THE ROBUSTNESS ASSESSMENT METHOD OF RAILWAY TIMETABLES

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Abstract

In the railway transportation system exist many constraints, which combined with disruptions can have important impact on the system operation. The position of trains in a timetable has effect on the transportation system robust-ness. One of the key issues is the allocation of time reserves due to the real occurrence of undesirable events and their consequences. Correct placing of the reserves, as well as optimization of the timetable will be possible after an assessment process that leads to weak node identification. The main goal of the paper is to elaborate a robustness assessment method which will take into account variability of processes in terms of operational factors. A robust timetable is resistant to strokes from undesirable events. In other words, for a full robust timetable there is lack of disruption propagation. The challenge arises how to quantify the robustness of the railway transportation system. Thus, the paper discusses issues related to robustness in context of time re-serves. Correct dealing with time reserves is a multidimensional issue.

Keywords: Robustness, timetable, process description, system qualities

1. INTRODUCTION

The railway transportation system is characterized by specific infrastructure constraints. The result is a high vulnerability to disruptions, which can cause in an important influence on the system operation. Therefore, there is the need to evaluate transportation process schedule prior to its implementation. A key factor in this aspect is the structure of timetables [1,2]. Therefore, a timetable assessment method is needed.

The paper is focused on system robustness in terms of the transportation process schedules. Thus, the concept of timetable robustness is introduced. It is the ability of a timetable to withstand design errors, parameter variations, and changing operational conditions [3]. According to [4], robustness in general is the capacity in absorbing or resisting changes.

As a supplement to resilience, which is the ability to quick system recovery after breakdown, robustness is the ability to keep the system performance level after the occurrence of unwanted events. A delayed train may affect other trains, and it can also the level of delay maintain till the end of the route. In other words, for a robust timetable the disruption propagation will be on the possible lowest level.

Many disruption factors may be compensated with proper time reserves included in the timetable. Correct dealing with time reserves is a multidimensional issue. Increasing time reserves increases also the robustness. On the other hand, after the time reserves increasing the network capacity decreases. That is why ongoing research results will be useful for timetable designing.

The issue of robustness quantification is an important research area. A fundamental challenge is to quantify robustness by an indicator, that may be helpful for the timetable optimization. Thus, the main goal of the paper is to propose a timetable assessment method in terms of robustness.

2. STATE OF ART

According to the literature, passenger rail traffic is described by the timetable, which is the detailed plan of operations [5,6]. It is theoretically possible to design a train timetable without gaps between trains. Application of such a theoretical approach with deterministic assumptions results in large inaccuracies [7-10]. The theoretical infrastructure capacity is going to be the maximum. But each disruption would shift to all other trains and will be not dumped for the failed train. Influence of operation intensity on disruption propagation was closer described in [11-13].

The timetables are designed with taking into account delays, by additional travel times [14]. Disruptions in time can be positive (delay) or negative (before time) [15]. The accepted criteria for disruption assessment consider delays greater than or equal to 5 minutes [16].

The train travel time should take into account foreseeable and unforeseeable events disrupting the journey [17]. Well-designed train timetables should guarantee 100 % punctuality in normal operating conditions [14]. The determined travel time should be based on the technical parameters of the railway line, as well as the technical characteristics of the rolling stock used by operators [18-20].

The recovery of the system after undesirable events is directly related to the system resilience issue [21,22]. The delay damping without dispatcher activities is also associated with the so-called timetable robustness [23-25].

The paper [26] presents an robustness assessment indicator for critical network points. It has been calculated as the inverse value of the sum of shortest time margins. It should allow to find weak links in the network.

The development of methods for timetable designing in terms of delay reduction is an important issue in the railway system. Advanced models and algorithms have been presented in [6,27].

In [28], a management support model for disturbed traffic was pro-posed. The model is based on the traffic reorganization or train cancellation cost in the context of railway staff. In [29] a support model for the decision making process under train traffic disruptions was presented. It provides a thorough approach to the system operation process.

Vromans [16] uses a rail transport system reliability concept. However, it only considers delays. The author identifies potential causes of interference, but assumes that time disturbances should be described using one disruption set, a so-called black box. In the work, Max-plus algebra was used to evaluate the timetables (see also [30]) in the context of time reserves.

Chen [31] presents models of railway service reliability and punctuality. The reliability model of railway services consists of the reliability of technical facilities that make up the system (the independence of events arising in the subsystems has been assumed), the interaction between the rolling stock subsystem and other subsystems, the intensity of traffic restoration after an interruption caused by an undesired event. However, the author does not explain how to determine the value of the dependency ratios used.

