Railway Reliability and Safety Modeling – Research Results in Terms of the Markov Approach

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Abstract : In this paper, the author’s research work is focused on modeling of railway transportation system’s reliability and safety. The paper begins with an introduction related to a literature review on railway transportation system functionality, reliability and safety modeling. Functional model of the railway transportation system can be shown as a process described by a set of states. The set can be divided into a specified number of subsets. Reliability analysis of the system should of course begin with examination of availability variation. It is important to differentiate between the system ability to carry out transportation tasks and reliable operation of system components. A proper state description requires consideration of additional features. Such a feature may be consequences of incorrect operation of system components. In addition to the technical effects associated with incorrect operation of system components there may be mentioned traffic consequences (traffic disruptions). Traffic disruptions are mainly related to execution time and route used for implementation of transportation tasks. Another important parameter for defining of system states bases on the traffic dependencies between trains running in the system. The defined states were used for reliability and safety modeling of the railway transportation system. The paper ends with validation results of the model, based on a simplified 29 states model and a few information about realized operation research.

IndexTerms **- railway, reliability, safety, model.**

I. INTRODUCTION

The task of transport systems is movement of goods and passengers from one place to another. The importance of transport systems increases with rising mobility of the population. Economic development entails the needs to improve transport services. Passengers expect interconnected routes, with minimum travel and waiting times. On the other hand, recipients of goods, in order to effectively compete in the market, engage in optimizing activities which lead to the use of the Just-in-Time and Time Window technologies (Acuna-Agost et al., 2011; T’kindt, 2011), etc. A transport system functioning in a reliable way is therefore characterized by availability of theoretically planned products in the transportation offer, proper number of executed transportation tasks, proper safety of passengers and cargo, the right place of destination, according to a timetable, punctuality, appropriate recipients and appropriate price.

II. LIREEARURE REVIEW

An important aspect of railway practice are issues related to determining the state of the infrastructure and linking this state with measures to improve safety (Auer & Schlöpp, 2012). In this approach, an alternative to technical maintenance are train speed limits.

Both the choice of when to introduce speed limits and execution of technical maintenance entail costs. An important group of studies are analyses of life cycle costs of vehicles or infrastructure (Kroon & Huisman, 2011). In Enzi (2012) and Hansemann & Marsching (2012) decision models for finding the time for technical maintenance of infrastructure at minimum total cost have been developed.

Another group of works on railway issues refers to dispatch activities at the time of disruption. One approach is to regulate the speed of trains in order to minimize unscheduled stays (especially felt by the passengers) and reduce energy consumption (Ding, 2011).

Wendler (2007) uses a semi-Markov model to determine time intervals between trains of different speeds. Kroon & Huisman (2011) proposed a model for supporting management of disrupted rail traffic. The model is based on the costs of reorganization of train traffic or cancellation of trains in the context of railroad workers (train drivers and train traffic service). What is more, Acuna-Agost et al. (2011) presented a model for supporting a decision making process while managing disrupted train traffic.

Vromans (2005) narrows down the concept of reliability of railway transportation system to punctuality. Only delays are taken into consideration. The author identifies potential causes of disruptions, however, he assumes that temporary disruptions have one common source. The work focuses on max-plus algebra used to evaluation of timetables (cf. Goverde, 2011) in the context of time reserves. Chen (2003) has presented a model of railway service reliability and a model of punctuality.

In modeling the reliability of technical systems an important role is played by models based on states-transition graphs. Colini et al. (2009) presented a Markov model of reliability of tram systems. Six possible states of reliability have been adopted for the vehicles. Other transportation systems are frequently modeled by complicated simulations (Giel et al., 2007; Guze et al., 2008; Jodejko-Pietruczuk et al., 2014, Kierzkowski, 2017a, 2017b; Kierzkowski & Kisiel, 2017; Werbińska-Wojciechowska & Zając, 2015).

A frequent subject of research is a separated element of the railway transport system. An example might be the analyses of technical objects included in the infrastructure. Krenzelok et al. (2009) developed a 40-state model of reliability and safety of railroad traffic control devices. Dolven et al. (2004) have applied Markov chains for modeling rail track, taking into consideration sudden damage and damage resulting from the technical condition of the track.

Schwartz (2010) have presented a method for the identification of barriers on the basis of a Fault Tree Analysis. The method is based on the so-called Swiss Cheese model, in which holes must overlap so that the arrow may go through (so that safety fallibility occurs).

