MODELS OF ROBUST RAIL TRANSPORT SYSTEM PLANNING

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Abstract

In rail transport robustness issues are primarily used in planning. The sequence of subsequent transport processes depends on the planning. Problems occur with regard to passenger rail planning from long-term strategic decision-making to detailed planning. The structure of timetable is a key factor, that has effect on the transportation system robustness. For a robust timetable there is lack of disruption propagation. Correct dealing with time reserves is a multidimensional issue. Increasing time reserves increases also the robustness, while the network capacity decreases. Robustness is the system capacity to absorb or resist changes. This article presents survey of literature on robustness in the rail transport system. Rolling stock planning also affects the system robustness, taking into account the combination and train allocations to routes. Crew rostering is a problem of scheduling the work of train crew members. These steps can be subdivided into successive steps as, for example: crew planning which often consists of arranging work schedules, and the assigning them to employees in accordance with working time standards. There may also be combined stages such as integrated line planning (the infrastructure must satisfy the requirements of the timetable) and timetabling. Therefore, the paper shows an overview of robustness concepts and models in relation to given railway problems.

Keywords: Rail transport, robustness, timetable, train delays

1. ROBUSTNESS IN RAIL TRANSPORT

The concept of robustness is used in different areas of science. Depending on the field, it has a different meaning. Its origins date back to the modern decision theory developed in the 1950s and use of scenario analysis and the Maximin Wald model as a tool to prevent unstable cases. It became an independent discipline as a robust optimization in the 1970s, developing in parallel in several scientific and technological fields. The concept of robustness has been used for years in statistics and operational research [1].

In railway, robustness is mainly used in planning, which determines course of depends further transport processes. It refers to the plan of work of machines, people and vehicles. According to [2], it means that unexpected problems can be dealt with without significant schedule modifications. In the article [3] robustness is defined as a tolerance for a degree of uncertainty, while in [4] it is the maximum initial delay that can occur without causing interference to other vehicles. This definition refers to the design of timetables and work schedules of conductor teams and drivers who are involved with the vehicle and perform tasks according to the timetable. Their timetable is closely related to it. In [5] the authors define robustness as the ability of a schedule to resist design errors, changes in parameters and operating conditions. Author of the article [6] described a schedule as robust when delays from one period do not spread to another. The approach is based on the fact that the schedule is periodic. The approaches for simulating planning processes are presented in [7, 8, 9]. In [10] robustness refers to 'robustness to inaccuracy'. Two definitions of robustness are provided. The first definition is the percentage of interference less than a certain unit of time that the timetable is able to tolerate without any current modifications. Disturbance refers there to one single event (delay) in the implementation of the schedule. The second definition refers to whether schedule can return to the initial stage unchanged by the disturbance for a limited period of time.

2. SUSTAINABLE DESIGN OF TIMETABLE STRUCTURE

The authors of [11, 12] present a flexible structure management delay of trains. The improvement of the railway systems quality in terms of punctuality and travel time requires the schedule analysis in terms of robustness to operational disturbance. The authors classify possibility of eliminating delays on provisions included in timetable and real time response by train track changing. Two dispatch models have been proposed to recover a zero delay at the end of the route. The main parameters analyzed are: departure time, possibility of trains overtaking at the station, sequence of trains, buffer time and junctions points. Delayed train passing a junctions points distance or station completely changes the traffic situation and makes it necessary to react in real time at traffic stations and junctions points.

The use of higher buffer times at stations allows for equalize the travel times, through reduction waiting time at the station to compensate for delays. The buffer can also be inserted in journey between stations. **Figure 1** shows buffer times on train diagram with other times limiting train movement. Two trains 101 and 102 running in opposite directions. The vertical axis is time (hours) and horizontal space (railway stations with track circuits). At two-track ”station A” affect two trains.