Vansteenwegen [32] determines punctuality in the context of the train arriving at the course's end station. At the same time, he states that delays of up to 5 minutes are a good result of the system's operation, stating that there may be situations in which they will be too big. The authors in [33] consider some intervals of delay in punctuality analyses. They gave as a border two minutes. In scientific studies there are also proposals for defining the limit at the level of 2.5 minutes of delay [34].

The most important factors affecting the punctuality of trains in the system were identified in [35,36]: number of passengers, degree of occupancy of vehicles on the train, capacity utilization, cancelled trains, temporary speed limits, technical infrastructure maintenance, train traffic organization.

Vromans [16] conducted an inventory of primary traffic disruption sources in rail transport: improper traffic planning (errors in the construction of the timetable), infrastructure damages, rolling stock damages, human factors, accidents at railroad crossings, vandalism, passenger-related events, weather phenomena.

In addition to the sources of primary events, Vromans also analysed the causes of secondary delays: infrastructure capacity constraints (train traffic dependence), rolling stock circulations, train crew scheduling, traffic control, dispatching, train interchanges.

The railway is considered as a critical infrastructure system (CIS) [37]. Then, the analysis concerns serious events with large consequences. In the CIS description, graph models are used [38-40]. In this aspect, the notion of the capacity reliability of the railway network is introduced [41]. The nodes model important stations, while in advanced models different types of nodes are introduced depending on the type of station.

Concluding the literature review, there is no method for robustness evaluation, that quantifies robustness and allows to compare two timetables in terms of robustness. Therefore the challenge for this paper rises to evaluate a robustness quantification and assessment method. The method should allow to receive a measure for timetable scenario comparing needed for optimization.

3. SYSTEM DESCRIPTION

The purpose of the rail transport system is to implement the transport process (for freight or passengers) from one place to another. The rail transport system is defined by resources that enable carrying out transport tasks. The physical resources are rolling stock and infrastructure. The organizational resources are procedures contained in the instructions and regulations, as well as the schedule determining the sequence and moments of processes implementation.

For any reliability, robustness or resilience assessment, it is necessary to determine the basic system elements. It allows to define the system's availability and failure states. Therefore, three sets of elements have been specified:

- trains,
- elementary sections,
- traffic control points.

At a given moment, it is possible to identify in the system elementary sections with trains on them and traffic control points which does not allow to enter the sections by other trains. Such a combination of a train (TRA), a traffic control point (TCP) and an elementary section (ESE) will be named as elementary system (ESY).

$$ESY = \langle TRA, ESE, TCP \rangle \tag{1}$$

In order to describe the rail transport system, an elementary section was introduced. The concept is based on the block section. The section is part of the track path between two traffic points (manual or automatic). There can be only one train in one moment on the section. Similar approaches were already used in the modelling of railway traffic management [42]. Also, the models of traffic reorganization after the occurrence of disturbances take into account this basic element of the system [43]. Elementary sections independent of block sections were used in safety modelling of dangerous cargo transport by rail [44], while Fukuoka [45] used straight track distances in the traffic safety models.

The elementary section is separated from the next one by a traffic control point. A traffic control point is not a part of the elementary section. The section basically consists of the track, with all related components. Additionally, an elementary section may also contain platforms, level crossings, structures and buildings, linear telecommunications infrastructure, as well as electric power supply.

Therefore, an elementary section (ESE) can be defined as ordered group of elements. Each of them is defined by reliability characteristics depending on its qualities. Therefore, each of the listed parts may be the cause of failures resulting in traffic disruptions.

$$\mathrm{ESE} = \langle \mathrm{TRK}, \mathrm{STB}, \mathrm{TEL}, \mathrm{LEC}, \mathrm{PLA}, \mathrm{PSE}, \mathrm{ENV} \rangle \tag{2}$$

where:

TRK - track with rails, sleepers, ballast, and other necessary elements

STB - structures and buildings needed for allocation of the track

TEL - linear traffic management information and telecommunication infrastructure

LEC - level crossings, with pedestrians and road vehicles

PLA - platforms on stations or stops

PSE - power supply equipment for electrical vehicles

ENV - connections, relations with the environment

The occurrence of an undesirable event, i.e. damage (or human failure) to any element of the elementary system, stops the train run.

The set of elementary sections and traffic control points between the nodes, enabling track changes, will be called as cluster. It has been assumed that damage to the elementary system causes the failure of the entire cluster to which the system belongs.

