Hindawi
Journal of Advanced Transportation
Volume 2022, Article ID 7025130, 18 pages
https://doi.org/10.1155/2022/7025130

Research Article

Impact Assessment of Interlocking Systems on Single-Track Railway Lines as a Measure Leading to Resilient Railway System

Michael Bažant[1] **and Josef Bulíček**[2]

[1]*Department of Software Technologies, University of Pardubice, Faculty of Electrical Engineering and Informatics, Studentská 95, Pardubice 532 10, Czech Republic*
[2]*Department of Transport Technology and Control, University of Pardubice, Faculty of Transport Engineering, Studentská 95, Pardubice 532 10, Czech Republic*

Correspondence should be addressed to Michael Bažant; michael.bazant@upce.cz

Received 4 January 2022; Revised 2 June 2022; Accepted 30 June 2022; Published 25 August 2022

Academic Editor: Seyed Ali Ghahari

Railway systems should be resilient to play a key role in creating sustainable development. Single-track railway lines are seen as potential bottlenecks due to limited capacity. More advanced railway interlocking systems (such as ETCS or satellite-based control systems) are being developed. On the other hand, the installation of these interlocking systems is a complex and time-consuming and costly task. For this reason, it is necessary to recognize the impact of potentially installed system with capacity, stability of timetable, quality, and other associated effects. The assessment is based on a set of simulation experiments using stochastic microscopic simulation model in the OpenTrack software tool. The focus is on railway operation with automatic block and automatic line blocking systems. If these two systems will have positive capacity effects, it is a basic presumption also for systems such as moving block (e.g., ETCS L3) to be effective. Research has shown that the significance of such measures can be best supported by linking to a matching timetable concept that will make full use of the benefits offered by these interlocking systems. The results reached in this research should be potentially applied, for example, by prioritizing of single-track railway lines for possible installation of such interlocking system. It can be achieved based on the capacity and operational effects examined.

1. Introduction

Railway industry plays a key role within an effort to create a sustainable environment. The issue is that there are many single-track railway lines. For illustration, 78.3% of railway network in the Czech Republic is single track (7324 km), whereas this situation corresponds with European context, where backbone lines are usually double track and single-track lines are considered for supplementary connections. Single-track lines are beneficial from the economic aspect, but they are associated with several operational problems. Occupation time is relatively long and trains often have to wait for crossing and clearing of a segment at stations, what is leading, for example, to decrease of travel speed.

Although this question has been known for years, it is becoming increasingly acute today. All railway lines are in a competitive environment with road traffic. Railway transport must be resilient to be a successful and punctual passenger and freight transport system. Qualitative demands are increasing due to this. The lines with relative limited extent of operation are not an exception. Maximal number of operated trains on a railway line is not a crucial factor as it used to be in the past. Reduction of dwell and travel time as well as increasing speed are important features nowadays at almost all single-track lines including lines with relative low number of operated trains. Infrastructure of many single-track lines itself is considered a bottleneck in this point of view.

Another associated issue is that the relation between infrastructure extent, traffic volume, and operational quality must be balanced. Improving the interlocking system should be part of this process. The concept of "interlocking system" applied in this article integrates traffic control system, signaling system together resulting into options how the line segment can be operated by trains. Line sections are more important than railway stations, but the two parts are interconnected.

The selection of the appropriate level of interlocking is determined by understanding of the capacity and operational effects associated with the interlocking system. In the railway sector, there is currently an extensive development of interlocking systems called as moving block that allow the presence of more than one train on a single track on a section of a railway line (e.g., European Train Control System (ETCS level) L2, L3, or satellite location-based systems). Some of these systems are based on cab signaling that do not use wayside signals, some combine cab and wayside signals. Specific way of technical solution is not crucial for this article.

The cost of these systems is significant. For this reason, it is necessary to select which railway lines and their line sections between stations are suitable for installation of such a system. Outputs of this research should be applied by prioritizing the railway lines to determine the order in which these systems should be installed. These priorities can be set after understanding how these systems will affect the capacity of railway lines and how they can contribute to the quality of operation on these lines.

It is necessary to define what are the possibilities of interlocking on single-track lines and how they will be covered in this article. In terms of the presence of multiple trains that run consecutively in a line section, line interlocking systems can be divided into four levels.

(1) (I1) Basic level represents trains that run according to sections between neighbor stations and the presence of a single train in them (line sections are not divided into spatial sections)

(2) (I2) The section is divided into a limited number of spatial sections by one block (the most common configuration). A larger number is possible but rather rare, whereas there can be one train in each. State-of-art blocks work automatically, so they are assumed in the article.

(3) (I3) The equipment forming several spatial sections is adapted to the operating conditions on the line (speed and braking distances) so that the interlocking system with associated signals can maximize the capacity of the line section. This is achieved by allowing multiple trains to follow each other on the track with minimized space separation. This is referred to as an automatic line block in the Czech Republic and in some other countries.

(4) (I4) This progressive level is so-called moving block. Trains can follow each other at different spatial intervals, the size of which corresponds to the speed of the train and the operating situation. Such a system is foreseen in ETCS L3 applications, but this principle may also be present in some other systems for regional lines or underground metro systems.

(5) (I5) Double-tracked line segment. This variant is applied as supplementary only for possibility to have regard to next step of infrastructure extent.

The technical solution of the line interlocking system determines the technological times important for timetable design. Levels I1 to I3 are assumed in the article, especially in the configuration of automatically operating devices (shorter technological time).

Interlocking systems at level I5 can locate a train on the infrastructure considerably more accurately and precisely than ever before. This opens up new opportunities in the traffic control area. In both instances, the cost and technical possibilities of the application of such new interlocking systems are an issue—in other words, not all lines or line sections can be equipped with such systems in the short term at least. This is the reason why it is needed to conduct this research to get some information for the decision-making process how to select the lines for the installation of such a system.

The inclusion of the moving block (I4) in the article is indirect. A small volume of traffic is usually operated on single-track lines. Necessity to alternate both directions is also there. It means that usually a small number of trains run together in fleets (platoons). Although moving blocks can shorten headway times, this can be replaced with data obtained from the research focused on automatic line block as an interlocking system. This is an acceptable model simplification, but for evaluation of the relation between capacity and quality of single-track lines.

For completeness of the solution and comparability, one line section is applied as a double track in one scenario (Sc08). This infrastructure variant is systematically labeled as I5.

The authors have long been engaged in research into the capacity of the railway infrastructure based on the use of stochastic simulation models. The aim of the research is to identify technological operational indicators that can be used to facilitate the description and assessment of this capacity.

Until now, the capacity of railway infrastructure has been determined mainly by time aspects of its use. The maximum (theoretical) capacity $n_{\max}$ can thus be determined according to the following formula:

$$n_{\max} = \frac{T}{t_{\mathrm{avg}}} = \frac{T N_t}{\sum_{i \in I'} t_{\mathrm{occup}i}} \ [-]. \tag{1}$$

This is the basic principle, the available time T [min] is divided by the average time of occupation by one train or operation t_{avg} [min]. Alternatively, this can also be expressed by the total number of trains $N_t = |I'|$, where I' is the set of trains under investigation and the occupation time of each train or operation $t_{\mathrm{occup}}i$ [min].

The second basic indicator is the occupation degree D_{occup} formula (2). It is the proportion of time used and the total available time T [min].

$$D_{\mathrm{occup}} = \frac{\sum_{i \in I'} t_{\mathrm{occup}i}}{T} \ [-]. \tag{2}$$

These indicators will continue to be used. However, they need to be complemented by qualitative perspectives and by perspectives that are more reflective of the prevailing nature of traffic and of the costs. The aim is to find a scale of infrastructure that is efficient, proportionate to operational requirements, and enables rail transport to be organized in the required quality. The main indicator that describes quality is delay, as confirmed, for example, by Börjesson and Eliasson [1].

Simulation models are inherently descriptive. The results only provide information on the replications performed, that is, on the assessed traffic variants. On the other hand, simulations are rather complex and time--consuming processes, and so, theoretical considerations must be also devoted to the simulation procedure itself. One of the additional objectives of this research is to recommend procedures performing such assessments effectively with modest demands on complexity and time.

2. Train Fleeting (Platooning)

Fleeting of trains means that two or more trains run in one line section in the same direction and at the same time. This is a prerequisite for an interlocking system that allows the presence of more trains on one track (by division into spatial sections) to be efficient.

For instance, in the city agglomeration of Hradec Králové-Pardubice in Eastern Bohemia, there are four cases where train fleeting can be applied because line sections are shared by two or more lines of passenger transport. Trains can be fleeted at these sections due to coordination at interchanging nodes. These sections are highlighted by the arrows in Figure 1 that illustrates the frequency of such cases in practice.

3. Hypothesis and Aim

Specific objective is to assess the effect of a railway line interlocking system on the traffic occurring on a single-track line, using stochastic experiments in a simulation model. Changing interlocking system can be a way how the capacity as well as the quality of operation can be improved.

Specifically, various interlocking systems are looked upon as measures to increase the railway track's capacity, with emphasis on qualitative rather than quantitative benefits. The goal is to find the background for a future methodology for efficiently selecting interlocking systems for low- and medium-traffic lines, where the quantitative aspect does not play a major role and to prioritize the equipment of the line sections.

The research hypothesis can be formulated as follows. Stochastic simulation can be successfully applied for the determination of the new analytical indicators of railway capacity as well as a tool that is able to identify the contribution of individual types of interlocking systems.

Traffic stability as the qualitative aspect of capacity can be applied as the main indicator.

Traffic stability will be calculated by formula (3) as the average change of delay $\Delta\, d[s]$.

$$\Delta d = \frac{\sum_{j\in J}\sum_{i\in I'}\left(d_{ij}^{\mathrm{OUT}} - d_{ij}^{IN}\right)}{N_t \cdot N_r}. \quad (3)$$

It is computed as the difference between the delay at the output from simulation $d_i^{\mathrm{OUT}}[s]$ and the delay at input to simulation $d_i^{\mathrm{IN}}[s]$ by a train of $i \in I'$ within a replication of $j \in J$. Trains are coming from the subset of I'. Number of assessed trains is marked as $N_t = |I'|$ and the number of replications as $N_r = |J|$.

4. State-of-the-Art

Effect of various interlocking systems on the capacity has been discussed previously [2]. Emphasis was on the European train control system level 2 (ETCS L2), which was compared to the interlocking system NS′54/ATB. For this, the authors used the compression method as per UIC 406, accentuating only the quantitative aspect of capacity. The criterion used by us in our research is the value of the delay, whereby we attempt to accentuate the qualitative aspect, that is, to look at the problem from another side. Simulation as an adequate tool for the assessment of railway interlocking as well as for the organization of railway operation is seen also [3, 4].

Overview of studies (25 various studies) focused on railway capacity assessments is presented previously [5], where various approaches are discussed—analytical, simulation, and combined approach. There are also listed commonly used software tools for capacity assessment. The differences between the United States and European approaches are also outlined and studies are also broken into several categories and there are also highlighted key similarities and differences between the United States and European rail systems, where 14 U.S. studies and 11 European studies are considered. Our approach could be incorporated into timetable-based simulation software as is common in Europe, whereas in the United States the predominant approach is without considering timetables.

