to the customers is its availability.

The dissertation includes a description of the indirect evaluation of the degree of availability of a vehicle fleet using the kilometre mileage data. With the aid of the comparison between empirical values and the planned operation theoretical model, it is possible to evaluate the degree of customer expectation fulfilment at specific transport routes. In the ČD environment, an advantage of the described method is that it is not necessary to collect new data, or more specifically, to alter the methodology for collecting the used data. However, its disadvantage is the limited ability to identify the causes of diminishing availability of specific vehicles, yet the basic information about the development of the vehicle group availability can be gathered using the method. (See Figure 3.)

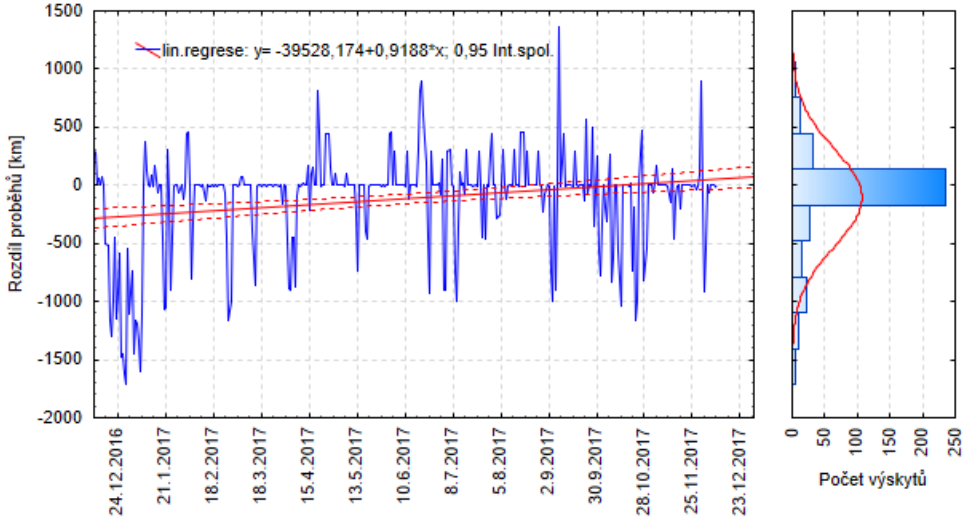

Figure 3 - Time series of differences in empirical and planned runs of selected fleets of vehicles

Vehicle availability is dependent on attributes which need to be tracked and evaluated to enable the identification of causes which decrease vehicle availability [3]. An appropriate data source has been identified for *maintainability* and partially *maintenance support performance* through the research of current data structures, and the random attributes determined by this data can be approximated through known distribution. Thus, the result of this part of the research is the conclusion that current data structures provide the data appropriate for vehicle dependability evaluation using standardised indicators. The partial results are the conclusions drawn from the evaluation of individual attempts at approximating various random attributes. The results show that the corresponding evaluation of dependability attributes requires the analysis of data, which is specifically collected for the dependability evaluation, among other reasons.

The Operationally-Economic Perspective

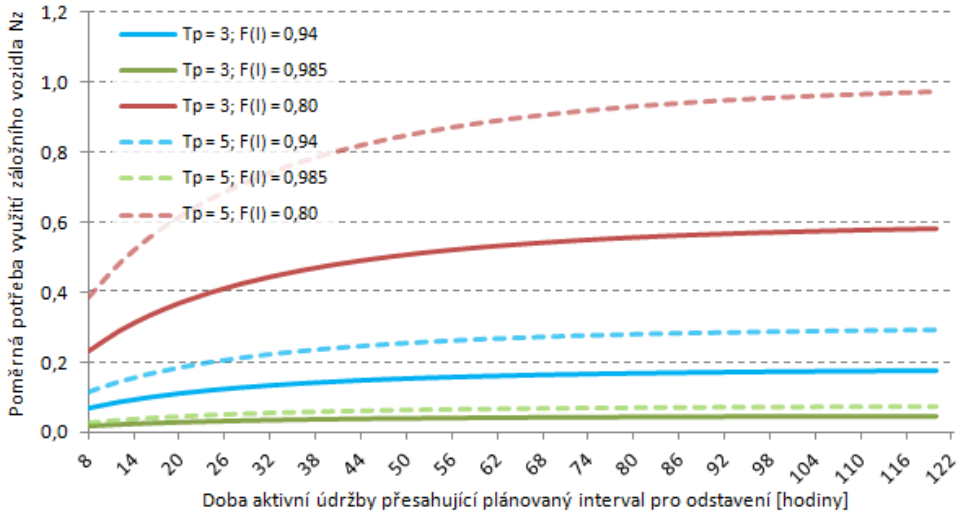

Figure 4 – Need for backup vehicle depending on the maintenance time that exceeds the scheduled interval by a random vector

A partial result of the dissertation is the verification of the applicability of the multivariate random variable for determining the need for a backup vehicle. It is then possible to quantify the degree of need for a backup vehicle

for various degrees of maintainability and availability (See Figure 4.). The method can generally be applied to random variables without any regard for their physical dimension, and it can also be beneficially applied to smaller vehicle fleets designated only for selected transport routes.