A train is a so-called chain of use [46], which is an ordered trio of three sets: train crew (train driver, manager, conductors), vehicles, and load (passengers or freight).

$$\mathrm{TRA} = \langle \mathrm{TRC}, \mathrm{VEH}, \mathrm{LOA} \rangle \qquad (3)$$

where:

TRC - set of operators, named train crew

VEH - set of vehicles

LOA - set of transported goods, passengers or freight

Traffic control points (TCP) can be divided into a few subgroups. Nevertheless, from the traffic analyse point of view, the defining of traffic control points will be similar to the trains and elementary sections, due to its components.

$$\mathrm{TCP} = \langle \mathrm{TRM}, \mathrm{SCE}, \mathrm{TSE}, \mathrm{SIE} \rangle \qquad (4)$$

where:

TRM - traffic manager

SCE - safety controlling equipment

TSE - trackside equipment

SIE - signalling equipment

As it was previously, each component can be the source of failures, which can lead to traffic disruptions. Depending on the type of traffic control point, the influence of the traffic controller and the driver changes. In the case of automatic traffic control points, the negative human impact is limited to the driver who can pass the signal at danger. On European railways in the years 1990-2010, such errors were the cause of approx. 27 % of serious railway accidents [47].

In the case of man operated traffic control points, there can also human failures occur. Especially for points that allow to change the track. Such errors constituted approx. 16 % of the causes of serious railway accidents in Europe [47].

4. PROCESS DESCRIPTION

The basic component of scheduling railway operation processes is the train timetable. For that, the so-called train diagram is used. An example was shown in **Figure 1**. The train diagram consists of two dimensions. One axis represents the railway line, in other words the driven distance by the train. The other axis represents time, increasing continuously. Lines parallel to the time axis represents traffic control points or train stops. The lines along the distance show next moments in time.

For the same direction, the space between two signals is called section or block section, in some situations also open track. At a given moment in time there can be only one train on such a section. For that coordinate system, a train is treated as material point. Train running is shown as angular line.

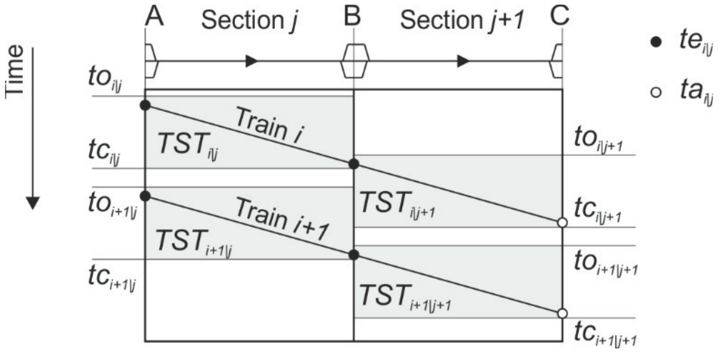

Figure 1 Train path on a train diagram [own study]

In relation to real operation, a train enters a section by crossing of the train running line with a line, that represents an operating control point. It leaves the section when it's running line crosses the line that represents the operating control point at the end of the section. Due to the operation processes, previous to the train entering a little time for train route preparation is needed. After the train leaves the section it takes some time for determining the accessibility of the section after the train has left. Therefore, the occupying time of a section is longer than the real presence of a train on it.

According to [48], the characteristic points for the train running on the infrastructure have been identified. A section occupation time-window is built on base of the time interval between entering of *i*-th train on *j*-th section ($te_{i|j}$) and arrival at the end of the section ($ta_{i|j}$). The arriving time lettered $ta_{i|j}$ is the planned time, which is the earliest possible arrival $ta'_{i|j}$ increased by the time reserve $\Delta ta_{i|j}$. Between the time-window opening ($to_{i|j}$) and the train entering $te_{i|j}$ a certain time has to pass. This time is needed for train entering preparation ($\Delta tp_{i|j}$). Similarly, the reporting of vehicle leaving needs some time ($\Delta tr_{i|j}$). The time-window closing lettered $tc'_{i|j}$ represents the fastest possible closing time, due to the shortest train running. Following from this, the planned length of a time-window ($tbp_{i|j}$) is the sum of the shortest section occupation ($tbs_{i|j}$) and an additional time reserve ($\Delta tc_{i|j}$). The value of the time reserve is mostly the same like the time reserve for train arriving ($\Delta ta_{i|j}$).