In the article by Abril et al. [6], there is pointed difference between theoretical and practical capacity with an introduction of Spanish MOM system that contains optimization module for obtaining feasible and optimized timetables. There is also comparison of various parameters of timetable (e.g., headway times, line sections length, train speed) and its impact on capacity. The article evaluates the relationship between the subsequent intermediate period and capacity on single-track and double-track lines, and attempts to tabulate this relationship. In our article, this principle is translated into schedule modifications in each scenario.

Method for designing a single-track rail line for a reliable high-speed passenger train service is presented in the article by Petersen and Taylor [7]. The operation under consideration is planned as homogeneous with one type of trains—high-speed passenger transport. Among other constraints that are relevant to our research, the primary focus is on the location and length of double-track inserts, with no fleeting considered. Different scenarios of double-track line lengths,

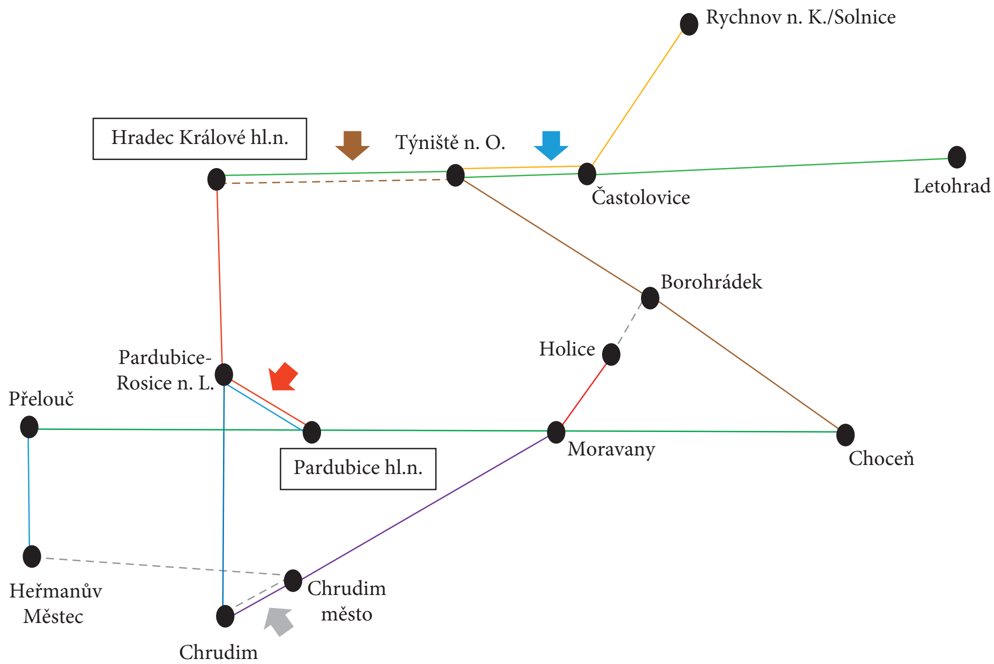


Figure 1: Simplified scheme of the railway network in Hradec Králové-Pardubice agglomeration with parallel regional train lines (marked with arrows).

the amount of delayed trains, as well as delay values were evaluated using computer simulation in this article.

We employ the OpenTrack tool for our simulations. This is a widely used software enabling discrete and continuous approaches to simulation to be combined [8]. It can be used in the modeling of both high-speed lines [9] and conventional lines [10] as well as suburban lines [11, 12].

Interactions of trains running at different speeds, including the capacity aspect, have been addressed previously [13], providing evidence of the importance of this topic. The author also pointed to the fact that railway traffic is a phenomenon that is affected by a number of external factors.

The same idea dominates the article by Mussone and Calvo [14]. The authors also discussed the potential of a comprehensive analytical assessment of the railway capacity. The topic is still actual, perhaps also in a new context—with respect to the question as to how to effectively select the need for and scope and method of setting up detailed microscopic simulation models.

Very often, the capacity issue in the context of an applied interlocking system is addressed for highly burdened lines in efforts to attain the maximum capacity. The article by Dicembre and Ricci [16] is an example of such a solution [12]

Unlike that solution, our research focuses on the issue of how a more advanced interlocking system can contribute to traffic quality on low- and medium-traffic intensity lines, where more importance is attached to the highest possible traffic quality than to attaining the maximum capacity.

The economic aspect is frequently stressed in the context of current railway market liberalization. Capacity assignment is a topic discussed previously [16].

Timetable-oriented point of view on the interaction between railway operation and infrastructure is presented by Široký et al. [17].

Railway capacity assessment in the international context is currently governed by the UIC 406 code. Still, despite the existence of the code, much space remains for additional research in this area. The compression method and (once again) the stochastic approach to traffic are discussed previously [18], where the application in Sweden is also described. Application in Slovakia is the topic analyzed by Šulko et al. [19].

5. The Simulation Model and Its Application to the Assessment of Infrastructure and Timetable Variants

In our research, a microscopic simulation model of a single-track line was set up in OpenTrack software tool. The model contains all needed data for research on microscopic level, including details about infrastructure, rolling stock, timetable, and behavior of trains in stochastic conditions.

The line is 50-km long and encompasses five interstation line sections. Input delays are stochastically generated. Train delays are generated based on the discrete probability distributions obtained through a survey made by the authors on the railway network in the Czech Republic.

We realize 200 replications for each scenario (scenarios are listed in Table 1), while replication contains traffic peak of 4 hours. To be able to collect data for delayed trains, we consider a replication time of 6 hours.

The primary objective of the research is the need to find the appropriate scale of the infrastructure and the technological equipment of the transport infrastructure to match the required volume of traffic. In addition to being cost-effective, this scale will also allow for reliable operation within the given options. The concept of the simulation

Table 1: Simulation scenarios.

Scenario	Infrastructure	Number of trains (full length of the line/C-D/E-F)	Train fleeting in line sections	Role in the study
Sc01	I1—trains are organized between stations	14/14/18	None	Basic (input) state
Sc02	I2 at sections C-D	13/15/18	C-D	Role of automatic block (I2)
Sc03	I2 at sections A-B, E-F	14/14/22	A-B, E-F	
Sc04		13/15/18	C-D	Role of automatic line block (I3)
Sc05	I3 at sections C-D	14/22/14	None	Role of I3 without fleeting
Sc06		14/22/14	C-D	Role of I3 with fleeting
Sc07	I3 at C-D, E-F	14/22/22	None	I3 extended to two sections
Sc08	I5 C-D double track (operated by I2)	14/22/14	C-D	Middle section C-D double track (I5)
Sc07-1	I3 at C-D, E-F	14/22/22	None	I3 at 2 sections together with increased mean value of delay

assessment is carried out as shown in Figure 2—we address all possible options of interlocking systems (I1–I4) in our research. Moving block, as it was stated earlier, is not shown in the individual scenarios, as a necessary condition for its effectiveness is the effectiveness of both the automatic block and the automatic line block, as it is essentially a higher level of both. It is not necessary to model moving block itself due to this. Moving block is replaced by automatic block and automatic line block.

The set of applied simulation scenarios is based on the logic shown in Figure 2. Variants of the types of line interlocking systems and various timetable variants were considered. The need of different timetables is caused by the fact that certain types of interlocking systems will only have a positive capacity effect in combination with a timetable that takes this into account.

As can be seen in Figure 3, the 50 km long line consists of five line sections connecting six stations marked A–F. Signaling devices enabling the presence of more trains in the spatial section are primarily inserted in the middle section C-D, in some cases in the outermost sections A-B and E-F. The timetable is based on 14 trains running throughout the line. The traffic is then reinforced in the last (suburban) section E-F by four or eight trains depending on the scenario. Further reinforcement is then added in scenarios Sc01–Sc05 and Sc07–1 in sections C-D, where eight section trains are added. This range of services covers a time window of 4 hours and consists of two types of trains—regional (slow) trains and long-distance (fast) trains. An overview of the simulation scenarios comprising this study is given in Table 1. The symbols I1–I5 stand for individual variants of infrastructure. The scope and infrastructure configuration are shown in Figures 3–8.

Scenario Sc07-1 is complementary and works with a higher mean value of stochastically generated delay of 12 min. Thus, a situation of relatively unstable traffic is created by this scenario. All other scenarios work with a mean delay value of 4 min.

6. Features of the Stochastic Modeling

Stochastic modeling provides the possibility to assess and evaluate not only the quantitative view, but also the qualitative aspects. These are very important for resilient railway systems.

Different train delay characteristics were applied in the scenarios:

(a) Typical delay: 63% trains at the input meet the exponential distribution patterns with a mean delay time of 255 s, the longest delay generated was 1200 s.

(b) Larger delays due to rebuilding or other building works on the adjacent sections: 80% trains at the input obey the exponential distribution with a mean time of 720 s, the longest delay generated was 1200 s.

The output parameters obtained from the above scenarios are described in the sections that follow.

There were calculated 200 replications for all considered scenarios (values about 5 seconds for half widths of the arithmetic means with 95% confidence interval as presented).

Unless otherwise stated, delay values represent average value over all 200 replications.

7. Simulation Scenarios and Results Obtained

Basic timetables can be modified in individual scenarios accordingly to be suitable for the applied interlocking systems as well as to be suitable for the assessed effects.

7.1. Scenario Sc01: Single-Track Layout along the Entire Length of the Line without Further Organization of Train Movements in Spatial Sections. The initial situation is a single-track line on which the traffic is organized according to line sections. Related train diagram (timetable) is attached in Appendix Figure 14.

There are four extra suburban trains of Direction 1 inserted in the final spatial section E-F. However, the timetable design has shown the limited capacity imposed by this traffic organization, which has necessitated the need to connect these trains in Direction 2 with the basic trains. This effect does not occur in some other scenarios when using the automatic block.

Figure 4 shows that the line tends to reduce the input delay in both directions during the run. In Direction 2 at

Interlocking system on railway line	No block I1	Block in the middle I2	Automatic block I3	Moving block I4-I5
Effect on capacity	min			max
Simulation scenarios	Sc01	Sc02, Sc03, Sc08	Sc04-Sc07	---

Figure 2: Concept of the simulation assessment within performed scenarios.