In analyzes of risk of unwanted events Fault Tree Analysis or Event Tree Analysis may be used for the case of the railway system. In Albrechtsen & Hokstad (2003) this kind of analysis has been extended to include the risk influencing factors. The issue has been shown on the example of a single-track line, for which the peak event is a collision of two trains coming from the opposite directions. An analysis of the factors affecting the risk shows the relationships and sequences of cause and effect going beyond a simple Fault Tree Analysis.

In Cremonini et al. (2003) risk assessment has been carried out in the transportation of dangerous goods by using events / vehicle kilometers as a measure of the intensity of event occurrence.

The studied models were analyzed in terms of considered essential features for the railway transport system. A collection of these features has been created based on the research on the state of knowledge in scientific publications (Restel, 2014, 2015a) and knowledge of railway industry experts.

Intensity of system using was identified as the basic functional quality have influence on reliability and safety. Then were identified traffic dependence of trains, infrastructure and rolling stock failures, delays and track changes, incorrect using of the system, human factors, hazards and safety failures, process leading to accidents. Performed transportation work directly affects the intensity of the train traffic.

Disrupted implementation of the transport process is defined as the operation of the train traffic not in accordance with the established timetable while improper use of the system means situations in which there are single errors of the system, but nevertheless the train traffic is conducted. Often, conducting traffic in such a situation takes place without traffic control devices (for account of the traffic orderly and the train driver). The human factor means the possibility of an accident due to the fault of a person. A more detailed literature review of this issue can be found in Restel (2014, 2015a, 2015b).

III. EVENTS WITH SMALL CONSEQUENCES AS A RISK INFLUENCING FACTOR

An Researches and analysis of unwanted events take place especially after serious accidents. Accou (2010) has written, that safety recommendations are primarily the result of proceedings after an accident. However, according to systemic investigation of safety take place for the case of serious accidents. It can take place only potentially for accidents and selected incidents.

In order to prove the importance of events of seemingly minor importance (e.g. train delay about 5 minutes), and their possible effect on the occurrence of a railway disaster, a railway accident model was built. For this case a Fault Tree Analysis was used. As a result of a Fault Tree Analysis (Restel, 2015b) it was found that train traffic disruptions have impact on probability of railway accident occurring.

In addition to the impact of delays on occurrence of human errors is also another area. Delays or disruptions in general alter structure of transport process, so that the planned schedule is not implemented (discrepancy in time and space). From this it follows that the train can move with a delay and / or on a different track. There are also other derogations, such as swapping of vehicles.

The most important aspect associated with the proper development of the segmental travel time and overall timetable is the safety of railway traffic. Scheduling of trains is done in a manner ensuring collision-free movement of trains. Therefore, trains moving in accordance with the timetable should theoretically allow safe movement of trains on the railway network without the necessity to use rail traffic control devices to improve the safety. In this approach traffic control devices provide a barrier preventing accidents. Disrupted train movement may therefore create a hazardous situation.

Using the model of a serious train accident, there have been identified four important, not yet identified, barriers preventing the accidents. The first barrier is to implement actions preventing decisions leading to incorrect system using. These activities are designed to train staff for a more effective solving of problems arising during operation. As a result, traffic crew have to solve emergency situations without changing to incorrect system operation.

Another barrier is the correct operation of the system, including using of all safety equipment and procedures. The third barrier is the undisrupted train traffic that prevents collisions of trains expedited by the traffic crew. On the other hand, that barrier protects only partially against train driver's failures. The last barrier is the correct assessment of the traffic situation by railway employees. The occurrence of a serious accident is possible if all barriers fail, only when there are at the same time the following factors: decision for incorrect system operation, incorrect system operation at a given time interval, traffic disruptions, human failures.

IV. RELIABILITY AND SAFETY MODEL

For the developed model, assumptions associated with the system whose reliability and safety can be modeled have been made. Most of the assumptions were presented in Restel (2014).

Railway transportation system functional model can be presented as a set of S states, with a finite number of states (Birolini, 2010). The most often distinguished subsets are the failure subset and the availability subset (Grabski & Jażwiński, 2009). Literature research and the study of operational data indicate inadequacy of this approach in the case of the railway transportation system. In order to take account of the inventoried essential characteristics of the model, the description of the states in five dimensions has been adopted. In connection with the adopted approach, the so-called super cube model has been developed. It was successfully used in the description of the safety parameters of the railway transport system (Harms-Ringdahl, L. Kecklund, 2004). A detailed description of the method was published in Restel (2015b).

