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Automatic train control systems as a challenge for the capacity in the Czech Republic

Klíčová slova

Kapacita, OpenTrack, simulace, systémy ATC

Keywords

Capacity, OpenTrack, simulation, ATC systems

Anotace

Tento článek vychází z disertační práce prvního autora. Disertační práce se zabývá vlivem zavedení automatického řízení vlaků na kapacitu tratí. To je v současné době, kdy se počátkem roku 2025 chystáme zahájit výhradní provoz systému ETCS, velmi důležité téma. Teoretická část analyzuje systémy automatického řízení vlaků se zaměřením na ETCS. V praktické části jsou simulovány různé úrovně systému ETCS. Tyto simulace vycházely z praktických dat z provozu EMU (Moravia) v Jihomoravském kraji. V závěru je úvaha, zda má ETCS pozitivní nebo negativní vliv na kapacitu.

Abstract

This article is based on the dissertation thesis of the first author. This dissertation thesis focuses on the impact of the implementation of automatic train control systems on the capacity of lines. This is very important now, as we start with the exclusive operation of the ETCS early in 2025. The theoretical part analyses automatic train control systems focusing on ETCS. In the practical part, different levels of the ETCS system are simulated. These simulations were based on valuable data from the operation of EMU (Moravia) in the South Moravia Region. The conclusion considers whether the ETCS positively or negatively impacts the capacity.

Introduction

Suppose we want to analyse and evaluate the impact of the implementation of automatic train control systems on the capacity of railway lines. In that case, we need to do deep research on all functions and operational rules that are valid for the Czech railway manager. This is one of the key research tasks in railway infrastructure capacity research. However, the impact of implementing these systems on the line capacity hasn't yet been satisfactorily described and comprehensively evaluated by the research work produced so far. Therefore, the research team and the primary author prepared the dissertation thesis by focusing on an overview of the automated train

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control systems, the automated train guidance systems, and the analytical and simulation methods used to determine line capacity.

Based on the analysis, the goal was to design a simulation model for train operation under the supervision of automatic train control systems. Using the results of this model, the degree of influence of this system's implementation on the lines' capacity is sought. The application part of the research is a three-level simulation model for train operation in different modes of automatic train control systems. Based on this analysis, specific conclusions are drawn to determine the impact of automatic train control systems on the capacity of railway lines. A case study supported the confirmation of the results, which is coupled.

1. State of the art

Analysis of the current state of scientific knowledge can be divided into three main parts: Analysis of the current state of development of automatic train control systems, Current state in the use of simulation tools and Analysis of the current state of scientific knowledge. Here, a deep literature review has been conducted.

Analysis of the state of the development of automatic train control systems – automatic train control systems significantly impact the train journey. The study shows that there are two dominant systems in the world, ERTMS and CBTC, each primarily targeting a different subsystem of the rail transport system. The ERTMS has been developed mainly for main and high-speed lines. The CBTC systems, on the other hand, are aimed at urban and suburban lines. However, from the point of view of traffic operation, it is advantageous to link these two systems. In principle, it would be an ETCS L2-based CBTC system for operation in fixed blocks and an ETCS L3-based CBTC system for operation in moving blocks. Based on the analysis results, the further focus is on the ERTMS (ETCS L2 and ETCS L3) in the proposal part of the article.

Analysis of the state of the art in using simulation tools – the study shows many usable simulation tools. The essential condition for selecting a simulation tool is the possibility of implementing an ATC system in the model. During the research, the authors selected a simulation tool that allows the simulation of ETCS (or CBTC). Regarding simulation details, the authors decided to use a microsimulation tool. From the results of the analysis carried out, the tools Villon [1], RailSys [2], PULsim [3], INCONTROL [4] and OpenTrack [5,6] seem to be suitable. For this research, OpenTrack software was finally chosen. This tool meets the criteria for implementing the ATC system in the model and the required details of the simulation model. At the same time, this SW is available in the Department of Transport Technology and Control laboratory.