One train placed in time on one section will be called further Train-Section Time-window (TST). Allocation of TSTs in a train diagram are shown in **Figure 1**. A train-section time-window can be described by six qualities.

$$TST_{i|j} =< TRA_i, ESE_j, te_{i|j}, ta_{i|j}, to_{i|j}, tc_{i|j} > \tag{5}$$

where:

$TST_{i|j}$ - train-section time-window for *i*-th train and *j*-th section

TRA_i - *i*-th train

ESE_j - *j*-th elementary section

$te_{i|j}$ - entering time of *i*-th train to the *j*-th section

$ta_{i|j}$ - arriving time of *i*-th train at the end of *j*-th section

$to_{i|j}$ - opening time of $TST_{i|j}$

$tc_{i|j}$ - closing time of $TST_{i|j}$

The first two ones place the train on a section. It means, the *i*-th train in the time table (TRA_i) and *j*-th section (ESE_j) of the railway line. The next two qualities assign the *i*-th train entering time on *j*-th section ($te_{i|j}$) and the arriving time at the end of the section ($ta_{i|j}$). The last two parameters built the time-window.

5. THE ROBUSTNESS ASSESSMENT METHOD

Many factors have influence on correct implementation of the timetable. Especially train type, traffic control device type, age of infrastructure, environmental influences and others [1]. Therefore, each TST may has another punctuality characteristics.

A TST can affect other TSTs. All interactions in a time table ($I_{i|j}$) can be seen as set of interactions (Γ) coming out from all TSTs.

$$\Gamma = < I_{i|j} > \tag{6}$$

Only direct interactions, from a previous TST to closest ones will be taken into account. Therefore, a *TST* can affect only two other TSTs. These are the next one on the same section ($TST_{i+1|j}$) and the next one on the following section for the same train ($TST_{i|j+1}$).

Influence of one TST on another is a function of the time interval between them. For the time dependence between TSTs of two different trains, one by one on the same section, the time interval $\Delta t_{i|i+1}$ has to be calculated. On the other hand, for one train on two following sections also the time dependency has to be calculated, but denominated $\Delta t_{j|j+1}$.

$$\Delta t_{i|i+1} = to_{i+1|j} - tc'_{i|j} \tag{7}$$

$$\Delta t_{j|j+1} = th_{j|j+1} - ta'_{i|j} \tag{8}$$

The real ending time (train arrival or TST closing) of the processes are random variables which can be approximated by theoretical probability density functions *f(x)*. It is assumed, that the probability density function's domain is described by the interval $[0, +\infty)$. The value zero represents the train arrival moment $ta'_{i|j}$ respectively the TST closing time $tc'_{i|j}$ due to the shortest train run. Therefore, the probability function describes the time deviation from earliest possible ending time. For a given TST it was also assumed, that the probability functions are identical for both, the closing time and the train arrival time.

After identification of all TSTs in the timetable and the approximation of the probability density functions, a dependency matrix can be prepared. An example is shown in **Table 1**. The dependency matrix shows the time gap between two TSTs, when the first one may disrupts the second one. According to the assumption of influencing only the two closest TSTs, the time gaps were filled. If there is no direct connection between the *TST*s, then infinity was filled instead of a finite time interval. The own dependency of a TST, that is shown by time values on the diagonal, represents the time reserve that is planned in the timetable for the train arrival on the given section.

Table 1 Train-section time-window dependency matrix [own study]

TST	$f_{i\|j}(x)$ i|j	$f_{i\|j+1}(x)$ i j+1	$f_{i\|j+m}(x)$ i j+m	$f_{i+1\|j}(x)$ i+1 j	$f_{i+n\|j+m}(x)$ i+n j+m
i|j	$\Delta ta_{i\|j}$	∞	∞	∞	∞
i j+1	$\Delta t_{j\|j+1}$	$\Delta ta_{i\|j+1}$	∞	∞	∞
i j+m	∞	∞	$\Delta ta_{i\|j+m}$	∞	∞
i+1 j	$\Delta t_{i\|i+1}$	∞	∞	$\Delta ta_{i+1\|j}$	∞
i+n j+m	∞	∞	∞	∞	$\Delta ta_{i+n\|j+m}$

After the dependency matrix has been completely filled, it is possible to calculate the probability that one TST will disrupt another one. The probability will be equal to the cumulated distribution function for the given probability density function.

$$F_{r|k}\left(TS_{r|k}\right) = \int_0^{TS_{r|k}} f_k(x)\,dx \tag{9}$$

where:

$F_{r|k}\left(TS_{r|k}\right)$ - cumulated distribution function for the time space between *r*-th and *k*-th TST

