IMPACT OF INFRASTRUCTURE TYPE ON RELIABILITY OF RAILWAY TRANSPORTATION SYSTEM

WPŁYW RODZAJU INFRASTRUKTURY NA NIEZAWODNOŚĆ SYSTEMU TRANSPORTU SZYNOWEGO

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Abstract: *In this paper, the author's research work is focused on infrastructure impact on railway transportation system reliability. The aim of research described in the paper is to determine correlation between type (and age) of used infrastructure elements, and number of occurring failures. For this purpose, subsystem of infrastructure and associated with it events, were divided into main groups. Examples of groups are: track, train operation devices (related to operating control points or railway line), level crossings, etc. The second aspect is correlation between type of infrastructure and failure consequences. It is required from transportation that it is possible to achieve the right place at the right time in a safety way. Therefore, from the point of view of transportation process, which is the main goal of transportation system, the most significant failure consequences are delays. Moreover, speaking about reliability and safety of railway transportation system, the question arises what is the relation between number of trains and number of unwanted events?*

Keywords: railway transportation system, infrastructure, reliability

Streszczenie: *Celem badań opisanych w artykule jest określenie korelacji pomiędzy typem (także wiekiem) użytkowanych elementów infrastruktury, a liczbą występujących zdarzeń. W tym celu podzielono infrastrukturę oraz zdarzenia z nią związane na główne grupy. Przykładowymi grupami są: nawierzchnia, urządzenia sterowania ruchem na posterunku ruchu, urządzenia sterowania ruchem na linii, przejazdy kolejowe itp. Drugim aspektem jest korelacja pomiędzy typem infrastruktury a skutkami. Z punktu widzenia realizacji procesów transportowych, najważniejszym parametrem definiującym skutki są opóźnienia. Ponadto istotne jest pytanie, jaka jest zależność pomiędzy liczbą pociągów a liczbą zdarzeń.*

Słowa kluczowe: transport pasażerski, strategia obsługiwaniania, system ekspertowy, opóźnienie czasowe

1. Introduction

Transportation processes may be disrupted as a result of various problems connected with:

- train failures,
- infrastructure failures (failures of rail, signalling etc.),
- random accidents occurrence (associated with environment).

Train failures can be classified into events related to train or passenger interactions and system failures resulting from vehicle unreliability. Vehicle reliability analysis has already been developed in researches for many decades.

On the other hand the infrastructure reliability has not been investigated and unfortunately, little attention has been given to this problem in reliability literature. However, there has been no attempt to describe reliability of other components of the railway transportation system (passengers, crew, infrastructure). Due to lack of adequate literature sources, the paper is mainly based on case study of selected Polish railway lines.

For an analysed Polish region, events due to trains (including passengers and staff) participates by 34.91% in all failures. Unwanted events related to infrastructure participates by 51.36%. The remaining 13.73% associated with environment of the system. The work ends up with summary and directions for further research.

2. Research on railway reliability - state of art

The rail system is investigated primarily at two levels of detail. The first is a detailed approach. Reliability and safety of specific components are researched.

The analysis of technical objects included in the infrastructure might be an example. The unit directly responsible for the safety of the railway - railway traffic control device are primarily analysed.

An important part in all the devices are those which work periodically, and the remaining time are standing by. That's where arises the problem of determining the time between failures, and linking it with real time. In this case, first determined is the operation time between failures. It sets out the daily amount of working hours and divided by 24 hours gives the coefficient used in determining failure rate. Using this coefficient it is possible to transfer to an absolute timeline [13]. In the case of traffic control devices Markov models are used for each technical object [13]. In [4] author used a Markov model to analyse the impact of different maintenance policies on the availability of the system.

Assessment of the reliability of rail vehicle components can also be carried out based on Markov processes, Reliability Block Diagrams [18] and Fault Trees [15]. Recently Markov processes have been used to model the degradation and damage of superstructure [6]. In addition to the studies based on mathematical models, the analysis on the operational data of failures have been performed. However, these analysis have been limited to statistical analysis and estimating parameters for future theoretical models [3], [16], [20], [23].

In addition to vehicles, discussed are issues of infrastructure and determine the relationship of the actions improving safety [2]. The issue is the optimal moment in terms of modernization of the infrastructure costs (damage, speed limits, the same upgrade). Solutions to this problem are obtained by Life Cycle Costs [17], where the decision algorithms for finding the support moment with minimal total cost are looked for [7], [9].

In [27] reliability of the processes in the analysis of the capacity of railway lines residually appears, where the task is to minimize the liquidation rate of delays, depending on the structure of the timetable. A similar issue is the capacity of railway junctions, in which the author examines the critical points of occupancy infrastructure in the context of route conflict.