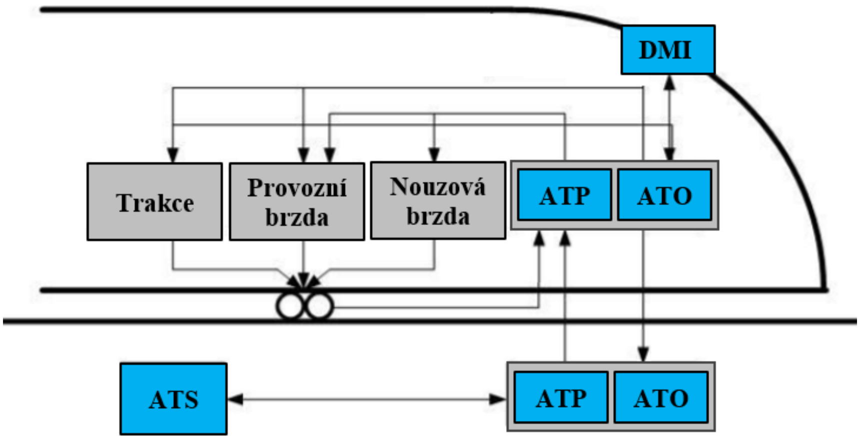

Figure 1 – Basic structure of the ATC system

The summary of the analysis of the state of the art is divided into three parts. The first part refers to analysing regulations and standards that deal with capacity. The essential documents that are relevant are:

- UIC Code 406 [7,8],
- Směrnice SŽDC SM 124 [9],
- Směrnice SŽDC č. 104 [10].

The second part deals with the search for scientific papers and articles related to the topic. A significant contribution of this analysis was the development of an overview of the approaches and methods used to address the research objective. The third part deals with the overall summary of the analysis. It was found that approximately 65% of the studies dealing with capacity use simulation or combined methods [11]. The simulation tools used are OpenTrack (Switzerland), MultiRail (United States), RAILSIM (United States), SIMONE (Netherlands), RailSys (Germany), DEMIURGE (France), RAILCAP (Belgium) and CMS (United Kingdom). In the analysis, the author needed to find sufficiently informative publications dealing with the topic in the conditions of the Czech and Slovak Republics. This confirms the correctness of the chosen aim of the thesis.

2. Research methods

System decomposition – is a task of system analysis in which the decomposition of the system into sub-systems is solved. The decomposition is performed according to predefined aspects. Topological, functional, factual, and hierarchical decomposition can be distinguished by subdivision. The essential prerequisite for successfully constructing a model is the decomposition of the system. The decomposition of the simulation model is based on the knowledge obtained from the analysis of the regulations and standards used to solve the capacity of the lines. The system decomposition method is used in this thesis to identify the critical elements of the systems from which the simulation model will be constructed, and which may influence the capacity of railway lines. These fundamental elements are the starting point for the selective approximation of the developed model. This approximation is necessary for a practical model fitting, which allows the inclusion of only elements that impact the evaluated indicators [12].

Transport systems modelling – is a research technique that, in principle, replaces the actual system with the system model. Depending on the details of the model, the input characteristics are approximated to the desired level of detail [13,14]. This model is built at the microscopic level. The construction of the simulation model takes place in four phases: inputting infrastructure parameters, inputting path parameters, inputting vehicle parameters, and inputting timetable parameters. A short overview of the different phases of model preparation is given in the following figure.