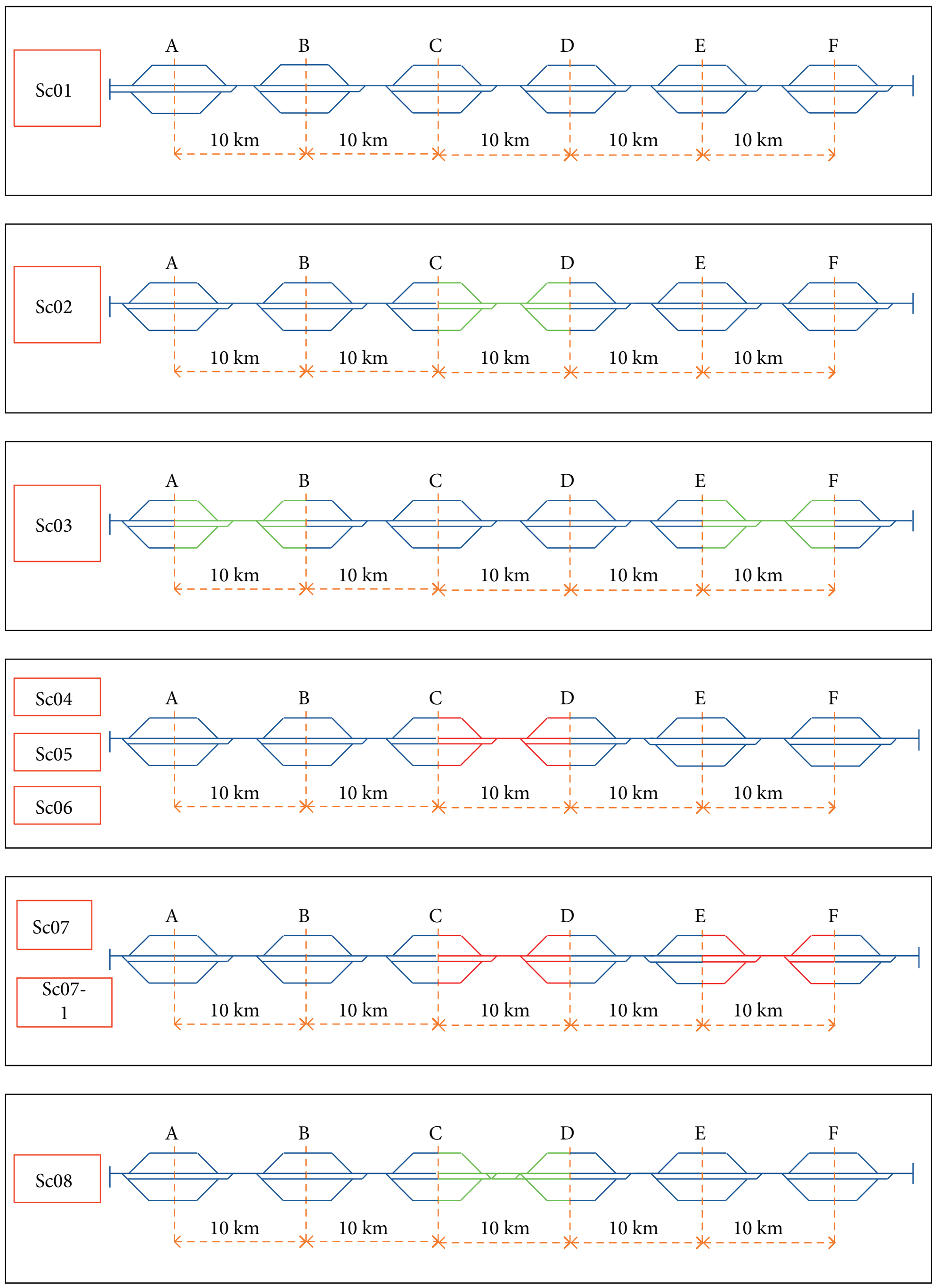


Figure 3: Infrastructure layout for scenarios with highlighted changes in line sections.

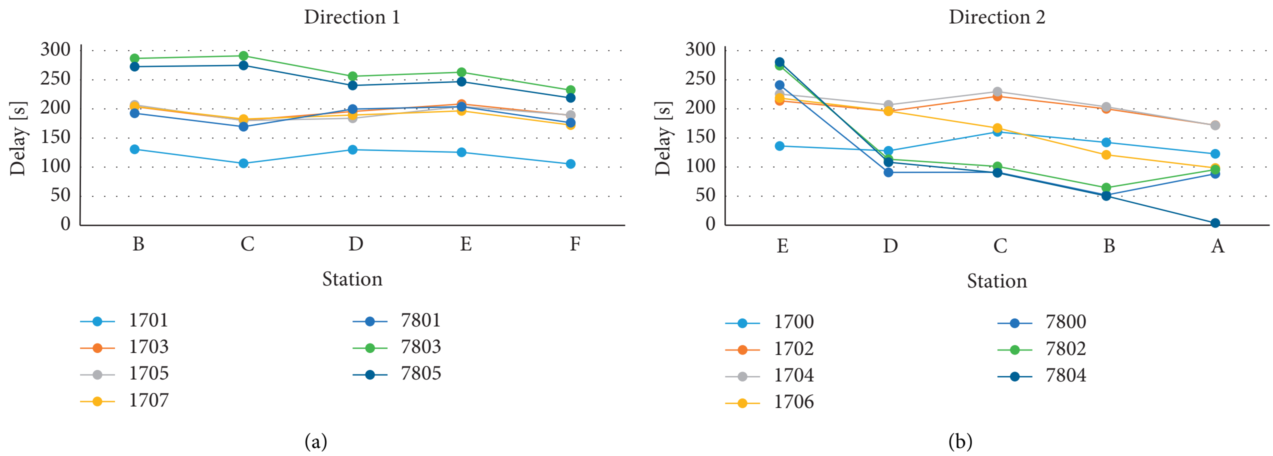


Figure 4: Evolution of average delay on arrival at individual stations in scenario Sc01.

station D, there is a significant reduction in delay, however, this is due to the crossing of trains at station E where passenger trains are scheduled to stay for 8.5 min. Trains 7800 and 7802 increase delay in the last section B-A due to the fact that they cross with oncoming trains at station B and depart (for the crossing operating interval) only 1.5 min after the oncoming train arrives.

The conclusion on this scenario is that a lower capacity can be expected in the interstation sections of the single-track line with the given mode of traffic organization.

7.2. Scenario Sc02: Single-Track Layout along the Entire Length of the Line with an Automatic Block in Sections. This scenario is principle based on the situation in scenario Sc01, which is extended by the introduction of an automatic block in the middle of section C-D, that is, in the middle of the entire modeled line. The placement of this section to the middle section of the line is based on a general judgment rather than an analysis of the timetable and traffic volume. The concept and the traffic volume are the same as in scenario Sc01, however, the timetable is modified to consider the option to run planned trains as fleeted on the section with the block. Trains are fleeted in a fast-slow sequence. Train diagram is in Appendix Figure 15.

The results for this scenario are shown in Figure 5. In Direction 1, train 1701 runs alone in sections A–D, so there is a noticeable attempt to reduce the stochastically generated input delays. At stations D and E, it crosses closely with oncoming trains, the average delay values start to increase. Another interesting effect is that for trains 1703, 1705, and 1707, the average delay values increase in the C-D section, while they decrease for trains 7803, 7805, and 7807. This is because the regional trains 78xx are overtaken at station C by the express trains 17xx. Therefore, the 78xx regional trains stay there for 16.5 min, which causes the delay to decrease, and the situation is similar in the opposite direction. These stays cause an almost absolute reduction of generated entry delays to zero for the price of unattractive stays for passengers and taking advantage of the fleeting opportunity.

7.3. Scenario Sc03: Single-Track Layout along the Entire Length of the Line with Automatic Block in Sections A-B, E-F. In contrast to the previous Sc02 scenario, there is an attempt to adapt the location of the automatic block to the extent of traffic, so one is placed in the last section of E-F, where the extent of suburban traffic is increased. The second automatic block is then inserted in section A-B (allowing a shorter interval between trains departing from both terminal stations).

The timetable was also adapted to the introduction of automatic blocks (see Appendix Figure 16). Train fleeting is used on both sections A-B and E-F. A significant change is the fact that the inserted trains 178xx in the (suburban) section E-F are introduced in both directions on the hourly interval and are thus no longer coupled in Direction 2 with the basic trains running on the entire line.

The evolution of delay of individual basic trains (operating on the entire line) is shown in Figure 6.

As in the previous cases, two basic elements affecting the stability of the timetable are evident in this operational scenario. The first one is the influence of the length of stay in the station (for traffic reasons), where its extension has a positive effect (see trains 78xx in Direction 1 with a stay in station C of 8 min). The second is that crossing with an oncoming train (almost) at the crossing interval can have a negative effect on stability (trains 17xx and crossing at stations B, D, and E in Direction 1). Train 1707 lacks a crossing at E at the end of the analysis period, which is reflected in the figure.

Subconclusion from the Sc01 to Sc03 scenarios: the introduction of an automatic block may not have a clear impact on the increase in capacity (analytically determined), whereas it depends on the constructed timetable. It also has been shown that the automatic block has benefits in terms of introducing some operational concepts (e.g., the possibility of running embedded commuter trains in the E-F section separately in both directions). On the other hand, a certain paradox has emerged, namely, that unattractive long stays in stations for traffic reasons can lead to increased timetable stability from the passengers' point of view.

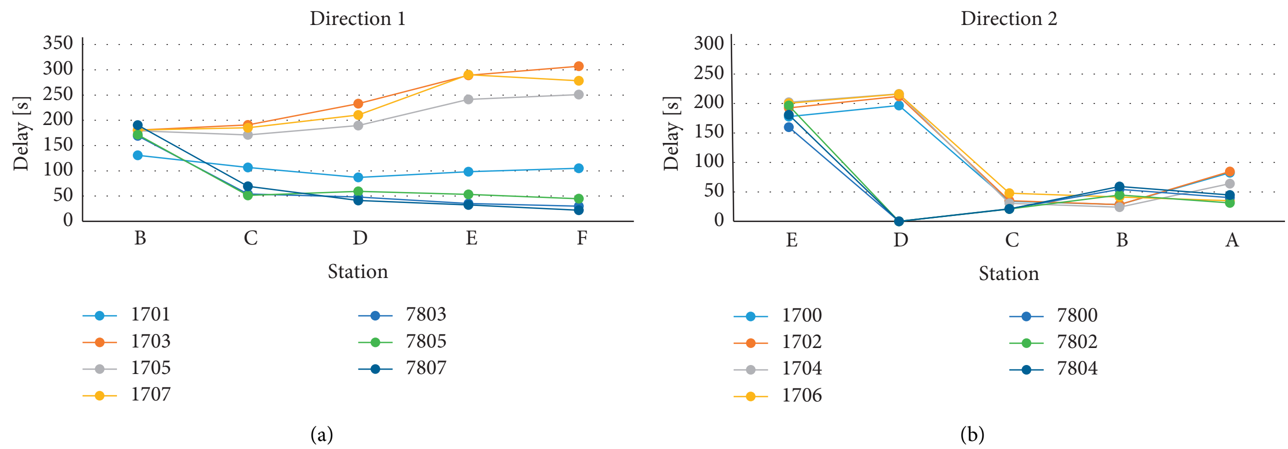


Figure 5: Evolution of average delay on arrival at individual stations in scenario Sc02.

For complexity, the segment E-F was assessed in an analytical way using Sc0–Sc03, as given in Table 2.