In addition to the internal system's effects, the train delay causes derogations approved by the customer schedule. As a result of that event [8] carrier records the losses, which were estimated in [14]. More detailed is an analysis of the event impact treated as a primary failure and associated consequential failure (excluding the impact of motion) [24].

Punctuality evaluation model contained in [5] contains terms referring to the interaction between the rolling stock subsystem and the other subsystems, which in the context of a lack of knowledge on the subject greatly reduces the possibility of practical use.

The paper [19] presents a simulation model of the railway network. Two railway lines with a joint centre section were divided into equal sections. Each section can stay in one of six states describing degradation, where 0 is the only failure state. Intensities of transitions between states are constant. Degradation model was supplemented with possible route speed (nominal 100 km/h, reduced 80 or 60 km/h) to give the eighteen-state model to determine the daily delays on the network. Although taken into account the situation of motion, it was found that the scope is too narrow. The timetable, the number of main tracks, the impact of the station to operate trains, traffic control points, etc. were completely omitted.

For analysis of the risk of failures in the railway system, as in the case of other technical systems the event tree may be used. In [1] the analysis extends of the risk influencing factors. The issue is shown on the example of single-track lines, for which the top event is the collision of two trains coming from the opposite direction. The barriers designed to prevent the occurrence of top event were inventoried, and then a tree of events leading to barrier failure was made. Base events were assigned operating attributes to the risk factors. Supplies combined with a more general level (organizational factors). At the highest level of generality factors stemming from legal requirements were placed. Carrying out a study to determine risk factors and sequences show the relationships of cause and effect

relationships that go beyond a simple Event Tree Analysis. In the present case it was shown that the most important factors that affect the risk are: human behaviour and operating conditions of the system.

In [29] was presented a traffic control system basing on local subsystem (stations operated by station inspector) and the subsystem of the regional supervisor. Conclusion is that, above all, human influence could be reduced by a parent verification of an operator actions system. However, similar to the standard signalling equipment it may occur a situation where one will need to bypass the system in order to enable the continuation of train run. In [26] was drawn attention to the increased number of tasks that must be performed by station inspector for the occurrence of accidents, or just disruption. Then the convergence of load growth and cognitive behavioural influences the traffic safety (over 90% of accidents in the rail transport system is formed after taking over responsibility for human [21], and transportation disasters occur in about 80% of the fault of the man [10]). The human factor is present in the whole system, not only in the direct running of trains by traffic control points [28].

In the railway transportation system are used many barriers to prevent threats [11]. Identifying of risk sources is described in more detail in [12], while [25] presents a method for the identification of barriers based on Fault Tree Analysis. The method is based on the so-called Swiss cheese model where the holes need to be imposed to the arrow passes (for the hazard to be). An hazard, which is the top event, is modelled by a typical Fault Tree with “if” and “or” gates. After completing the tree it is searched for the first gate or any of the branches, starting with the top event. An event which is above a given gate is connected directly or with a barrier, and is used to determine the barrier.

In conclusion, there are no models of intermediate accuracy, which takes into account the specific features of the structure resulting from the timetable and infrastructure features. The relationship between the characteristics of railway transport system and failure frequency as well as consequences of adverse events were not examined. Lack of knowledge in this area prevented the practical application of mathematical models of system reliability and safety of rail transport. In the next part the results of the first researches conducted in this area were shown.

3. Dependencies in the system

Before testing the effect of the most important factors, the most important features of the system' were inventoried, most of them are shown on a dependence map (Fig. 1). The map is shown in Figure 1. The relationships between parameters are shown in the relevant branches. A branch with the double-headed arrow shows a direct and strong impact on the characteristics of the preceding to which the branch is facing. A branch of a single full cave indicates a partial dependency. Branch of unfilled headed shows two-way influence. Parameters marked in red were used in the tests described later in this article.

not possible to train colliding with the car, deduct the man, train derailment or collision of two trains.

From the above, it is concluded that the absolute time does not sufficiently describe the periods between failures. Determining the daily working time and relate this to 24 hours, seems to be a good solution just for the simple analysis of reliability and safety of the individual devices, and only when the timetable is fixed. For the entire system or a fragment (e.g. railway line) another measure is needed to take into account seasonal factors in the form of passing trains. Such a measure is a operation work measured in train kilometres. It can be used for the whole system, selected railway lines, and even the selected type of trains and vehicles. The measure for a meaningful comparison of railway line reliabilities is proposed in [22].