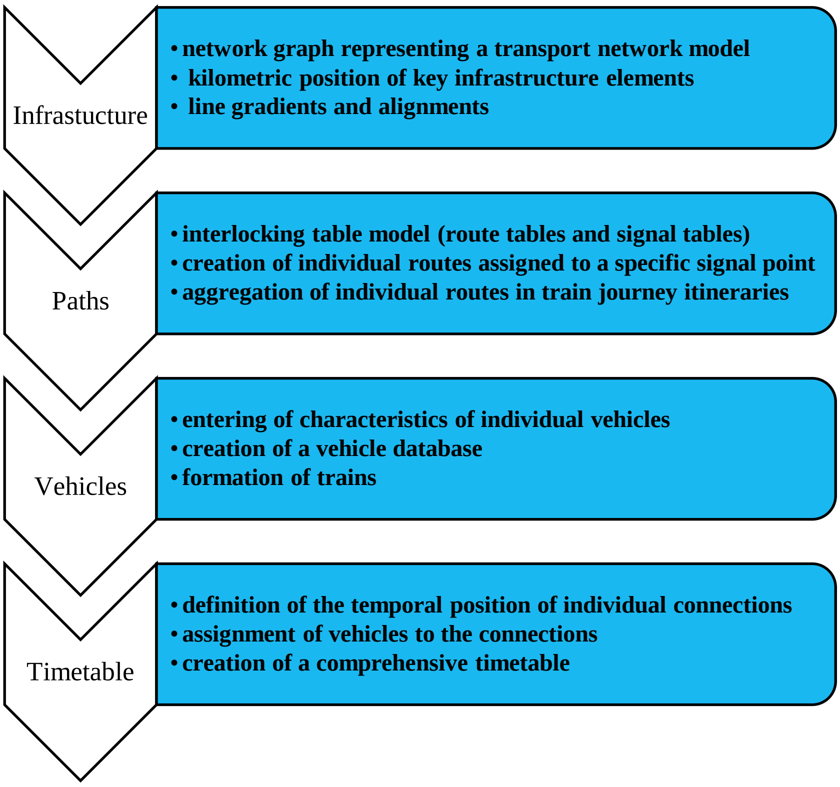

Figure 2 – Schematic representation of the different stages of simulation model preparation

Computer simulation is a research method with a simulation model representing a selected system's performance. The model validation check is done in three steps, which are referred to as model verification, calibration, and validation. Simulation techniques are the best tool for observing the performance of a natural system. The simulation model and simulation are the core parts. All simulation scenarios are detailed, and the proposed parameters are evaluated.

Statistical analysis is a discipline that deals with the acquisition, processing, and analysis of data for decision-making in systems. It investigates the state and evolution of mass phenomena and the development of relationships between them by making mass observations. Its use is appropriate in multiple repetitions of experiments and data evaluation. Statistical analysis can be used to examine the probability of different operational scenarios. The authors used probability theory, random variables, and regression analysis in this research. The statistical analysis methods are used to support the processing of simulation scenarios and to determine the effect of changing input parameters on the outputs. For the random variable, this mainly involves determining the values of the input delay at the input to the model. However, this method can also cause delays in the model during the simulation. Regression analysis compares the change in each input's values to the simulation model's output values [15].

3. Simulation model design

At the same time, a simulation model for the applied part of this research is formulated. The model is further developed, and the simulation results are continuously evaluated. In the final section, the results are generalised, and specific conclusions in the defined area of research are established. Previous department research [21-24] was tight with the ATC problems. There were included topics like the modelling of automatic metro operation, modelling of railway operation on a closed loop line, modelling of operation on a line with a simplified railway interlocking system, technical possibilities of increasing the capacity of the intermediate section on a monorail line, dependence of the increase in traction energy consumption on the rise in line speed and simulation of ATC systems operation.

Three-level simulation model – it is designed to research the capacity of railway infrastructure from multiple perspectives. Each of the three levels of this simulation model has further sublevels (variants), which are defined based on several types (levels) of ATC track equipment. The model is divided into the following three levels: main line (track) - first level (T), station head – second level (S) and combined operation - third level (K). A schematic of the three-level simulation model is shown in the following figure 3.

The conditions for preparation of the simulation model – the primary conditions are defined by UIC code 406 [7], Směrnice SŽDC SM 124 [9] and Směrnice SŽDC č. 104 [10]. Other standards and regulations that are important to respect for the correct creation of the simulation model are SŽ Z8 Part IV European Train Control [16], SŽ TSI CCS/MP1 Methodological Guideline Principles for the design of the ERTMS track-side part for lines with the exclusive operation of European Train Control [17], selected technical specifications for the design and operation of ETCS, SŽ SM069 - Guidelines for Timetable Development and Allocation and Use of Track Capacity [18], SŽ D1 PART ONE [19] and SŽDC S3 Railway Structure Part IX Switches and Switch Structures [20].