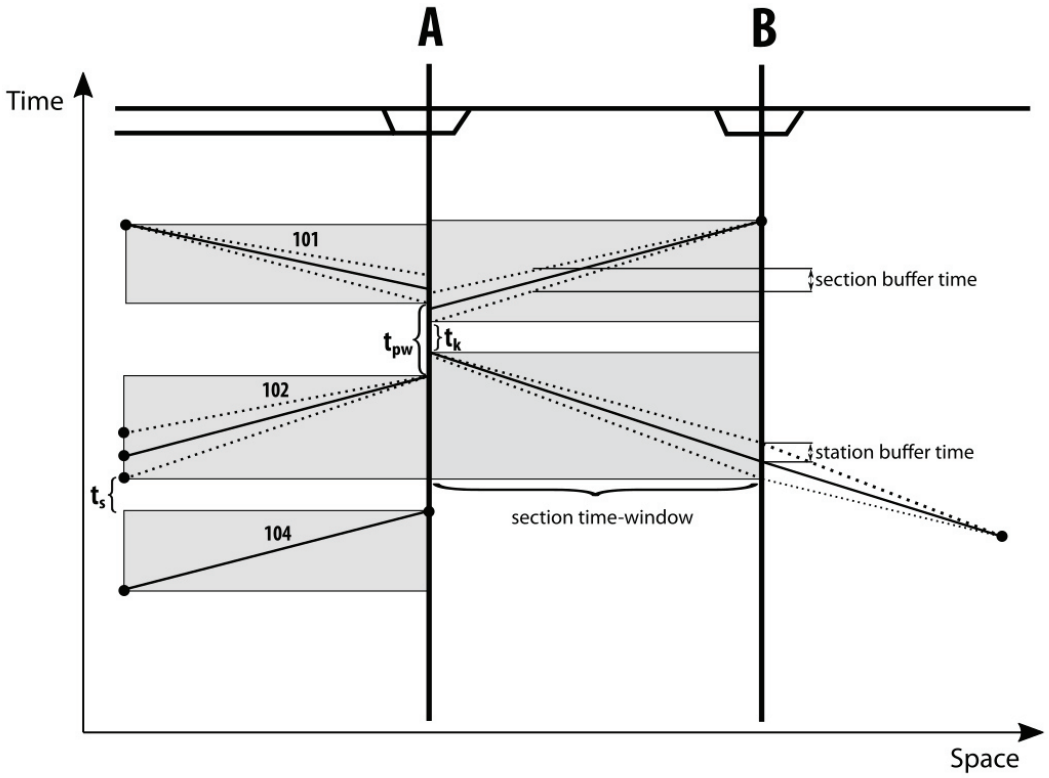

Figure 1 Buffer times on a train diagram

Figure 1 shows the following component times:

- buffer time within the section makes it possible recovering punctuality during the journey between the stations,
- station buffer time is a reserve within the station, which may consist in a longer stoppage,
- interval of time after train's sequelae (t_s) defines the minimum time between the arrival of a train at an adjacent station and expedition to the same path of the next train in the same direction,
- interval of simultaneous reception and dispatching of trains (t_{pw}) - time, which in case of conflict of train paths accepted and dispatched from the station must elapse from the moment of departure from the station of the train, which is dispatched on the pathway to the moment of arrival at the station of the train, which is received from another pathway,

- train crossings spacing [t_k] - this is the minimum time interval between a train's arrival at a station and its departure on the same train path in the opposite direction. This interval is required for all activities related to preparation of the routes and announcement of trains [13].

These actions lead to significant increase in the total time of train travel. Travelling by train that does not take full advantage of the traction and infrastructure possibilities becomes unattractive for the passenger. However, these measures help to improve punctuality.

If the possibility of delay in timetable is not taken into consideration, methods of current response to disturbances should be considered. This model is aimed at avoiding and leveling delays depending on the disturbances on the route.

The first model is react to delays using only buffer time. Including the buffer time in the timetable is described in [14, 15, 12]. It is then possible that the delayed train arrives at the destination on time. In the present case only one of two trains arrived on time at the last station. In case of interaction of two trains on the route possibilities of reducing the delay value depend on infrastructure conditions (line section, number of tracks).