4.1 The Markov Model

As a result of these proprietary operational studies the main 44 states have been determined for the model of railway transportation system reliability and safety which is being developed. The model consists of two layers – correct and incorrect using of the system (Restel, 2014). The layer of correct use includes all states in which the system is operated in accordance with assumed procedures.

Disrupted traffic can occur only when traffic was previously conducted in the system and an adverse event occurred causing partial faultiness of the system. On the other hand, partial faultiness, as an adverse event does not necessarily disrupt train traffic.

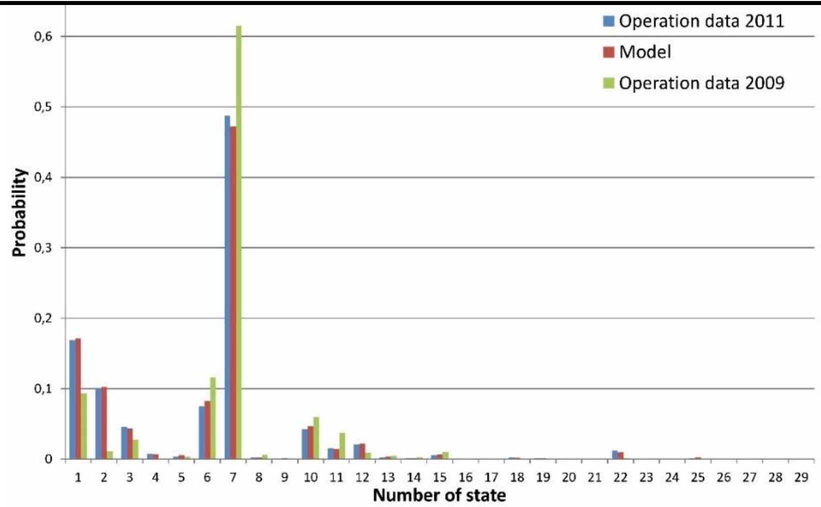

Fig. 1 Comparing of empirical data with results from the proposed model (railway line A-C)

Determination of transitions to the state of a serious accident has been based on the assumption of necessary prior occurrence of a human error (a train driver's or traffic orderly's). States belonging to the layers of incorrect use of the system constitute a set of hazardous states. In contrast, the states of partial faultiness in this layer constitute states of a direct threat to safety (this applies to the states taking into account human errors) (Restel, 2015b).

The developed model of has been mathematically described by a linear differential equation system with constant coefficients. It is therefore assumed that the probability of transitions between states is described by exponential distributions, and, consequently, the intensities of transitions between the states are independent of time. The system of 44 Chapman-Kolmogorov differential equations have been prepared. More details of the model were presented in case of a simplified one in Restel (2015b).

4.2 Model Validation and Operation Research

Due to the completeness of operation data, the most complete source are infrastructure managers. Depending on the structure of the company, data is collected in one or several locations. Knowledge base which is held by the traffic management center contains a large number of strategic and commercial information. For this reason, they are subject to confidentiality, and are therefore not publicly available. Because of that, a cooperation agreement was needed. The method of data collection by the infrastructure manager is often not fully automated (requires human intervention). Conscious or unconscious mistakes in this process lowers the correctness of the results.

After the reduction of the number of states for the purposes of validation, a simplified model for the GRIF computing environment have been introduced. The said computing environment is used for calculation of Markov processes. A simplified model is composed of 29 states and 83 transitions (Restel, 2014).

The verification of the model has been carried out with the use of three pre-estimated sets of intensities of transitions between the states. Using the GRIF computing environment stationary probability values of residing in the states have been determined for a simplified model. Stationarity have been obtained after 2-15 days.

After determining the probabilities and residence times in states on the basis of empirical data and after performing the calculations for the model, the values obtained have been put together and the test of the model compliance with reality have been conducted. The Chi squared test at the statistical significance $\alpha = 0.05$ has been chosen. The critical quantile for the distribution takes the value of 41.337 for the studied case.

The next analyzed case shown in Figure 1 presents railway line A-C. It presents the comparison of model results with two operation periods. It can be seen the compliance of the model to data from year 2011, which was confirmed by the Kolmogorov-Smirnov test. But for year 2009, there is no correspondence. The reason for this is a sudden change of superstructure technical condition. At the end of 2009, a modernization of superstructure was completed, and thus the boundary conditions in 2010 have changed (operation data from 2010 was used for model parametrization).