7.4. Scenario Sc04 Is Focused on the Comparison between Automatic Line Block and Automatic Block. The first important thing is to decide whether to use an automatic line block or an automatic block (or a more advanced interlocking system). Two (side) variants are compared. Where an automatic block is used, section C-D, that is in the middle of the line, is divided into two spatial sections. The automatic line block divides the same section into partial spatial sections 1 km each.

Four couples of long-distance trains and three couples of regional trains with longer running times are used. The timetable has been set up so that fleeted traffic is practiced in the middle section with an automatic line block, which means a long-distance train and a regional train running one after the other so that the division of the section into two spatial sections is deliberately used. The same timetable (Appendix A2) is used in the variant with an automatic block, though the latter would enable the ensuing interval to be shortened.

The simulation revealed that the mean delay of the trains arriving at the destination station (F or A), except for the regional trains in Direction 1 was shortened by the introduction of the automatic block (Table 3).

From Table 3, it is clear that the introduction of the automatic block is most beneficial to the long-distance trains in Direction 1, where the mean delay at the arrival at the destination station at the end of the 50 km line was 80 seconds. The largest increase in the delay, on the other hand, was found for the regional trains in the same direction where the mean delay is 73 seconds. This is kind of paradoxical, because the regional trains run tightly following the long-distance trains, and so one would expect that the change of the interlocking system enables more trains to move within the interstation section.

At this point, it can be concluded that the replacement of an automatic line block with an automatic block in one "isolated" section is qualitatively beneficial to some (small) extent.

7.5. Scenarios Sc05 and Sc06: Train Fleeting. Fleeting was assessed on the middle section C-D of the single-track line model—the only section that is equipped with an automatic block with 1-km long spatial sections. For emphasizing, the traffic in this section was made denser by inserting additional trains running only in this section of the model. The rate is one couple of added trains per hour. The traffic concerns six trains per hour (three in either direction: long-distance, regional, and added train sets).

Two timetable variants (named as scenario Sc05 and scenario Sc06) were set up and compared: the number of trains was identical, but the added train running patterns were different. Scenario Sc05 included alternating train runs, the automatic block being thus virtually unused, as shown in Figure 7. Train diagram for scenario Sc05 is attached as Appendix Figure 17 and train diagram for Sc06 as Appendix 18.

The scenario Sc06 includes running the trains as fleeted to use the section division into spatial sections. To preserve the real aspects of traffic on medium burdened lines, only two trains in the same direction are considered in a fleet, but the interlocking systems allow even more. Moreover, the trains are fleeted in the odd direction only, whereas this approach provides the opportunity to compare group traffic (Direction 2, trains with even numbers) and fleeted traffic (Direction 1, trains with odd numbers).

First, the development of the mean delay times at the arrival to the stations (A–E) is compared for the entire line applying alternating traffic of the added trains as shown in Figure 7. This development is shown in Figure 9.

This can also be compared to the development of the delay of the same trains with additional trains being run within sections C-D in the fleeted mode in one direction and in the group mode in the other direction (Figure 8). The results are shown in Figure 10.

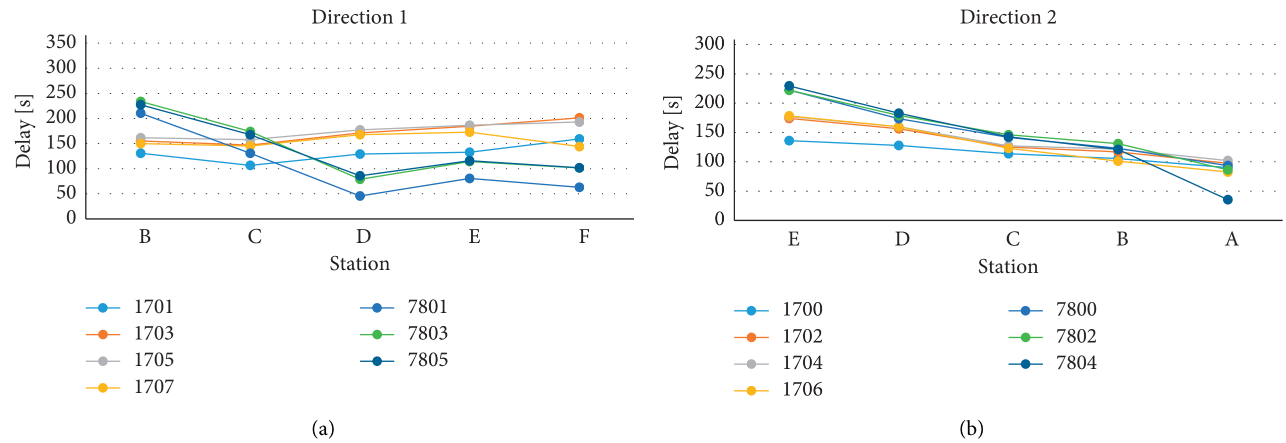


Figure 6: Evolution of average delay on arrival at individual stations in scenario Sc03.

Table 2: Analytical assessment in segments E-F.

Scenario	Sc01	Sc02	Sc03
n_{max} (trains/4h)	27	27	31
D_{occup} [−]	0.648	0.648	0.708

Table 3: Comparison of an automatic line block and an automatic block in sections C-D.

Average delay at arrival (s)	Direction 1		Direction 2	
Type of trains	Line block	Automatic block	Line block	Automatic block
Regional	32	105	29	26
Long distance	235	155	67	51

For the trains with odd number (in Direction 1), the delay decreased slightly, by 10.0 s in average, for the long-distance trains (1701, 1703) and increased by 1.6 s for the regional trains (7801, 7803, 7805) that run along the entire line.

The patterns for the long-distance trains and regional trains are also different from the even trains (in Direction 2). The delay of the regional trains (7800, 7802, 7804) decreases continuously along the entire line. Compared to the alternating traffic mode, the mean delay is 2.6 s lower. This traffic model is inconvenient for long-distance trains, the delay is 5.3 s longer. This is due to the structure of the timetable (timetable composition), where the regional traffic trains are run within section F-E 15 minutes after the preceding trains, whereas the long-distance trains leave station F after a tight crossing (to the interval) the passenger train in the opposite direction. The regional trains pass the long-distance trains in E, the latter reducing their delay.

The situation of the added trains (22xxx series) running within the middle section C-D only is as follows. The stochastically generated delay is increased in both traffic variants—by 18.1 s (in average) in the odd Direction 1 and 9.2 s in the even direction for the alternating traffic mode. If the traffic is organized in the fleeted/group mode, the delay also increases, but only by 4.8 s in the odd Direction 1 and 1.3 s in the even Direction 2.

The simulation indicates that the installation of an automatic block in the middle section is beneficial to some extent but not very much from the global aspect. What is found to be significant is the link to the timetable structure in cases when timetable is designed, so that it respects infrastructure specifics.

Scenario Sc07: assessment of the extended application of automatic block on one of the suburban line sections with increased volume of suburban traffic: impact of different delay values.

Automatic block in two sections within the railway line is considered. The first one is sections C-D in the middle of the line. The second one is the suburban section E-F at the end of the line in Direction 1. There are eight more suburban trains inserted to this section. Average train delay values on arrivals at individual stations for average delay of 4 min are in Figure 11. Train diagram is in Appendix Figure 19.

7.6. Scenario Sc08: Assessment of Double-Track Line Sections C-D in the Middle of the Line. Double-track section C-D is used for crossing trains by moving both trains. The aim is to assess whether this approach can be effective also for the improvement of operational stability (reliability). For that reason, regular crossing of trains moving in the section is not planned in timetable. Train diagram attached in Appendix A5 is applied also for this scenario.

When the results in Figures 10 and 12 are compared, it is obvious that more significant change occurred in the Direction 2 only. Average delay of long-distance trains decreased from the span 120–160 s to values slightly less than 100 s. This positive effect is related to the fact that these long-distance trains cross with a pair of added and long-distance trains that run in the opposite directions. If these trains are delayed, they cross at double-track line sections.

Partial conclusion: considering double-track line only in one of the line sections is beneficial for operational stability

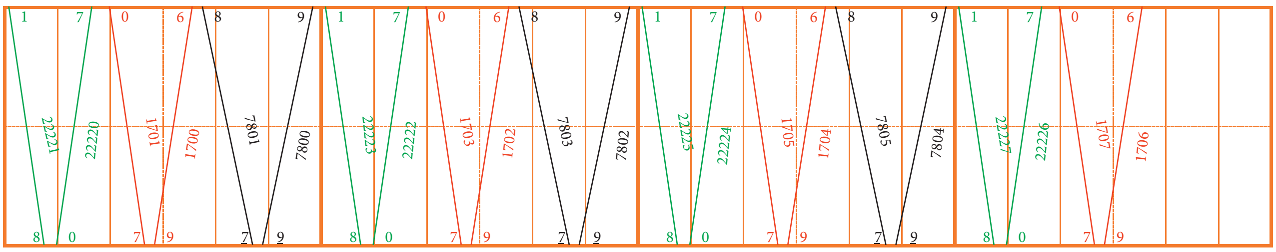


Figure 7: Scenario Sc05—trains running within the middle section of the line, the automatic block was unused (red, long-distance trains; black, regional trains; green, trains added to the middle section only).

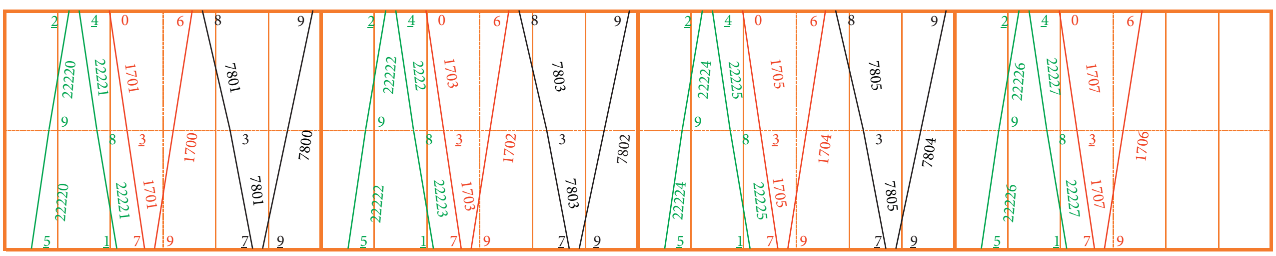


Figure 8: Scenario Sc06—trains running in the middle line section, as fleeted.