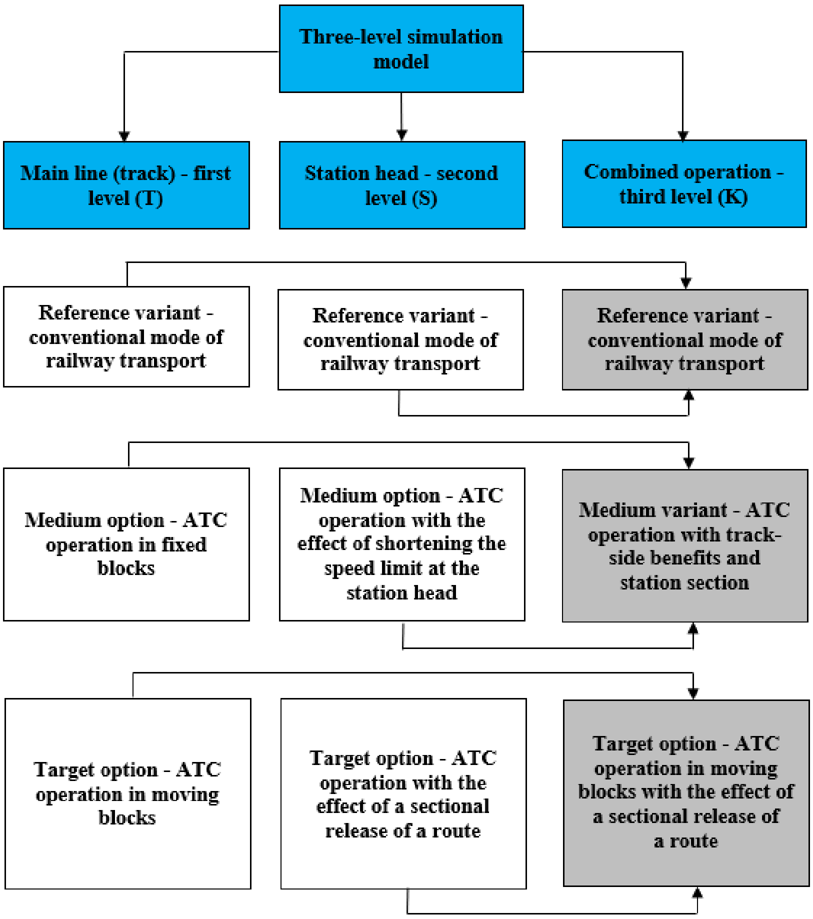

Figure 3 – Three-level simulation model

Modelling speed braking curves is one of the essential tasks in preparing traffic simulations in OpenTrack software. The braking curves for operation without ETCS are based on the "UIC model". From the point of view of ETCS braking curve modelling, the most critical curves for the calculation are the service braking curve - Service brake deceleration (SBD) and the emergency braking curve - Emergency brake deceleration (EBD). From them, the curve - Indication (I) is derived and used in the model as the curve for service braking. EraTool, the official tool for generating braking curves, models the ETCS braking curves. All considered trainsets were modelled as alpha trains. Figure 4 compares the distance required to stop for the braking curves modelled according to the UIC model and for the braking curves modelled by EraTool.