On the occasion of model development also a number of studies was conducted, related to the influence of infrastructure type on system reliability. One example are traffic control devices. Cumulated Distribution Functions were prepared for time between failures and operation work between failures in case of these devices. One example was presented in Figures 2-3.

There has been a lack of conformity between the Cumulated Distribution Functions of time between failures (Figure 2). On the other hand, Cumulated Distribution Functions of operation work between failures of line 2 and 3 were similar (Figure 3). Both were confirmed by Kolmogorov-Smirnov test at a significance level of 0.05.

On railway line 2 and 3 were installed the same types of traffic control devices. Dominated by centralized mechanical devices (in some places relay devices), and three position half automated linear interlocking. In contrast, on line 1 are installed (after upgrading) electronic devices operated from a local control center.

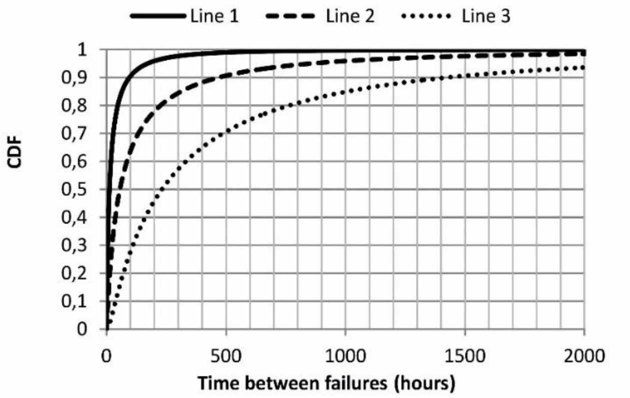

Fig. 2 Cumulated Distribution Function for time between failures of traffic control devices (based on data from Polish Railway Lines)

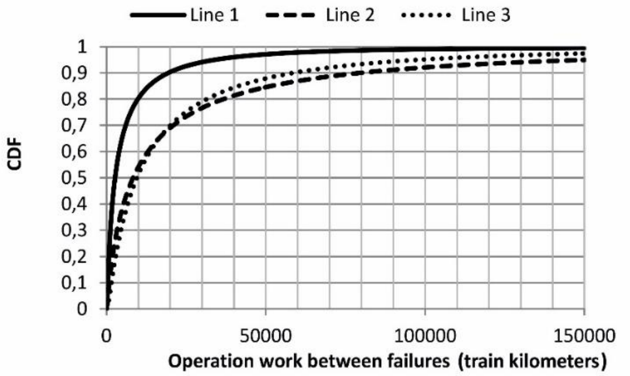

Fig. 3 Cumulated Distribution Function for operation work between failures of traffic control devices (based on data from Polish Railway Lines)

Traffic control devices relate to high standards of quality in maintenance, since they are directly responsible for the safety of the train traffic. For this reason, the devices are often subject of technical inspections and preventive service, after which they achieve technical condition as good as new devices. Because of the high quality of the repair, even the oldest devices, aging has not influence on the intensity of failures.

It can be concluded that the lack of conformity for the Cumulated Distribution Functions of operation work between failures between line 1 and 2/3 are caused by type of devices.

From this it follows that at a significance level of 0.05 Kolmogorov-Smirnov there are no grounds to reject the hypothesis that the type of traffic control devices have an impact on the incidence of events. In addition, the assumption has been confirmed to express periods between events in operation work, and not in time (compliance for line 2 and 3, that have the same type of devices).

V. CONCLUSION

An The studies of the state of art have shown the lack of models of reliability and safety of the rail transportation system taking into account functional qualities. In particular, the need for considering the following factors has been identified: reliability of infrastructure and rolling stock subsystem, intensity of system using (traffic dependence of trains), the impact of the human factor in conjunction with the functioning of the system, disruptions in train traffic, the exposure of the system to situations of emergency and safety unreliability. Therefore, the following objective of the work has been formulated. Such conclusions have been drawn from both the operation research on literature sources, operation tests of the system as well as observation of the practice of conducting rail traffic and system management.

A concept of the system has been developed based on which faultiness states have been defined and the concept of partial faultiness of the rail transport system has been introduced. Barriers which have not yet been systematically taken into account and which prevent the occurrence of railway accidents have been identified.