The possibility of investigating the impact of *maintenance support performance* and *maintainability* on the need for further backup vehicles can be significant in the consideration regarding the provision of alteration of individual vehicle dependability data collection systems.

5 Dissertation Contributions

The basic requirement for quality management systems is customer orientation. The dissertation includes a new description of the relation between customer expectations and vehicle dependability - it is apparent that individual transport clients have different requirements. Yet, based on the analysed public contracts, it is possible to determine two primary attributes which involve the total vehicle dependability, or more precisely the availability in fulfiling the desired transport role.

5.1 Using the Train Delay Data

For it to be possible to conduct a more detailed analysis of the causes behind train delays, the dissertation author created his own software for train delay data collection. Then, based on this data, he proposed a methodology for its evaluation which enables the analysis of the possible causes behind malfunctions and to consider measures for vehicle maintenance which would minimise the occurrence of train delays, thus generally it is possible to fulfil the requirements for quality management systems regarding the improvement of processes based on data evaluation thanks to the methodology and its application proposed by the author.

The dissertation includes several data analyses and examples of train delay studies, some of which can be generalised and applied to any given carrier.

Some of them can also be applied for ČD when an appropriate data structure is used. The published examples are most often only general descriptions, but they can provide valuable information for workers involved in vehicle maintenance and operation when applied to a given vehicle group.

A description of the proposal of the integration of information from various information systems currently used in ČD is included in the dissertation. The advantage of such integration would be the routine collection of data regarding the occurrence of train delays, which is only slightly intensive in terms of manual data entry by the workers at the given units. The implementation of the described proposal would enable the creation of an objective summary of the train delay issue, based on which the considerations regarding the alterations needed to minimise the negative impact on customers could take place.

5.2 Dependability Attributes and their Evaluation

The dissertation includes a description of a method of indirect evaluation of availability based on the data regarding the daily vehicle mileage. Since there is no link between information systems which would enable the tracking of the functional conditions of vehicles, as well as their transport performance, in the ČD environment, the usage of kilometre mileage analyses is one of the few options in terms of quantitative evaluation of the dependability degree.

The method of comparison between the real mileage of vehicle fleets and the vehicle fleet theoretical operation model can be used without any large requirements for information system alterations.

Since the causes behind the decrease of dependability in specific vehicles cannot be determined using the methodology of fleet dependability degree evaluation, the author also focused on the options regarding the evaluation of availability and other standard vehicle attributes. For the purpose of their tracking, the current options regarding the usage of data in the ČD

environment are published in the dissertation. Furthermore, a new delimitation of time intervals according to the responsibility of vehicle operation and maintenance units is also published in the dissertation. This delimitation is a key factor in further analyses of risks attached to vehicle dependability, precisely in the manner specified with the current quality management systems norm.

The dissertation describes the research of the applicability of the indicators for *maintainability* and *maintenance support performance,* based on which it is possible to acquire a real perspective on the current condition of the data in the ČD environment. Due to the developments in the areas of legislation and railway transport market, it can be presumed that in the future it will be necessary to track and evaluate the dependability using the standardised comparable attributes. The published research of data evaluation for such dependability attributes shows that the quality of the data has crucial influence over the results. A key factor for the researched issue is also the collection of data with the purpose of dependability evaluation. A large contribution of the conducted research is the gathered insight regarding the significance of the collection of specific data, which is credible and usable for the evaluation of dependability in railway transportation. This applies generally for all carriers and subjects operating in the passenger rail transport industry.

The dissertation includes a description of a method for determining the need for a backup vehicle using the multivariate random variable. This method can be used to appropriately interpret the impact of the alteration of attributes such as *availability*, *maintainability* or *maintenance support performance,* on the operationally-economic planning and other internal processes of carriers. Its inclusion in the dissertation has primarily the purpose of demonstrating the significance of dependability evaluation in maintenance management. The basic requirement for the procedural access of the organisation includes the application of the PLAN-DO-CHECK-ACT

cycle to attain process improvement. If the degree of dependability required by the customer is to be safely attained, it is necessary to also continually improve the railway vehicle maintenance and management process. Without the information entered in the CHECK phase, the systemic increase in vehicle dependability cannot be ensured.

In the present day, a large number of technically-technologic assets (e.g. *IoT*, *Preventive maintenance 4.0*) are available, which enable the collection and analysis of significantly larger volumes of data, than there were in the recent past years. The usage and implementation of these assets can currently (and in the future) provide the carriers with significant advantages compared to their competitors. The author of this publication attempted to contribute to the general insights regarding the facts about which data is worthy to be collected and evaluated to attain the improvement of railway vehicle dependability and maintenance

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Abstract

This self-summary describes the dissertation, which focuses on the collection and analysis of data to evaluate the dependability of passenger transport railway vehicles. The starting point for its composition is customer expectations regarding railway transport dependability. The research involved in the analysis showed that the significant indicators are *transportation accuracy* and *adherence to train unit order*. Basic descriptions of the methods of analysing the relation of these indicators to vehicle dependability are presented here. The results of the performed research can be applied to the proposals for alterations of information systems used by carriers and subjects responsible for maintenance. The application of the described insights in the area of data collection and evaluation can result in acquiring the tools for improving the railway vehicle maintenance process to achieve the corresponding degree of their dependability.