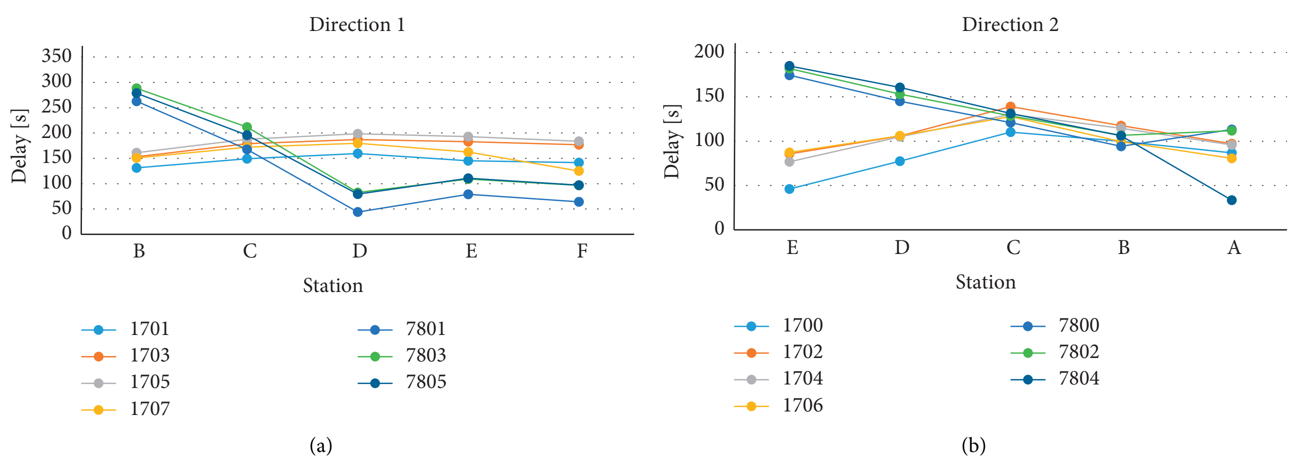


Figure 9: Evolution of average delay on arrival at stations in scenario Sc05.

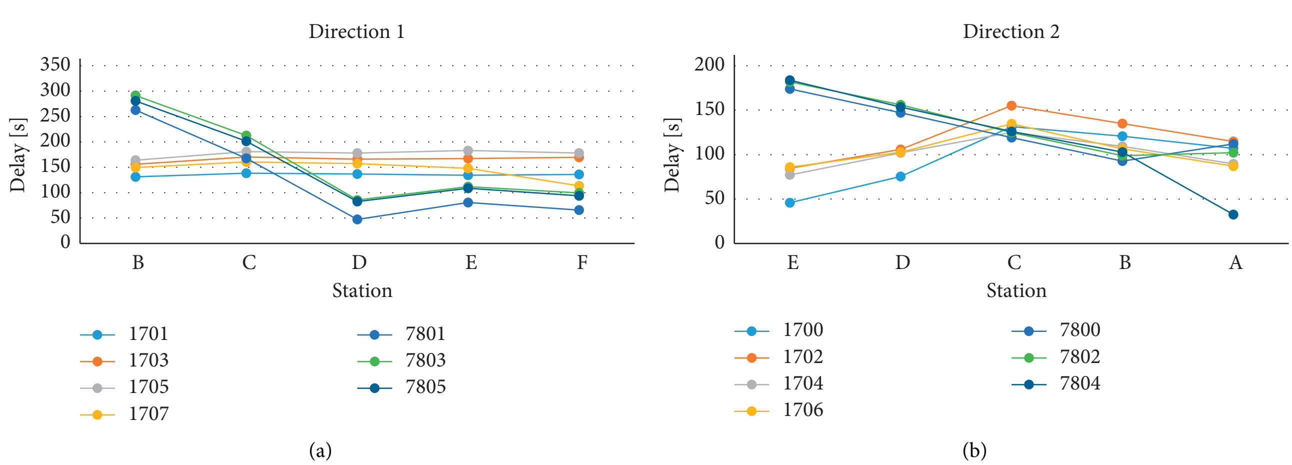
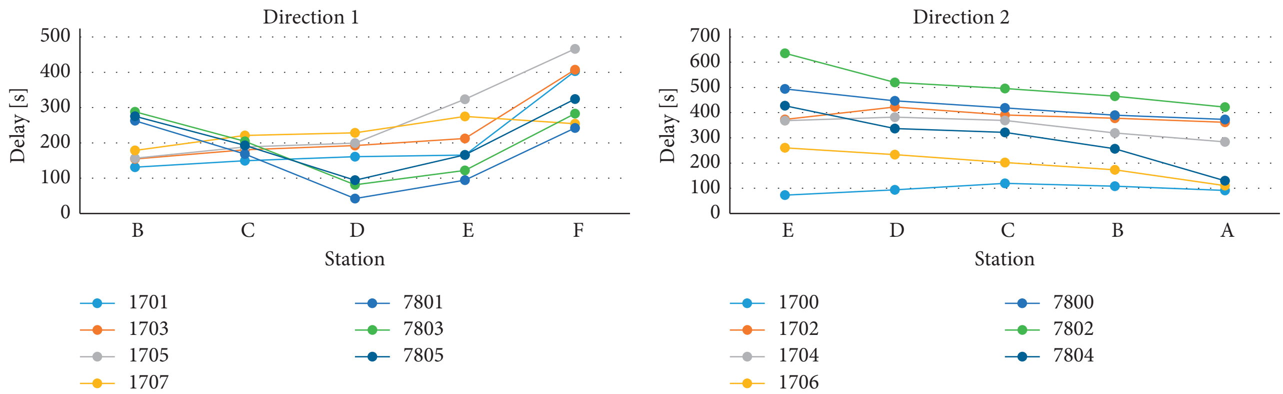
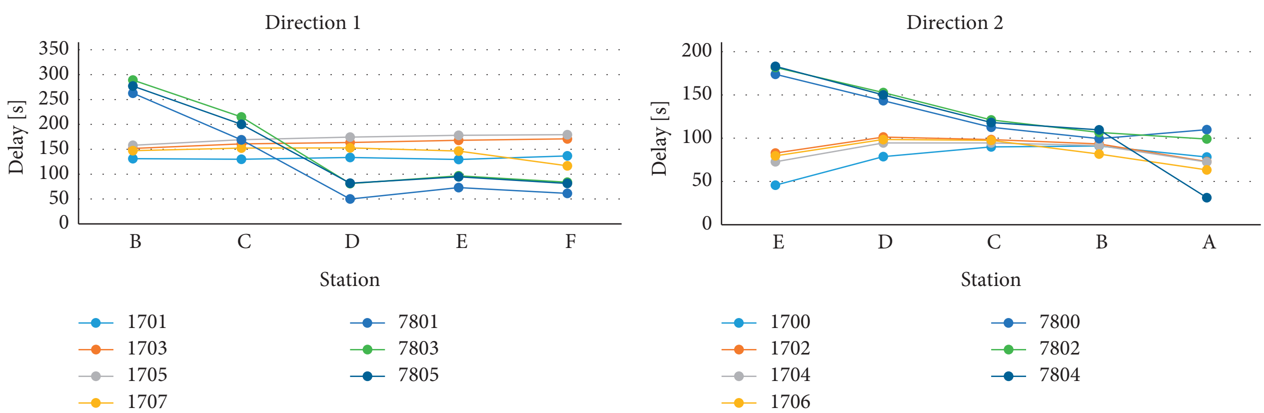


Figure 10: Evolution of average delay on arrival at stations in scenario Sc06.



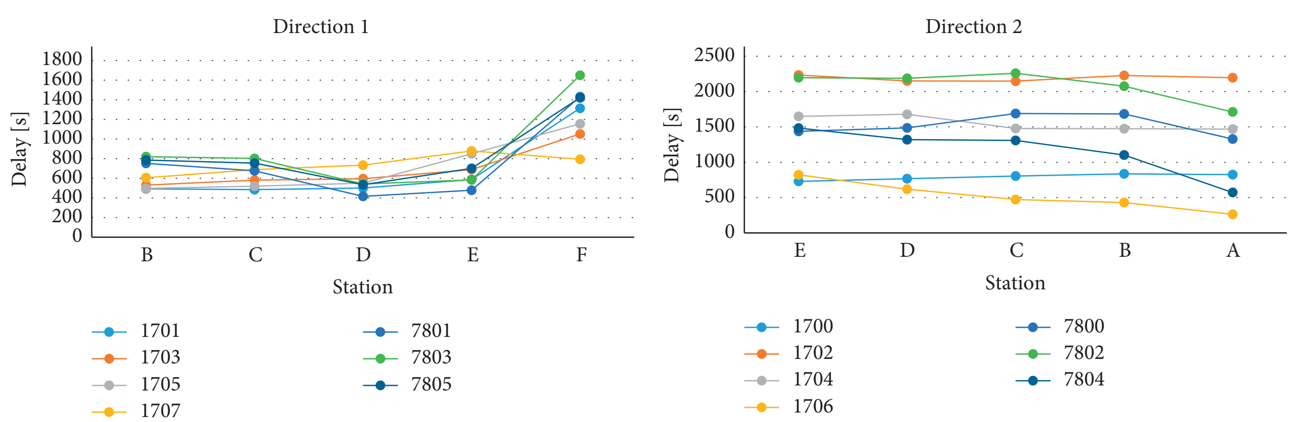
(a) (b)

Figure 11: Evolution of average delay on arrivals at stations in scenario Sc07.



(a) (b)

Figure 12: Evolution of average delay on arrivals at stations in scenario Sc08.



(a) (b)

Figure 13: Evolution of average delay on arrival at individual stations in scenario Sc07-1.