The developed way of defining the states has made it possible to take into account the identified, significant functional, reliability and safety qualities. Subsequently, attention was paid to a small piece of data that is used to improve safety of the system. A large flow of events with small consequences, but with influence on accidents, was indicated. The proof is based on a Fault Tree Analysis. Events with small consequences were supplemented by examples of catastrophic events and causes of these events. Attention was paid to errors in design, materials, operation and human errors that led to disasters. The presented modeling method allows to evaluate timetable quality in relation to process reliability before its execution. The practical use of the model will be investigated in further researches.

REFERENCES

[1] B. Accou 2010. “Guidance on good reporting practice,” European Railway Agency, France

[2] R. Acuna-Agost, P. Michelon, D. Feillet, et al. 2011. “SAPI: Statistical Analysis of Propagation of Incidents. A new approach for rescheduling trains after disruptions,” *European Journal of Operational Research*, vol. 215(1), pp. 227-243

[3] A. Akbalik, B. Penz 2011. “Comparison of just-in-time and time window delivery policies for a single-item capacitated lot sizing problem,” *International Journal of Production Research*, vol. 49(9), pp. 2567-2585

[4] E. Albrechtsen, P. Hokstad 2003. “An analysis of barriers in train traffic using risk influencing factors,” In: *European Safety and Reliability Conference (eds T Bedford and P van Gelder), Maastricht, The Netherlands, 15-18 June 2003*, pp. 25-31. Lisse: Swets & Zeitlinger

[5] F. Auer, A. Schlöpp 2012. “Substance determination of permanent-way components (in German),” *ZEV Rail Glasers Annalen*, vol. 136(9), pp. 324-334

[6] A. Birolini 2010. “Reliability Engineering – Theory and Practice,” Heidelberg: Springer

[7] HK. Chen 2003. “New models for measuring the reliability performance of train service,” In: *European Safety and Reliability Conference (eds T Bedford and P van Gelder)*, Maastricht, The Netherlands, 15-18 June 2003, pp. 397-401

[8] A. Colini, P. Erto, M. Giorgio, et al. 2009. “A practical Markovian model of the availability and reliability of mass transport service with non-exponential repair times”, In: *European Safety and Reliability Conference (eds R Briš, et al.)*, Prague, Czech Republic, 7-10 September 2009, pp.1525-1532. London: Taylor & Francis

[9] MG., Cremonini, P. Lombardo, P. Paci, et al. 2003. “Industrial areas and transportation networks risk assessment,” In: *European Safety and Reliability Conference (eds T Bedford and P van Gelder)*, Maastricht, The Netherlands, 15-18 June 2003, pp. 439-445

[10] Y. Ding 2011. “Simulation model and algorithm for train speed regulation in disturbed operating condition,” *ZEV Rail Glasers Annalen*, vol. 135(10), pp. 386-391

[11] OF. Dolven, BH. Lindqvist, PR. Hokstad 2004. “Statistical Modelling and Analysis of Failure and Inspection Data for a Railway Line,” In: *Probabilistic Safety Assessment and Management Conference and European Safety and Reliability Conference (eds C Spitzer, et al.)*, Berlin, Germany, 14-18 June 2004, pp.591-596

[12] M. Enzi 2012. “Right time to reinvest superstructure considering the aspect of Life Cycle Costs (in German),” *ZEV Rail Glasers Annalen*, vol. 136(3), pp. 68-75

[13] R. Giel, M. Młyńczak, M. Plewa 2007. "Logistic support model for the sorting process of selectively collected municipal waste,” In: *Theory and engineering of complex systems and dependability: proceedings of the Tenth International Conference on Dependability and Complex Systems DepCoS-RELCOMEX*, June 29 - July 3, Brunów, Poland. Springer, pp. 369-380, 2015

[14] R. Goverde, “Railway timetable stability analysis using max-plus system theory,” *Transportation Research Part B*, vol. 41(2), pp. 179-201

[15] F. Grabski, J. Jaźwiński 2009. “Functions of random arguments – reliability, safety and logistics issues (in Polish),” *Wydawnictwa Komunikacji i Łączności*,

[16] S. Guze, K. Kołowrocki, J. Soszyńska 2008. “Modelling Environment and Infrastructure Influence on Reliability and Operation Processes of Port Transportation Systems,” *Journal of Konbin*, vol. 4(1), pp: 2-38, DOI: 10.2478/v10040-008-0008-8