The second situation is a model of responding to delays in the interaction of two trains using buffer times and rearrangement of train sequence. The less delayed train runs most closely to original track in graph of traffic and the second train overtakes the first train at the station. Compared to the previously described situation, it allows both trains to reach the end station on time. This case better use of infrastructure capacity and is therefore more advantageous in terms of time.

The authors introduce topological list. They support dispatching activities in scope of change of train order. It shows the states in which a train may be in as a result of the action of another and possibility of displacing a delayed train set in a way that has as little effect on the others as possible. It is possible to save this algorithm in the form of an axis or a tree. On the topology transition axis the search procedure continues until a possible change in train order can be found.

In [11] the process can be analyzed using the CPM critical path. When using the CPM in the topological list, if it is possible to change the sequence of trains, the CPM process is branching out. If it is possible to change the sequence of trains, successive levels of branches are marked and the CPM is applied to each sub-topological list. This procedure continues until found another possible change of train. The proposed dispatching algorithm shown in the **Table 1**.

Table 1 Dispatching algorithm [11]

Step	Description
1	Check the possibility for changing the train order
2	Branch on the current topological list
3	Replace the current topological list for CPM
4	Update the current best dispatching schedule
5	Update the input timetable according to the dispatching schedule
6	Move to the adjacent branch
7	Backtrack to the branch in the previous level

The dispatcher's algorithm should find a shipping schedule based on optimal topology transformation. Before using the CPM, the vertices are the first compiled into a topological list using a topological sorting algorithm. Each change in train order will also change the topological list of vertices.

3. MICRO-MACRO APPROACH TO ROBUST RAILWAY TIMETABLING

The article [5] proposes a hierarchical framework of timetable design combining macroscopic and microscopic network model. Scheduling points operated by the relevant train type (local or interurban) are stations and stops. The frequency is represented by the number of trains per hour and the path of the train depends on the infrastructure capacity needed to run it. A conflict is defined as overlap in time and space between two train paths. This is due to the fact that one train cannot use the railway infrastructure without interfering with the running of another train. The efficiency of the schedule shall reflect the time periods spent on railway connections to the waiting times and the boarding of travelers. Scheduling feasibility is the ability of all trains to respect the scheduled timetable. The timetable is feasible if individual processes are feasible during the planned process hours and planned train paths are free from any conflicts between trains. All trains are then able to run smoothly with others. This is directly related to the occupation rate of the infrastructure. It is higher when the time reserves and stable timetable are lower. Schedule robustness is the ability to resist design errors, changes in parameters and operating conditions.

A stable and feasible schedule is created at the microscopic level, and then optimized at the macroscopic level in terms of minimum travel times and maximum reliability. Timetable arrangement is an iterative process of two different models: the microscopic model and the macroscopic model. The microscopic model determines reliable train running times at a very detailed local level and checks the availability and stability of the timetable. The macroscopic model is an aggregated representation of the infrastructure and the schedule for the entire network by identifying arrival or departure times at or from stations that optimize a given destination function (e.g. minimize travel time). This macroscopic model contains methods for estimating the propagation of delay in order to evaluate decomposition for robustness to stochastic operational disturbance. Topics relating to reliability in rail transport are also described in the publication [16, 17].

The authors of the article [18] describe disruptions such as rolling stock breakdown, signal failures, and accidents. These are recurrent events during daily railway operation. Such events disrupt the deployment of resources and cause delay to passengers. Obtaining a reliable disruption length estimation can potentially reduce the negative impact caused by the disruption.