$TS_{r|k}$ - time space between *r*-th and *k*-th TST

$f_k(x)$ - probability denisty function for deviation from the shortest process time of the *k*-th TST

Table 2 Train-section time-window cumulated distribution function matrix [own study]

TST	Ordinal r \ k	i|j	i j+1	i j+m	i+1 j
		1	2	m	m+1
i|j	1	$F_{i\vert j}(\Delta ta_{i\vert j})$	1	1	1
i j+1	2	$F_{i\vert j}(\Delta t_{j\vert j+1})$	$F_{i\vert j}(\Delta ta_{i\vert j+1})$	1	1
i j+m	m	1	1	$F_{i\vert j}(\Delta ta_{i\vert j+m})$	1
i+1 j	m+1	$F_{i\vert j}(\Delta t_{i\vert i+1})$	1	1	$F_{i\vert j}(\Delta ta_{i+1\vert j})$

According to the literature, where it was stated that robustness is the system ability to withstand disruptions. In this paper it is proposed to quantify robustness by probability. It is the probability that no disruptions will occur, caused by other disrupted TSTs or by own unwanted events. Therefore, it is the product of all probabilities placed in the cumulated distribution matrix.

$$Ro = \prod_{r=1}^{m\cdot n} \prod_{k=1}^{m\cdot n} F_{r|k}(TS_{r|k}) \qquad .(10)$$

where:

Ro - robustness measure, probability of no inetractions between any two TSTs in the timetable

$F_{r|k}(TS_{r|k})$ - cumulated distribution function for the time dependency between r-th and k-th TST

$m \cdot n$ - total number of TSTs in the timetable

For a selected railway line in Poland, basing on operational data were identified deviations of train running in relation to defined sections. Due to similar conditions for all trains launched on the line, one probability distribution was approximated for all train runs, and proven by the Chi-squared test at the significance level 0.05. The results are shown in **Figure 2**. Using afterwards the theoretical distribution and the time gaps between TSTs, the cumulated distribution function values for the matrix in **Table 2** can be calculated.

For the analyzed case, the probability of no interactions between TSTs is *Ro=0.0294*. After some modifications of the timetable, the robustness measure was recalculated *Ro'=0.0318.* Therefore, in terms of robustness, the second timetable is better than the first one.

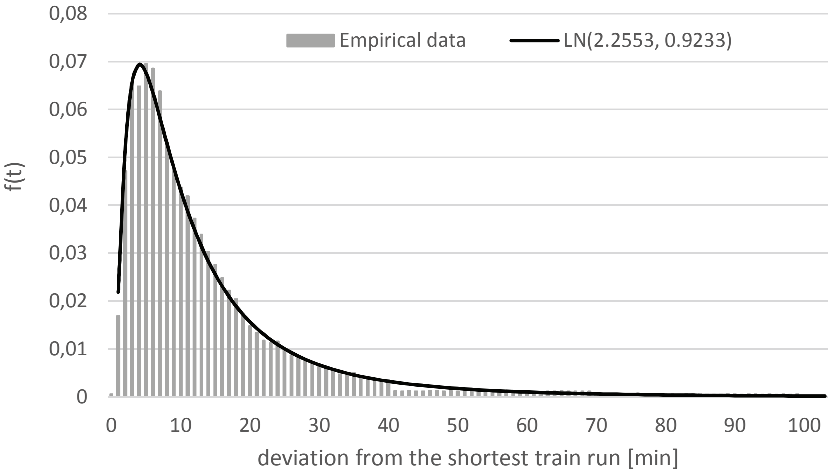

Figure 2 Empirical distribution for deviations from the shortest train run and approximated lognormal distribution [own study]

6. CONCLUSIONS

The literature review shows, there is lack of precise nomenclature related to robustness and resilience of the railway system and its timetable. It was found that there is no universal measure for robustness assessment. The practical robustness evaluation is solved only for chosen network parts or by simulation. Nevertheless, these approaches are time-consuming.

The paper shows a system and process definition for a precise problem description in terms of robustness. A system description was proposed in terms of failure occurrence. These description allows to identify the sources of undesirable events and their influence. Afterwards thee time table was divided into small parts, are called Train-Section Time-windows. Such a timetable model allows to quantify the railway system robustness based on the transportation process implementation.

A new robustness measure was proposed. The probability of no interactions between processes in the railway system has not been used for robustness assessment yet. It allows to compare different timetable structures and to pick the best one in terms of robustness.

The results are promising. For further studies it is planned to prove the method on base of more timetables and more railway lines. Moreover, further research on optimization of timetables due to robustness and resilience is planned.

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