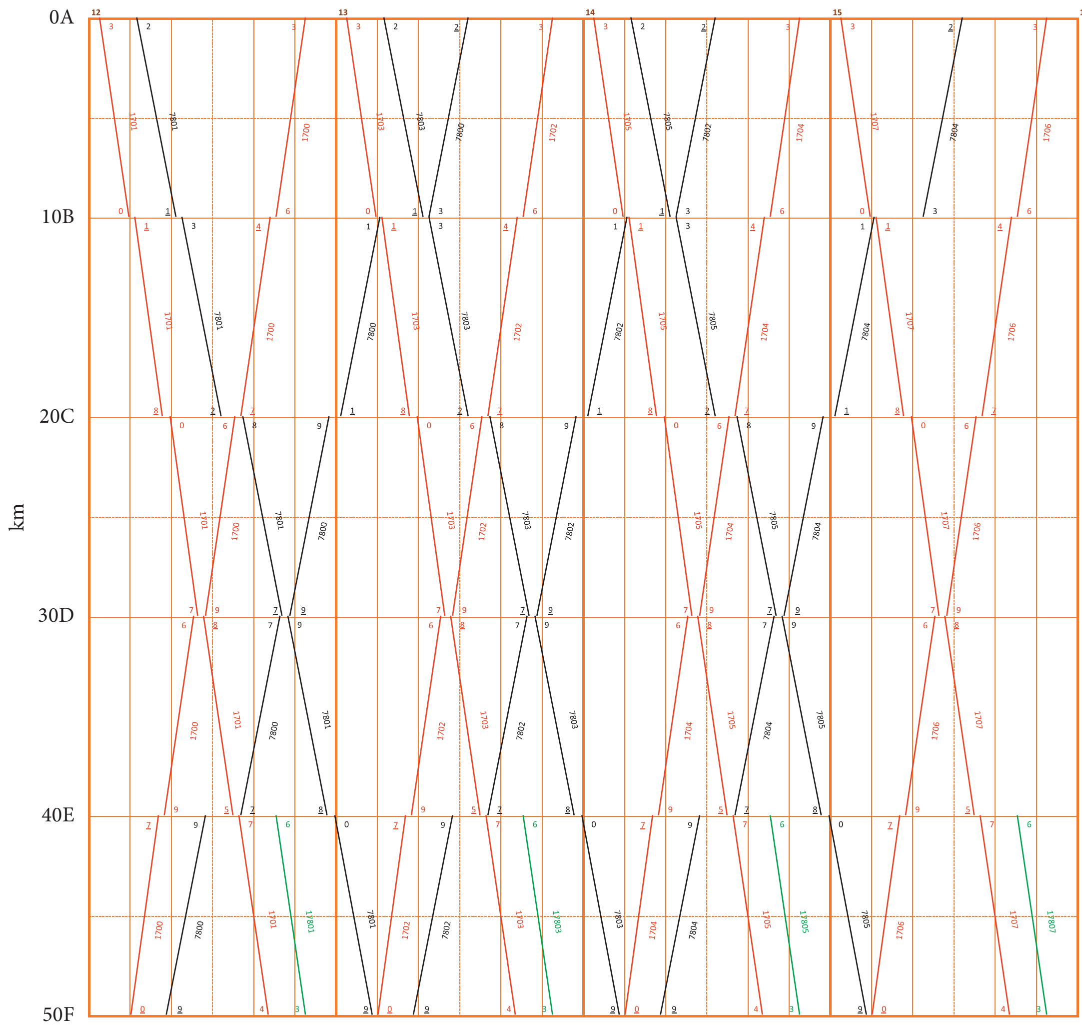


Figure 14: Sc01.

when crossing by moving is possible due to the structure of the timetable and due to a delay.

7.7. Scenario Sc07-1: Assessment of the Influence of Increased Delay. The assumptions are the same as for the scenario Sc07, including the use of the train diagram in Appendix A6. The goal of the scenario Sc07-1 is to simulate an operation with high variability in the timetable (with almost random operation)—mean value of train delay is 12 min. Average delay reached on arrival to stations is shown in Figure 13.

Automatic block in the line sections E-F supports the operation of suburban traffic, but the resulting values of delay increases due to the high volume of traffic. There is a registered decrease of delay values for regional trains in Direction 1 in sections C-D. On the other hand, delay increases for long-distance trains. Therefore, a close relation to the time positions of individual train routes is evident. No substantial impact of automatic block application can be found in Direction 2 in the line sections C-D.

Partial conclusion: automatic block can be helpful, but significant contributions are more related to the opportunity to realize the defined operational concepts (e.g., train fleeting) than to operational reliability in general. Impact of timetable composition is more important.

8. Discussion

8.1. Comparison of Scenarios. From the mutual comparison of the scenarios Sc01, Sc02, Sc03, we can perceive certain connections with the application of the automatic block and automatic line block as basic measures enabling the presence of multiple trains running in the same direction. Not only the link to the timetable has been demonstrated, but also the fact that sometimes unattractive train sojourn times due to

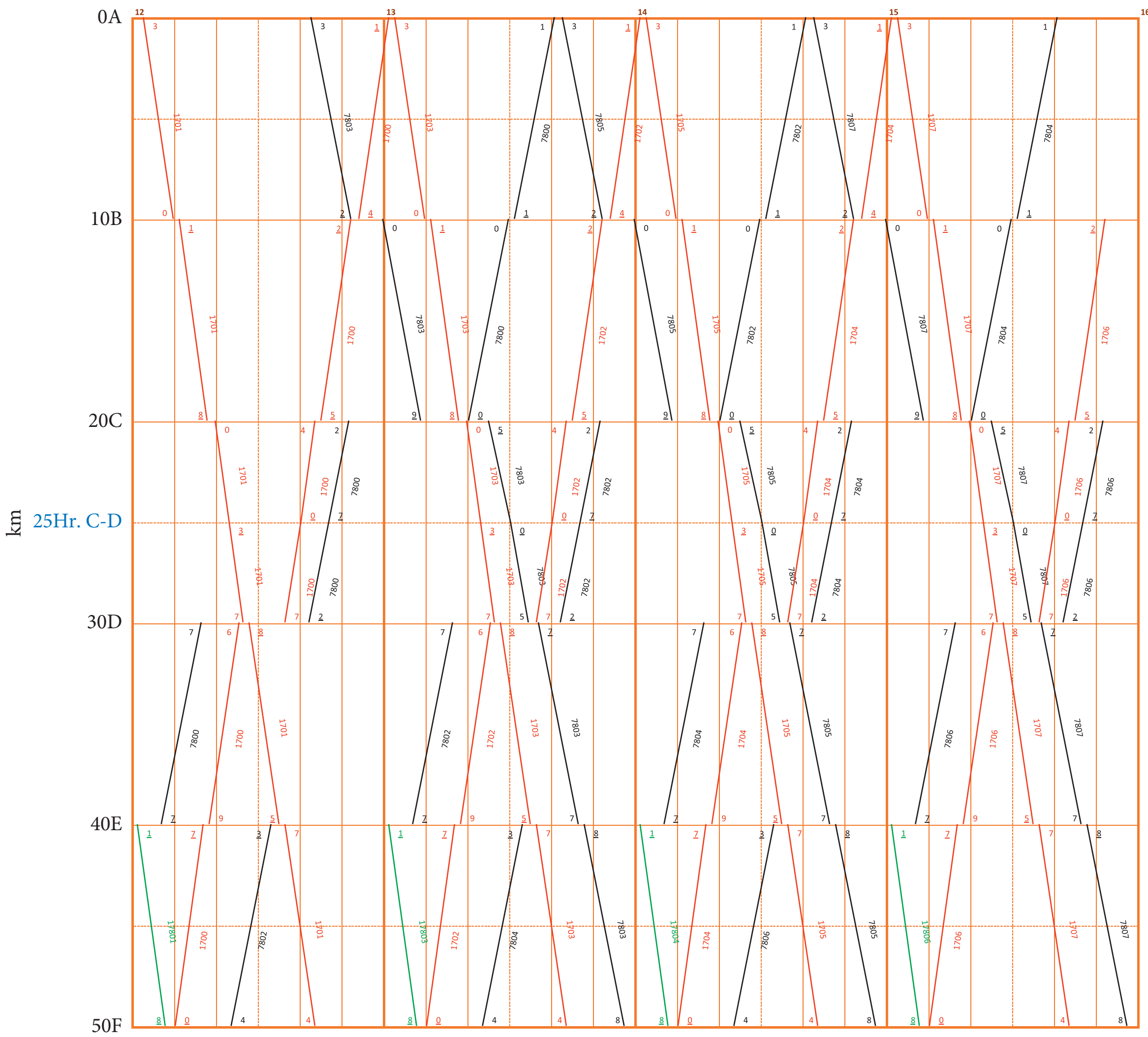


Figure 15: Sc02 and Sc04.

crossing can paradoxically lead to increased timetable stability.

The Sc04 scenario was focused on comparison of the automatic block and automatic line block as a measure against each other. The automatic line block leads to a reduction in the magnitude of the delay (Table 2). The delay was reduced by 10.3–34.0%, but in one case even increased more than threefold. This is because the automatic line block allows to shorten the subsequent headway. On the contrary, however, the case of increased delay again shows the particularistic nature of the solution and the link to the timetable. If a decision must be made on which type of interlocking system allows the presence of more trains in a section should be chosen on a particular line (e.g., due to the difference in investment costs), a more in-depth assessment with a simulation model can only be recommended.

The comparison of the Sc05 and Sc06 scenarios is interesting in terms of the influence of planned fleeting, which is a prerequisite for the effectiveness of such interlocking systems, in this case an automatic line block, where alternating and fleeting modes of train passing are compared. The results show similar delay values for individual trains in Direction 1, while in Direction 2 the delay values are slightly higher in the case of fleeting. On

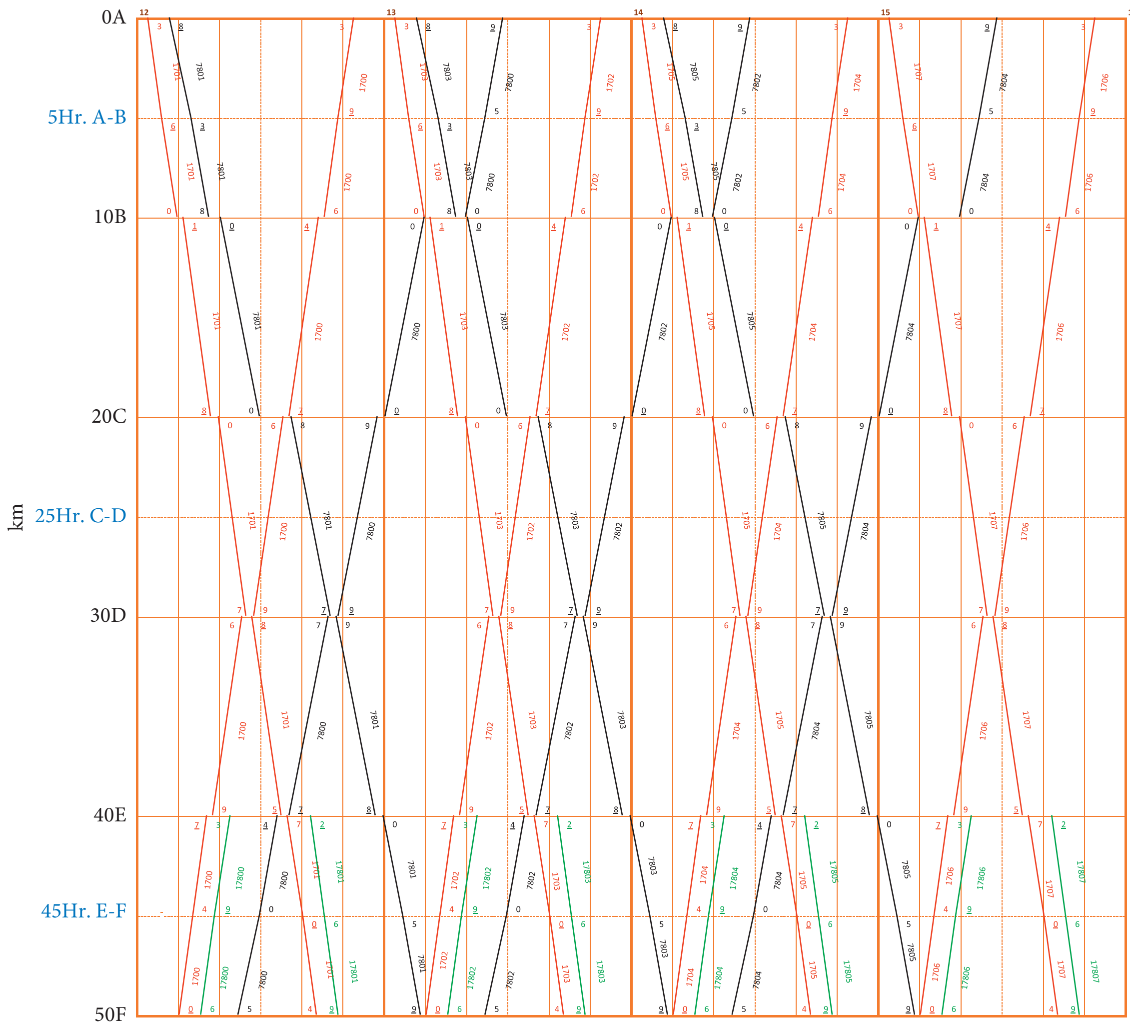


Figure 16: Sc03.

one hand, the increments are about 20 s per train, which does not indicate a very significant problem, but it is fully consistent with the technological interpretation of the issue that fleeted traffic can be expected to be more susceptible to delay increments. It should be noted that in both scenarios the extent of traffic in the C-D section under consideration is increased to almost full occupancy by running the newly added trains only in this section.