The authors [5] described the process of designing the timetable on the basis of a hierarchical structure. In the first iteration, the schedule is not prepared yet, so the microscopic model calculates the minimum travel times that are sent to the macroscopic model to construct the schedule. The achieved macroscopic timetable is returned to the microscopic model which calculates the blocking times of the sections by the train necessary to detect track conflicts based on the operating times (i.e. time supplements planned by the macroscopic schedule). If there are path conflicts, they are resolved and calculated new times and retransmitted to the macroscopic model. The macroscopic model solves the problem of optimization, which includes heuristics linear integration, minimizing the weighted sum of working time, total time and reliability cost. The reliability cost is defined as the delay propagation time obtained from the Monte Carlo simulation of respective timetable solutions. This iterative process is repeated until all latent conflicts are detected and schedule is analyzed both macroscopically and microscopically. After feasibility, microscopic model assesses stability of the timetable (i.e. ability to reduce delays). If the schedule is not stable, new operating times are calculated, for example by increasing the value of time allowances or caching times. This is done until the verification of the schedule stability reaches the required level. Transformations from the microscopic to the macroscopic and vice versa require appropriate procedures that are designed to aggregate-deaggregate input and output data. This interaction continues until the schedule developed by the macroscopic model is microscopically feasible and stable. As a result, the final framework result is a feasible and stable schedule with a suboptimal interaction between performance and robustness.

The time-distance diagram corridor with block section time-windows used is important with regard to the impact of delays and possibility of individual train movements. It represents the occupation of infrastructure on particular sections of the route. The interaction between trains is easy to read. The vertical axis shows the time in minutes and the horizontal axis shows the stations on the route. In analyzed case trackside corridor is used in 70 %. It has been observed that the number of micro-macro iterations increases as the number of trains on the line increases. In case the number of trains was 16 the model required three iterations. For 20 trains the number of iterations to obtain a conflict-free model has risen to 10.

A timetable is designed for a railway line with a few sections, and it locates trains in time and space. Therefore, a train timetable (train diagram) consists of few diagrams that combine a train path and a section. Definition of a single Train-Section Time-window (TST) and probability of train meetings in case of more than two trains are presented in [19]. Time windows to individual sections of rout in graphical timetable are shown in **Figure 2**.

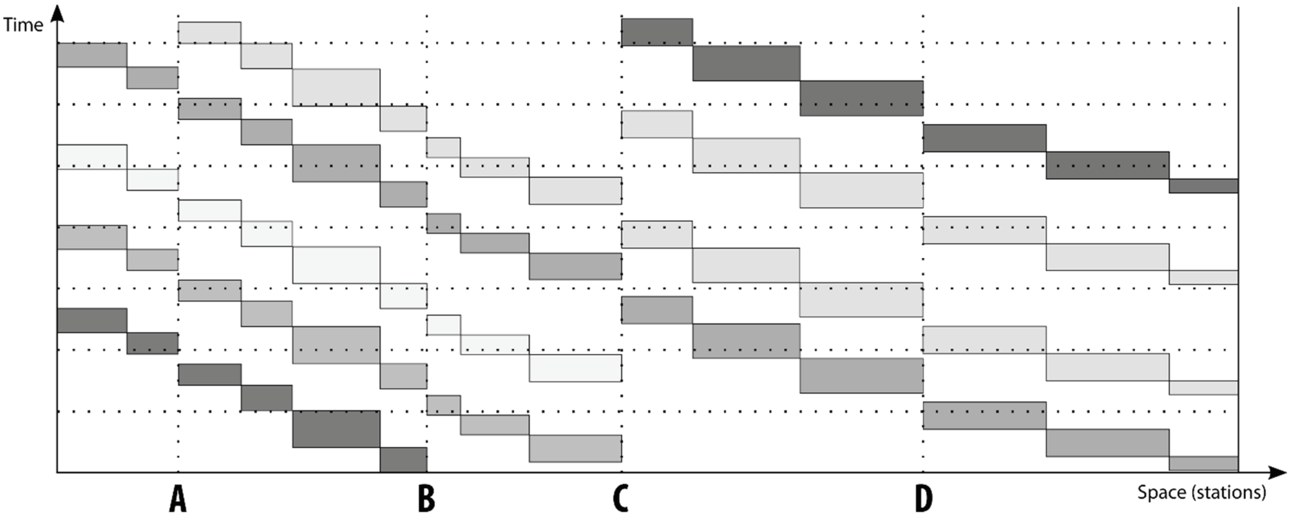

Figure 2 Train blocking time diagram

Figure 2 shows the use of infrastructure on an exemplary railway line. Subsequent trains are shown in the figure as TST showing the occupancy of individual distances. Successive leaving sections unblocks previous block distances. Occupancy of the infrastructure affects the resilience of the railway transport system, because the delay of one train causes changes in the running of subsequent trains. The problem is described in [20].