[17] F. Hansemann, S. Marschnig 2012. “GleisPROPHET - next step to sustainability (in German),” *ZEV Rail Glasers Annalen*, vol. 136(9), pp. 350-357

[18] L. Harms-Ringdahl, L. Kecklund 2004. “Safety Functions in Railways - a Structural Analysis of Safety Rules,” In: *Probabilistic Safety Assessment and Management Conference and European Safety and Reliability Conference (eds C Spitzer, et al.)*, Berlin, Germany, 14-18 June 2004, pp. 2751-2757

[19] A. Jodejko-Pietruczuk, M. Plewa 2014. "Reliability based model of the cost effective product reusing policy,” In: *Safety and Reliability: Methodology and Applications - Proceedings of the European Safety and Reliability Conference, ESREL 2014*, pp. 1243-1248

[20] A. Kierzkowski, 2017a. “Method for management of an airport security control system,” *Proceedings of the Institution of Civil Engineers. Transport*, vol. 170(4), pp. 205-217, DOI: 10.1680/jtran.16.00036.

[21] A. Kierzkowski 2017b. “Model of reliability of security control operation at an airport,” *Tehnički vjesnik*, vol. 24(2), pp. 469-476, DOI: 10.17559/TV-20150812153802

[22] A. Kierzkowski, T. Kisiel 2017. “Simulation model of security control system functioning: A case study of the Wroclaw Airport terminal,” *Journal of Air Transport Management, Part B*, vol. 64, pp:173-185, DOI:10.1016/j.jairtraman.2016.09.008

[23] T. Krenželok, R. Briš, P. Klátil, et al. 2009. “Reliability and safety of railway signalling and interlocking devices,” In: *European Safety and Reliability Conference (eds R Briš, et al.)*, Prague, Czech Republic, 7-10 September 2009, London: Taylor & Francis, pp. 2325-2330

[24] L. Kroon, D. Huisman 2011. “Algorithmic Support for Railway Disruption Management,” In: *Van Nunen J, Huijbregts P and Rietveld P (eds) Transitions Towards Sustainable Mobility*. Heidelberg: Springer, pp. 193-212,

[25] S. Marschnig, P. Veit 2012. “Life Cycle Management in the Reality (in German),” *ZEV Rail Glasers Annalen*, vol. 136(9), pp. 335-341

[26] F.J. Restel 2014. “The Markov Reliability and Safety Model of the Railway Transportation System,” In: *European Safety and Reliability Conference (eds T Nowakowski, et al.)*, Wroclaw, Poland, 14-18 September 2014, Leiden: CRC Press/Balkema, pp. 301-311

[27] F.J. Restel 2015a. “Defining states in reliability and safety modelling,” In: *Theory and engineering of complex systems and dependability: proceedings of the Tenth International Conference on Dependability and Complex Systems DepCoS-RELCOMEX*, June 29 - July 3, 2015, Brunów, Poland. Springer, pp: 413-423

[28] F.J. Restel 2015b. “Concept of railway transportation system resilience - an introduction,” In: *proceedings of the 25th European Safety and Reliability Conference, ESREL 2015*, Zurich, Switzerland, 7-10 September 2015, CRC Press/Balkema, pp. 565-572

[29] S. Schwartz 2010. “Identification of safety barriers at a level crossing (in German),” *ZEV Rail Glasers Annalen*, vol. 134(1-2), pp. 38-44

[30] V. T’kindt 2011. “Multicriteria models for just-in-time scheduling,” *International Journal of Production Research*, vol. 49(11), pp. 3191-3209

[31] A. Tubis, S. Werbińska-Wojciechowska 2014. “Inventory Management of Operational Materials in Road Passneger Transportation Company – Case Study,” In: *Carpathian Logistics Congress Proceedings*, pp. 65-70

[32] M. Vromans 2005. “Reliability of Railway Systems,” PhD Thesis, TRAIL Research School, The Netherlands

[33] E. Wendler 2007. “The scheduled waiting time on railway lines,” *Transportation Research Part B*, vol. 41(2), pp. 148-158

[34] S. Werbińska-Wojciechowska, P. Zając 2015. “Use of Delay-Time Concept in Modelling Process of Technical and Logistics Systems Maintenance Performance. Case Study,” *Maintenance and Reliability*, vol. 17(2), pp: 174-185