When comparing the Sc05 and Sc07 scenarios, where the Sc07 scenario assumes automatic line block in two sections (C-D, E-F), it was found that greater delays are experienced in the Sc07 scenario. However, this is due to the change in train sequence on departure from terminus F. Again, this points to the context of the chosen timetable and practical conditions.

The impact of unstable, but in a way irregular, traffic was monitored by comparing the Sc07 and Sc07-1 scenarios, where mean input delay values of 4 and 12 min, respectively, are applied. The achieved (output) delay values were higher, but the trend of stability was the same—in Direction 1, with a tendency of delay reduction for selected trains in the part of line A–D and instability at station F. While the opposite direction 2 was slightly asymptotically stable in the Sc07 scenario (delay decreased throughout the line), in the Sc07-1 scenario there is also a slight increase in delay for some trains.

From a comparison of the Sc05 and Sc08 scenarios, where the Sc05 scenario assumes an automatic line block in the C-D section and the Sc08 scenario assumes the C-D section as double track and equipped with automatic block, there is no significant difference in terms of the achieved delay values.

The comparison has shown that the benefit of interlocking systems enabling the presence of multiple trains running consecutively on one section of a single-track line must be seen primarily in the context of the applied timetable. Such interlocking system is beneficial in sections where it is necessary to reduce the subsequent interval between trains. This can be recommended, for example, in the first sections after stations that are the hub of an integrated timetable so that a slower regional train can leave earlier to follow a fast train or in the case that there are running trains of two lines of passenger transport (which are

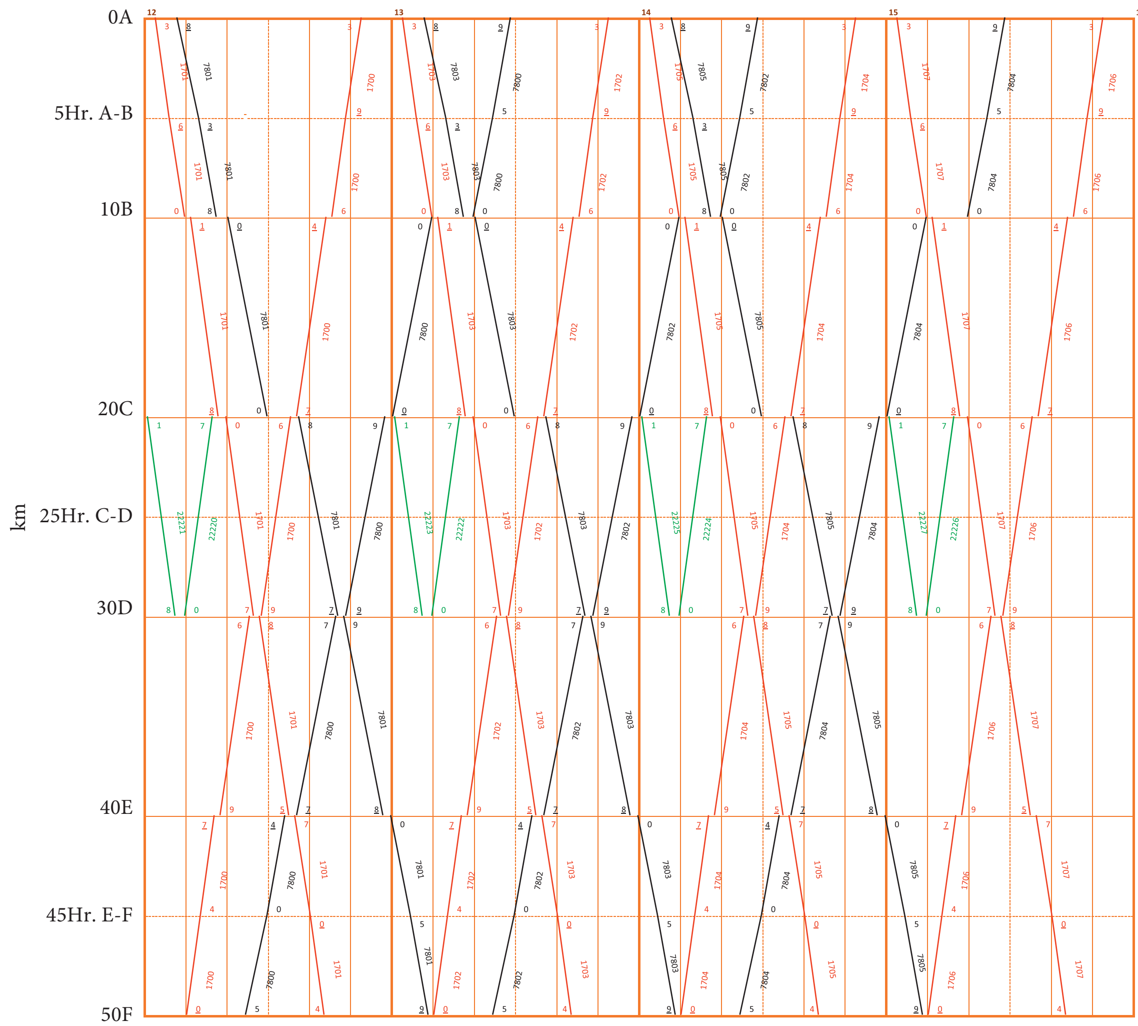


Figure 17: Sc05.

divided in some of the next stations). Naturally, the application should also be considered if the number of trains carried needs to be increased—capacity in the classical quantitative sense. However, it should be pointed out, and the results of the simulation assessments carried out show this, that it is advisable to verify the positive effect in every practical case, at least in the form of timetable design. There may be a problem of trains crossing such a route in other sections of the line and this may require additional support measures.

8.2. General Discussion. Performed simulation experiments presented in the article are atypical. The simulation is not focused on busy lines where it is needed to maximize the number of trains. Simulation was focused on single-track lines where qualitative aspects and individual types of interlocking systems were assessed at first. The main aim is to create a base for recommendation on what type of interlocking systems to install on railway lines with medium or small density of traffic and how to evaluate designed solutions.

The second atypical feature is that the interlocking system is applied only in one of the sections between stations. The issue is whether such an individualized installation can be beneficial or if it is needed to install it in more extended sets (e.g., on the entire railway line).

Generalized recommendation based on individual partial simulation assessments is that the installation of an automatic block (or more advanced line interlocking

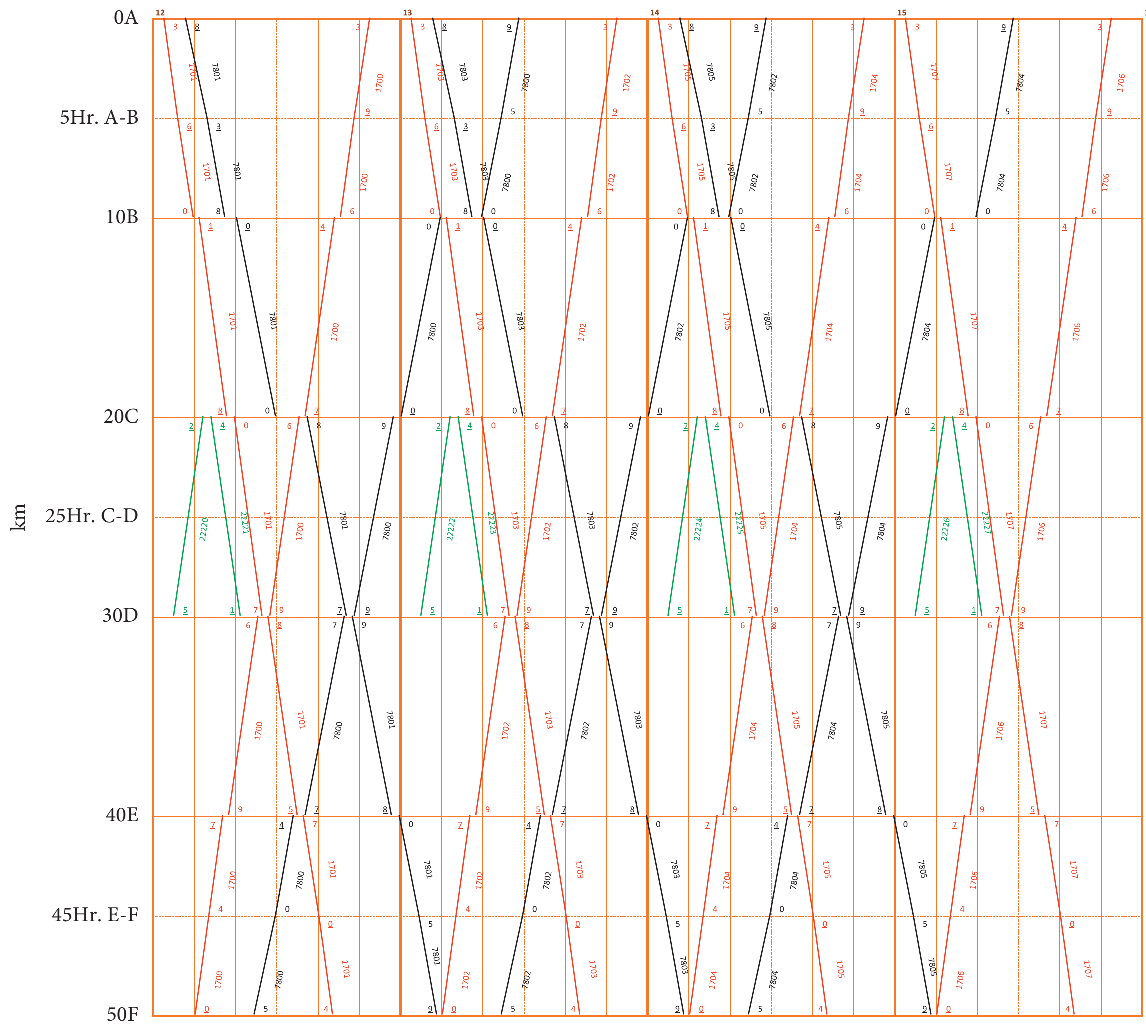


Figure 18: Sc06 and Sc08.