4. PLANNING PHASES OF THE RAIL TRANSPORT SYSTEM

The articles [21, 15] include problems of long-term strategic decision-making process in passenger railway and detailed planning of operations. Operational research methods have an increasing role in the planning process. Recently, more attention has been paid to the resilience of planning issues. In the context of the resilience of the railway system, it is often defined as the ability to continue operations at a certain level in the event of disturbances such as delays or failures. This has led to the need to pay attention to ways of ensuring continuity of operation in the event of disturbances. In approach integrated routing and passenger exchange at the station, the robustness measure is defined as weighted travel time extension (1).

$$WTTE = \frac{r_t - n_t}{n_t} \tag{1}$$

where:

r_t - realised passenger travel time (min)

n_t - nominal travel time (min)

Based on the calculation of the indicator is possible to compare the results between the timetables for different railway lines. A robust rail system minimises the real total travel time in case of small frequent disturbances taken into account during travel times. Another issue is to generate a replacement schedule in case of delays. Priority are decisions concerning the running of individual delayed trains on track sections. This method is based on a linear programming and is being tested on the Harz railway network in Germany. The problems of planning railway lines vary in different countries, but there are several basic planning stages from the longest decision-process to the daily operations on railway lines. These planning steps are relatively independent and cannot be considered as a single problem. The size and complexity of each individual problem means that only a sequential approach can be applied in practice. Possible steps of rail planning, indicating their relative time horizons is shown in the **Figure 3**.

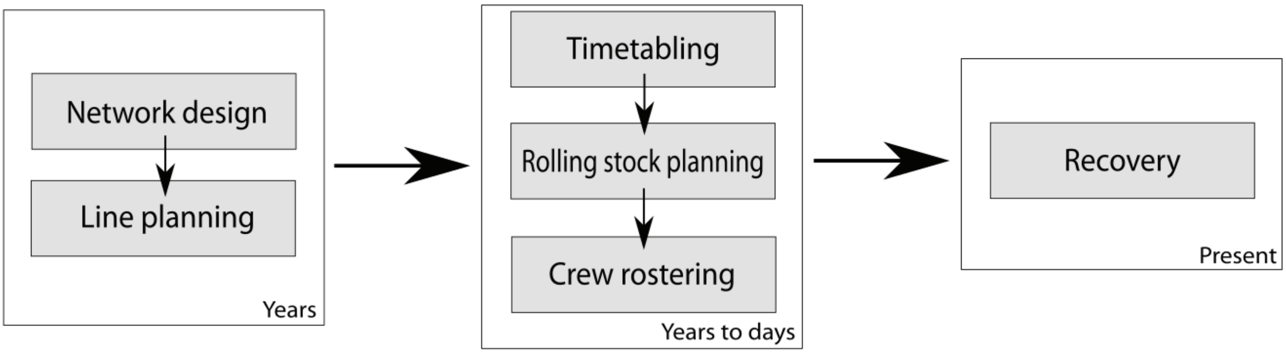

Figure 3 Overview of the possible steps of rail planning, indicating their relative time horizons [21]