The result of the above statements is a hypothesis that the best description of the size of the intervals between failures to analyse the reliability of railway transportation in the operational work is expressed in train-kilometres. In order to verify this hypothesis, were compared measures for intervals between system failures.

It was assumed that failures of rolling stock are independent of infrastructure. Such an assumption should be true, because in the railway there are no large differences in technical condition of infrastructure such as in the road transportation system. However, when the technical conditions goes bad, then the speed limit and permitted axle loads are reduced. This is done because it compensates the increased dynamic impact.

In order to verify the accuracy of the assumptions on the use of operational work as a more correct measure describing period between failures, the rolling stock subsystem is selected. There was also checked independence of rolling stock failures from infrastructure and on the other hand dependence from operational work.

For the same type of rolling stock, which is used on different railway lines at the same time period, there were prepared cumulated distribution functions of periods between failures expressed in time and in operational work. Furthermore, were also prepared cumulated distribution functions of failure consequences - delays.

It was assumed that confirmation of operational work application correctness will be given, when the operational work distributions are consistent and for the same case the time distributions are not consistent. The cumulated distribution functions of delays should also be consistent.

Interval between failures cumulated distribution functions (CDF) for rolling stock were done to three railway lines over which the same types of vehicles move (some of the same vehicles).

Analysed lines differ mainly in the number of trains and operational work. For each line it was drawn CDF of time between failure (Figure 2) and the CDF of operational work between failure (Figure 3).

Fig. 2. Time between failures cumulated distribution function for rolling stock.

Fig. 3. Operational work between failures cumulated distribution function for rolling stock.

According to the suspicion there is compliance of CDF for periods measured in operational work (Figure 3). However, for the time between failures there is no convergence. As already stated, this is due to the different number of running trains. In addition to the visual convergence of the cumulated distribution function (CDF), Kolmogorov-Smirnov' test has been conducted. At the 0.05 significance level there is no reason to reject the hypothesis of operational work between failures CDF compliance (for rolling stock). Time between failure compliance hypothesis must be rejected.

Similarly was tested the compliance of delay CDF (Figure 4). Also in this case, at a significance level of 0.05 there is no basis for rejecting the hypothesis of compliance. The above analysis shows that the failures depends on the train operational work, and does not depend on the type of railway line, and depends slightly on time.

Fig. 4. Delay cumulated distribution function for rolling stock.

5. Kinds of infrastructures and failures

Type of traffic control devices

A similar experiment was carried out for operational work and time between failures to traffic control equipment. There was non-compliance of distribution of time between failures (Figure 4), and compliance to the operational work CDF to lines 2 and 3 (Figure 5), confirmed by the Kolmogorov-Smirnov' test at a significance level of 0.05.

On railway lines 2 and 3 are running the same type of traffic control devices. Dominated by mechanical centralized (in some places relay devices), with three position block signalling. However, on line 1 after the modernization electronic devices has been installed, operated from a local control centre.

Traffic control devices have to have high quality standards in maintenance because they are directly responsible for the safety of train ride. For this reason, the device often pass technical inspection and preventive maintenance, after which they became as good as new devices. Given the high quality of repairs, even for the oldest devices it can be concluded that the lack of compliance for signalling equipment between lines 1 and 2, 3 is due to a difference in the types of devices. It is not, due to aging or degradation of devices.

Fig. 5. Time between failures cumulated distribution function for traffic control devices.

Fig. 6. Operational work between failures cumulated distribution function for traffic control devices.

From this it follows that due to the significance level of 0.05 Kolmogorov-Smirnov test, there is no reason to reject the hypothesis that the type of traffic control devices have an impact on failures. In addition, the theory has been confirmed by the Expression of periods between failures in train operational work (consistency of distribution lines 2 and 3).

Due to lack quantity and quality of data about delays resulting from traffic control devices, this aspect has not been tested.

Track type and its technical condition

In the case of track superstructure, maintenance policy is different. Due to the high investment costs associated with repair and modernization of railway lines, (e.g. the Polish Railways) it is used the optimization of the behaviour of maximum safety.

As a result of degradation the likelihood of superstructure failure is increasing, resulting in train derailment. To reduce risk in this case, with no major short-term funding, the values of two parameters decreasing: maximum speed and axle load. Due to limitations in the running of trains that may result from the reduction of axle load in practice speed is usually limited. The permitted speed in a specified moment can be used as an indicator of the technical condition of the track. The article presents only a preliminary study on the relationship between type of

superstructure, condition and failure frequency. The reason for this is incomplete information on the technical condition of railway lines.