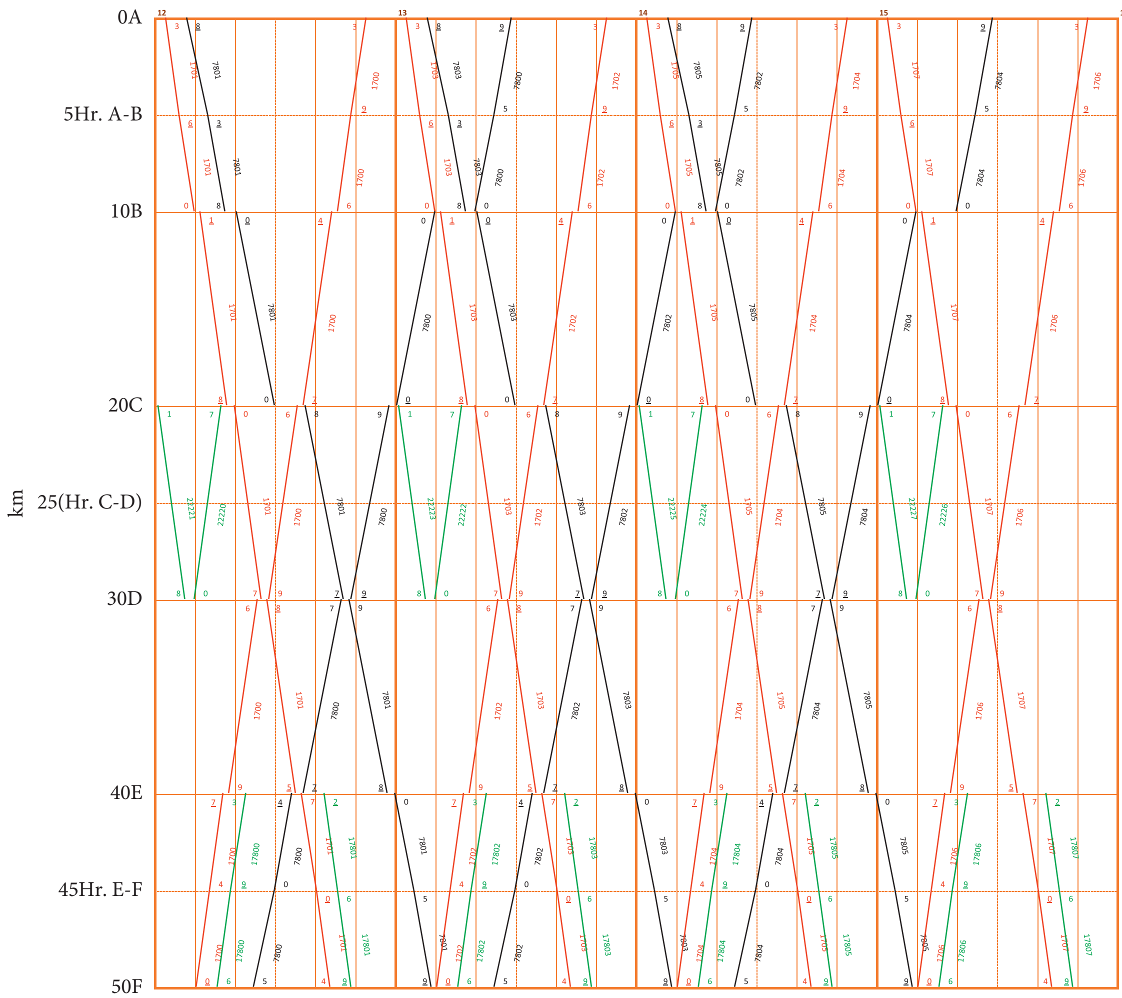


Figure 19: Sc07 and Sc07-1.

system) contributes to stability (quality) only for a small part. Benefit cannot be expected automatically in comparison with stochastic aspects of operation assessed with the simulation model. However, almost all partial assessments have shown that if the measure is linked to a timetable concept that would support the positive effects of the facility, its effectiveness can be increased, even if it is installed only in selected sections. The results and recommendations are that the scope of the infrastructure must be planned together with the operational concept.

Research hypothesis has not been rejected. It was recognized that stochastic simulation can also assess the possible benefits of the selected types of line interlocking system on operational quality and stability on moderately loaded lines. The performed simulation assessments resulted in some recommendations that can be technologically justified and possibly generalized. Naturally, especially in extreme cases, if the expected benefit of the device is ambiguous, it is only possible to recommend the application of a microscopic simulation model focused on the assessed line in specific (and thus more precise) conditions.

9. Conclusions

The research shows that there are several other possibilities and conditions in this area which could be the subject of similar assessments using stochastic simulation to create a comprehensive view of the issue. This provides the possibility of further research in this area and clarification or extension of conclusions.

The research presented in the article confirmed that the issue of capacity of railway lines in the context of quality (stability) of traffic is an interesting topic even in the case of railway lines with a medium level of traffic. The application of microscopic simulation in the OpenTrack tool can be beneficial not only for the assessment of specific railway lines, but also at the theoretical level.

Specific results of the research are mentioned above in the discussion part of the article. In general, the relation between train fleeting and the presence of interlocking system that allows the presence of multiple trains in a single line section was assessed as key aspect. As a result, a recommendation is made to consider the installation of such interlocking systems on single-track line sections where multiple passenger services are operated as a priority. It was confirmed that train delay in simulation should be a qualitative indicator of capacity also in this specific issue, which is the subject of this article. For a comprehensive assessment, it is still recommended to build a specific simulation model containing all local specifics. On the other hand, this research forms the basis for finding ways to use single-track lines in a resilient railway transport system.

Appendix

Timetables for Individual Scenarios

A1: Timetable for the Scenario Sc01—**i**nitial state: trains are organized only between stations. Automatic block (I2) and automatic line block (I3) are not applied at any section (Figures 14–19).

Figure 15: Timetable for the Scenarios Sc02 and Sc04.

Figure 16: Timetable for the Scenario Sc03—automatic block (I2) applied in the border sections A-B and E-F.

Figure 17: Timetable for the Scenario Sc05.

Figure 18: Timetable for the Scenarios Sc06 and Sc08.

Figure 19: Timetable for the Scenarios Sc07 and Sc07-1—automatic block (I2) applied in the border sections A-B and E-F, even-spacing operation in section C-D (also with automatic block).

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This study was supported by the PosiTrans project: ERDF/ESF Cooperation in Applied Research between the University of Pardubice and companies, in the Field of Positioning, Detection and Simulation Technology for Transport Systems (PosiTrans) (CZ.02.1.01/0.0/0.0/17_049/0008394).

References

[1] M. Börjesson and J. Eliasson, "On the use of 'average delay' as a measure of train reliability," *Transportation Research Part A: Policy and Practice*, vol. 45, no. 3, pp. 171–184, 2011.

[2] R. M. P. Goverde, F. Corman, and A. D'Ariano, "Railway line capacity consumption of different railway signalling systems under scheduled and disturbed conditions," *Journal of Rail Transport Planning & Management*, vol. 3, no. 3, pp. 78–94, 2013.

[3] E. Quaglietta, "A simulation-based approach for the optimal design of signalling block layout in railway networks," *Simulation Modelling Practice and Theory*, vol. 46, pp. 4–24, 2013.

[4] M. Rondón and F. Gomide, "Line block analysis in railway dispatch and simulation systems," *IFAC Proceedings Volumes*, vol. 33, no. 9, pp. 389–393, 2000.

[5] H. Pouryousef, P. T. Lautala, and T. White, "Railroad capacity tools and methodologies in the U.S. and Europe," *Journal of Modern Transportation*, vol. 23, no. 1, pp. 30–42, 2015.

[6] M. Abril, F. Barber, L. Ingolotti, M. A. Salido, P. Tormos, and A. Lova, "An assessment of railway capacity," *Transportation Research Part E: Logistics and Transportation Review*, vol. 44, no. 5, pp. 774–806, 2008.

[7] E. R. Petersen and A. J. Taylor, "Design of single-track rail line for high-speed trains," *Transportation Research Part A: General*, vol. 21, no. 1, pp. 47–57, 1987.

[8] A. Nash and D. Huerlimann, "Railroad simulation using OpenTrack," *Comprail*, 2020.

[9] Z. Chen and B. M. Han, "Simulation study based on OpenTrack on carrying capacity in district of Beijing-Shanghai high-speed railway," *Applied Mechanics and Materials*, vol. 505-506, pp. 567–570, 2014.

[10] H. Haramina, A. Schöbel, and M. Bojić, "RačunalnomodeliranjeisimulacijaželjezničkogprometanareláacijiSavskiMarof - DugoSeloprimjenomprogramskogalataOpentrack," *Hrvatskihželjeznica*, vol. 13, no. 2, pp. 17–20, 2014.

[11] S. Harrod, F. Cerreto, and O. A. Nielsen, "OpenTrack simulation model files and output dataset for a Copenhagen suburban railway," *Data in Brief*, vol. 25, Article ID 103952, 2019.

[12] M. Milosavljević, S. Milinković, S. Vesković, I. Branović, and S. Aćimović, "AnalizasistemaBgvozaprimenomsimulacionogpaketaOpenTrack," *YU INFO*, vol. 20, pp. 473–478, 2014.

[13] S. Harrod, "Capacity factors of a mixed speed railway network," *Transportation Research Part E: Logistics and Transportation Review*, vol. 45, no. 5, pp. 830–841, 2009.

[14] L. Mussone and R. W. Calvo, "An analytical approach to calculate the capacity of a railway system," *European Journal of Operational Research*, vol. 228, no. 1, pp. 11–23, 2013.

[15] A. Dicembre and S. Ricci, "Railway traffic on high density urban corridors: capacity, signalling and timetable," *Journal of Rail Transport Planning & Management*, vol. 1, no. 2, pp. 59–68, 2011.

[16] N. Stojadinović, B. Bošković, D. Trifunović, and S. Janković, "Train path congestion management: using hybrid auctions for decentralized railway capacity allocation," *Transportation Research Part A: Policy and Practice*, vol. 129, pp. 123–139, 2019.

[17] J. Široký, P. Šrámek, K. Magdechová, E. Tischer, and P. Hlavsová, "Timetable Performance Evaluation," in *Proceedings of the 23rd International Scientific Conference. Transport Means 2019*, pp. 1427–1432, Lithuania, October 2019.

[18] N. Weik, J. Warg, I. Johansson, M. Bohlin, and N. Nießen, "Extending UIC 406-based capacity analysis - new approaches for railway nodes and network effects," *Journal of Rail Transport Planning & Management*, vol. 15, Article ID 100199, 2020.

[19] P. Šulko, J. Gašparík, and M. Dedík, "Line track capacity – analysis if the implementation of the UIC 406 methodology in ŽSR conditions," *Trans Motauto World*, vol. 3, no. 4, pp. 181–184, 2018.