Network design involves determining the topological structure of the railway network, the location of the stations and passenger exchanges. Line planning is defining the subset of stations and the route between them, which are lines of trains, deciding on the frequencies, speeds and types of trains for each line. Timetabling is the determination of exact times for events that should occur in railway units, such as driving between stations, times spent on platforms and specific station infrastructure. This level of planning also applies to train paths. Rolling stock planning is a problem of allocating trains to timetables, taking into account the combination and stabling tracks of trainsets. Crew location is a problem of scheduling the work of train crew members described in [22,23]. These steps can be subdivided into successive steps as, for example: crew planning often consists of two steps: arranging work schedules and then assigning them to employees in accordance with working time standards. There may also be combined stages such as integrated line planning (the infrastructure must satisfy the requirements of the timetable) and timetabling. However, there are clear differences and discrepancies between the following steps: network design - rarely changes and the decisions taken during the design process must remain valid for many years, while the work schedule of the crew may vary from one day to the next. This planning process described in [24] makes the resilience of the rail transport system a complex issue that depends on the parameters assumed throughout the planning sequence. It is important that railway operator cooperate in the field of planning. The last stage, which takes place in the daily operation of railway connections, is to regain the state of uninterrupted disturbance. This is made possible by the time reserves provided for in the preceding stages. The sensitivity analysis described in [25] may also be carried out in the planning of the rail transport system.

The time buffer included in timetable is disadvantageous for passengers. However, it does increase the system's robustness to operational disturbance. Therefore, a *WAD* (Weighted Average Distance) coefficient has been introduced. It is the weighted average distance of buffer times added to the travel time. This measure is intended to indicate the extent to which the buffer affects the train access to the final station and departure from the first station. If there are $N + 1$ trips on a line, from trip $t = 0$ to trip $t = N$, and each trip has supplement time s_t , then we may define *WAD* as follows (2) such as [26].

$$WAD = \frac{1}{N}\frac{\sum_{i=0}^{N} i \cdot s_i}{\sum_{i=0}^{N} s_i} \tag{2}$$

In this case, a *WAD* value of 0 would mean that all buffer is assigned to trip t = 0 and a *WAD* value of 1 would mean that all buffer is allocated to trip t = N, and *WAD* of 0.5 would mean that the buffer is equal for both the first and second half of the trip.

5. CRITICAL POINTS IN TIMETABLE

Studies in the article [27] show that the robustness index at a critical point can be used to increase the stability of the timetable. This article presents the application of the optimization method: ex-post evaluation by means of a microscopic simulation. The aim is to understand the increase of the Robustness at critical point (*RCP*) to a certain level within the schedule for the pairs of trains analyzed. A case study is presented in which the initial schedule and schedule with increased *RCP* are reviewed. The *RCP* is calculated from the formula (3).

$$RCP = L_P + F_P + H_P \tag{3}$$

Each critical point is represented by a specific station and a pair of trains that interact at that point.

Geographical location at such a distance that there is a temporal relationship. Train 105 refers to a train that starts this journey from a critical point behind another train (103) or is overtaken at a critical point by a second train.

The critical point robustness refers to the following three marginal parts, which are illustrated in **Figure 4**:

- L_p - the time margin before the critical point at high L_p value increases the likelihood of train 103 arriving on time at station B,
- F_p - time margin after critical point, high value of F_p increases possibility of train delay 105 in favour of punctual train journey 103,
- H_p - safety time between departures of both trains at critical point, i.e. safety margin between train 103 and train 105 at station A, at high value of H_p the possibility of punctual realization of timetable increases even in case of delayed delay.

The ex-post evaluation shall include a quantification of the measures concerning train delays and resilience of operations as well as their impact on the quality felt by passengers in order to assess their wider effects. The following parameters were measured: total delay at the final station, share of trains delayed by less than 3-5 minutes at the final station, total delay since scheduled arrival times and share of trains delayed by less than 3-5 minutes at indirect stations. The result shows that resilience is increasing at local level and that there is a need to analyses the link between ex-post measures and *RCP*. The aim is to improve the method used to increase the *RCP* and thus its overall impact on timetable stability. The aggregated punctuality for all connected trains indicates minor changes between initial and optimized timetable. However, the problem needs to be tackled on a case by case basis. Trains at a critical point with a low *RCP* value in the initial timetable show significant improvements in the optimized timetable.

In the article, critical points of *RCP* were inventoried on a selected section of the railway network in Sweden. The selected times are 8 - 11 in the morning and the total number of trains in this period is 79. The line is approximately 400 km long and includes long-distance traffic as well as suburban and freight trains. 33 critical points have been identified. On the basis of macro and microscopic analyses and train delays at the designated critical points, the timetable for the times constituting the *RCP* was changed. The simulation carried out reduced the real train delays by reducing or increasing the buffer times within the station. For critical points important is risk analysis presented in [28].