Comparing the technical condition of the line based on speed limits is not correct due to possible differences in the maximum speed depending on construction. Therefore, for the purposes of research is used a factor of actual speed limit to construction speed, as an indicator of railway line technical condition. On the basis of publicly available information, it was found that the rate coefficients for the scanning lines are characterized by the following relations:

$$\frac{V_{a1}}{V_{c1}} \approx 1 > \frac{V_{a2}}{V_{c2}} > \frac{V_{a3}}{V_{c3}}$$

where:

- Va1/Vc1 – actual speed limit /construction speed limit on line 1,
- Va2/Vc2 – actual speed limit /construction speed limit on line 2,
- Va3/Vc3 – actual speed limit /construction speed limit on line 3.

Indeed, line 1 has been recently modernized and is in the best condition. Line 2 is degraded to a greater extent (expert's opinion) in accordance with which the speed ratio is smaller. In the worst condition is line 3, also the speed factor was the least. It should be noted that line 1 has a different type of track superstructure (noncontact-track with concrete sleepers along the entire length), which may have an effect on failure frequency.

Fig. 7. Time between failures cumulated distribution function for track superstructure.

Fig. 8. Operational work between failures cumulated distribution function for track superstructure.

Due to lack quantity and quality of data about delays resulting from track superstructure, this aspect has not been tested.

Type of the energy supply system

Energy equipment along a line supplies electricity to vehicles are regularly serviced. The maintenance policy is similar to the traffic control devices. Because of that after maintenance conditions of this devices are as good as new. During operation period are many elements replaced, such as transmission lines, copper wire, etc. However, the structure and the type of equipment do not change until a comprehensive modernization of the whole railway line. Energy devices periodically loaded by power consumption, when a train passes.

It follows that investigating consistence of CDF for the time between failure and operational work between failure can be inferred about impact of power equipment type on number of failures occurring. Moreover it can be concluded if these events are dependent on operational work or time.

Figure 10. shows CDF compliance in case of operational work between failures. Figure 9. shows lack of compatibility for CDF of time between failures. Graphical results confirmed Kolomogorow-Smirnov test at a significance level of 0.05. On this basis, it can be stated that the number of failures depends on operational work and does not depend on type of equipment.

Fig. 9. Time between failures cumulated distribution function for energy supply system.

Fig. 10. Operational work between failures cumulated distribution function for energy supply system.

Due to lack of data about delays resulting from energy supply systems, this aspect has not been tested.

Unwanted events related to passengers

Similar analyses were performed in the context of the passengers (for the same train categories). It turns out that the CDF of delays resulting from passenger events are consistent. On the other hand there is no compatibility between CDF of time between failures and also operational work between failures. It follows from this that both, time and operational work, does not directly affect the number of events. Presumably, the correct measure for the periods between events will be transport work measured in passenger-kilometres. No data on the number of passengers does not allow to verify this hypothesis at this moment.

Fig. 11. Time between failures cumulated distribution function for passenger events.

Fig. 12. Operational work between failures cumulated distribution function for passenger events.

Fig. 13. Delay cumulated distribution function for passenger events.

6. Train traffic capacity and number of tracks – secondary delays

Above was proven the impact of operational work on the occurrence of primary failures. Figure 13 shows the effect of traffic on the number of secondary delays. Traffic volume is represented by interval between trains (minimum technical gaps were included before).

Fig. 14. Part of trains with secondary delays (over one day) in relation to time interval between trains and number of tracks.

The relationship between the part of secondary delayed trains (during the day) and the interval between trains is non-linear. Of course, also affected by the size of the initial delay.

The second aspect is the number of tracks. Visible are significant differences in the functions of the single-track and double-track line.

It follows that both, number of tracks and train traffic have impact on number of secondary delayed trains.

7. Conclusions

This article describes first results of research on impact of system parameters on the railway system reliability. It has been proven correlation between system failures (connected with rolling stock, signalling equipment, power equipment track superstructure) and train traffic (operational work). It was found that the rolling stock failures are independent of the railway line on which it moves.

Then it was found that the type of traffic control devices have an impact on number of failures in the system, and that this number depends on operational work on a railway line.

It has been observed dependence of track superstructure age and condition on failures. This hypothesis has not been confirmed, however, the author supports this hypothesis and will it verify in the future.

No research on seasonality has been made, but for some sub-systems seasonality is noticeable. An example is rolling stock, which in winter damage more frequently than in summer.

Further studies will analyse events related to theft, vandalism, weather events and accidents. Data will be collected on delays and other measurable effects, and the analyses will be made, that currently cannot be done. In addition, impact of the technical conditions will be tested, especially track superstructure.

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