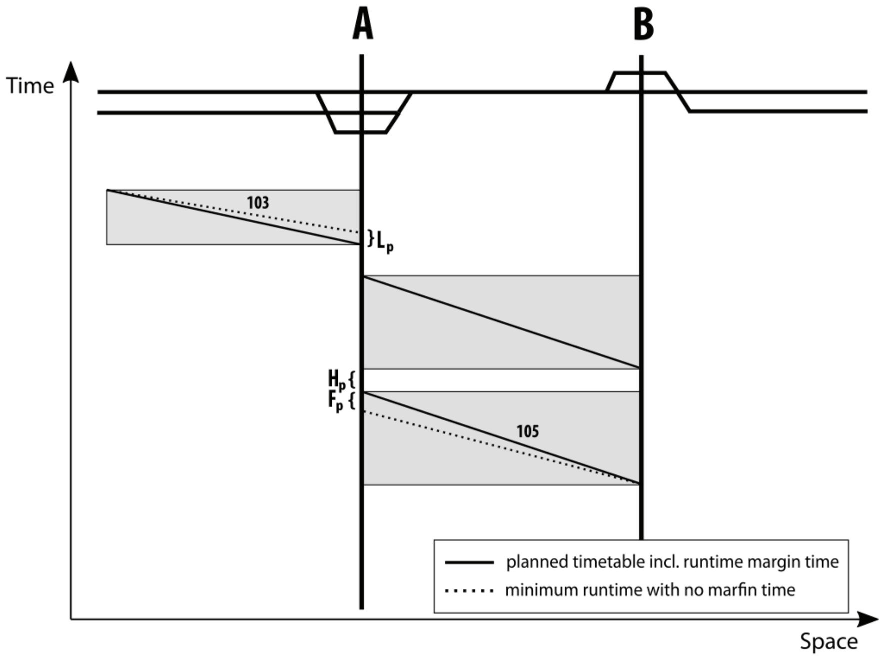

Figure 4 Buffer times on a train diagram

Article [29] is about timetable robustness in critical points. European rail networks are highly busy at many points in the railway network. This results in a delay-sensitive traffic system with low robustness. One of the key challenges is to assess its resilience and identify strategies to reduce its operational disturbance. The most common way is to analyze the schedule in terms of the rail line capacity and eliminate critical points. Existing measures of robustness are useful when comparing different timetables in terms of their robustness. However, they are not so useful as to suggest directly where improvements should be develop. In the article, the authors propose a new indicator taking into account the critical point concept. It is defined as the inverse of the sum of shortest differences in distance between rail vehicles in railway tracks. This concept allows to find critical points in the schedule. Reliability at critical points is calculated. This article presents the results of experimental studies, in which the benchmark of critical points was made. The evaluation concluded that attention should be paid to timetable points where trains enter or overtake the railway line. From the robustness point of view, the time difference between critical point is important. It is also proposed to delay trains that are already delayed by extending station stops in order to allow trains to run on time. The measures of resilience of train schedules can be divided into two groups: ex-ante measures related to timetable characteristics and ex-post measures which are based on rail line operational conditions. The operating conditions may not be calculated unless the schedule is actually realized or simulated with interference on rail line. Timetable measures can be calculated and compared at an early stage in the planning process without knowledge of operational disturbances. A similar method of assessment is presented in the article [30]. **Figure 5** shows the basic difference between the two groups.

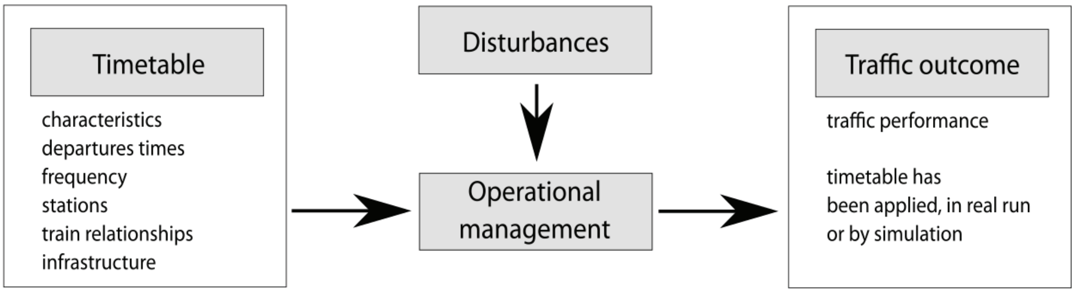

Figure 5 Two types of robustness measures used for the analysis timetable robustness

A critical point is defined both in time and space. It always consists of two trains running in the same direction and on the same path of a given section of line. There are two situations that we consider critical point: the time and place when the train is about to enter the path just taken or when the train is about to overtake another train. These situations are similar with regard to the relationship between trains in case of delays. Analysis of decomposition for weak points should begin with finding these situations in the train diagram. An example of a critical point on the southern Swedish main line during the morning summit period is given. The suburban train is expected to start at 8.05, as soon as the long-distance high-speed train has passed at 8.02. This means that if a long-distance train is delayed by a few minutes, there will be a conflict with the suburban train; two trains want to use the tracks at the same time. Train dispatcher in Sweden have instructions that a train running on time should be given priority over a delayed train interacting with a critical point.

The article describes the algorithm of timetable optimization with consideration of critical points. Stages of the algorithm can be found in **Table 2**.

Table 2 Algorithm of timetable optimization with consideration of critical points [29]

Step	Description
1	Finding critical points for trains entering the network
2	Find the critical points when a train overtakes another train
3	Calculate the headway margin at the critical points
4	Calculate the runtime margin for the entering train after the critical point
5	Calculate the runtime margin for the operating train before the critical point
6	Calculation of the *RCP* as the sum of headway margin and two runtime margin

The Weighted Average Distance (*WAD*) dependence is used to check the distribution of time reserves included in the timetable on the analyzed railway line. The even distribution of reserves facilitates the process of recovering punctuality in the event of a disturbance on the section and not only within the station points.

The authors [26] use the *WAD* to calculate the relative distance to the execution margin from the beginning of the line to take the allocation. Dividing the line into *N* sections and letting s_t denote the amount of margin related to section t, *WAD* can be calculated as follows (4).

$$WAD = \sum_{t=1}^{N} \frac{2t-1}{2N^2} \cdot s_t \tag{4}$$

WAD is a relative number between 0 and 1, where *WAD* = 0.5 means that the same margin amount is placed in the first half of line, as in the second half, where *WAD* < 0.5 means that a larger margin is placed in the first half.

6. CONCLUSIONS

Robustness has become an increasingly important factor both in research and in application to railway planning problems. The emphasis is clearly on the robustness of the timetable, but more authors apply similar ideas to other areas of the railway plan, such as rolling stock planning. For railway systems, several indicators and measures have been introduced to ensure robustness with an emphasis on timetable. However, it is not clear a one metric indicator can be achieved to the satisfaction of all stakeholders, as the different indicators focus on different interest.

Structure of the timetable and the constituent times have a significant impact on the propagation of delays. The inclusion of additional reserves reduces the capacity of the railway network

Without considering the planning problems, the overall plan may lose the robustness that is planned at the different planning stages. Rolling stock plan designed to be robust. In large-scale disruption scenarios the rolling stock plan can always be restored to a good plan. If the crew schedules planned are not able to cover the required train movement in practice rolling stock plan may actually lose robustness. A robust line plan must not compromise robust timetables.

Analysis of the critical points of the timetable is an important step in increasing robustness. It varies depending on the infrastructure and rail traffic conditions. No inventory has been made of the various possible situations. The probability of different types of critical point affecting the resilience of the rail network shall be considered, among them is how overtaking possibilities near a critical point affect the corresponding robustness.

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