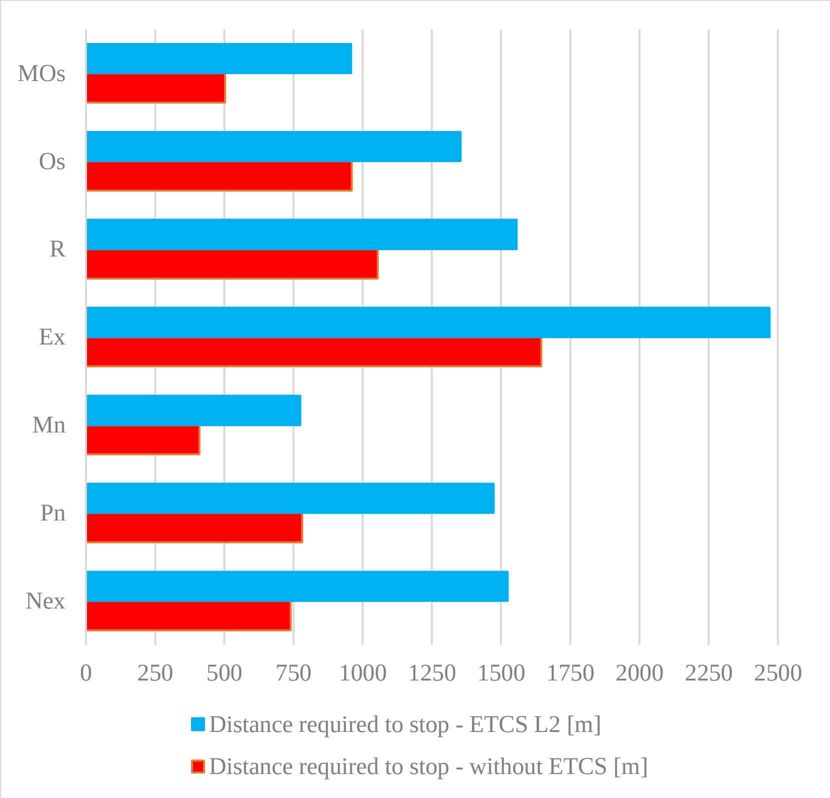

Figure 4 – Braking curve comparison

This section describes the simulation process for each part of the three-level simulation model for each level.

The main line (track) simulation – first level (T) – is performed on a 10 km long test track. To evaluate the results of the simulation of the main line, the method of comparing the size of successive intermediate periods according to the sequence of individual trains is used. The integrated tool of OpenTrack software called Headway Calculator determines the headway. This tool tests, using a multiple simulation, the values of the headway. The half-interval method is then used to determine the resulting value. To confirm the correctness of the calculation of headway, 2,352 replications were performed. Thus, each pair of trains was tested several times on each line model created with the corresponding size of the fixed block.

Station head simulation – second level (S) – the simulation model created for this level is built to observe the effect of the station head configuration and the type of ATC system used during the headway period. The station head length is determined for each of the four simulated variants. The design speed of the turnouts determines the station's head length. The distance of the entrance signals of the fictive station is always 5 km. A total of 4 station head variants were tested, representing speed groups of 40, 60, 80 and 100 $km{\cdot}h^{-1}$ at the train speed to the turn. As in the simulation of the main line (track) - first level (T), the integrated tool of the OpenTrack SW – Headway Calculator is used to provide the values of the headways. A total of 7,056 replications were performed in this level of the model. Each train pair was tested on 12 prepared infrastructure models.

The combined operation – third level (K) – is a model of a complete infrastructure network, which methodologically follows the two previous levels of the three-level simulation model. A model of a single-track line with a total length of 34.6 km was built.

There are four stations on the line, each with four traffic tracks. The stations are labelled Station A, Station B, Station C, and Station D. The intermediate lines are always 5 km long. The station tracks have a consistent length of 800 m. The size of the station head, the station head, and the speed of the switches to the branch line respect the distribution from the second level of the model (S). In contrast to the previous simulation level, a test timetable had to be constructed for this level. The delay increment method was chosen to evaluate the combined simulation. The delay increment is the difference between the input and output delay.

Simulation evaluation and conclusions – this section evaluates the results of each level of the three-level simulation model.

Evaluation simulation main line (track) - first level (T) – the first output of the model is the determination of the total average headway value for the reference variant, which is 122 s. This corresponds to the average headway value for block sections of 0.5 km using ETCS level L2. The second output is an illustrative assessment of the effect of the type of signalling equipment used and the length of the fixed block (using ETCS L2) or the use of a moving block (using ETCS L3). The results obtained are shown in Figure 5.

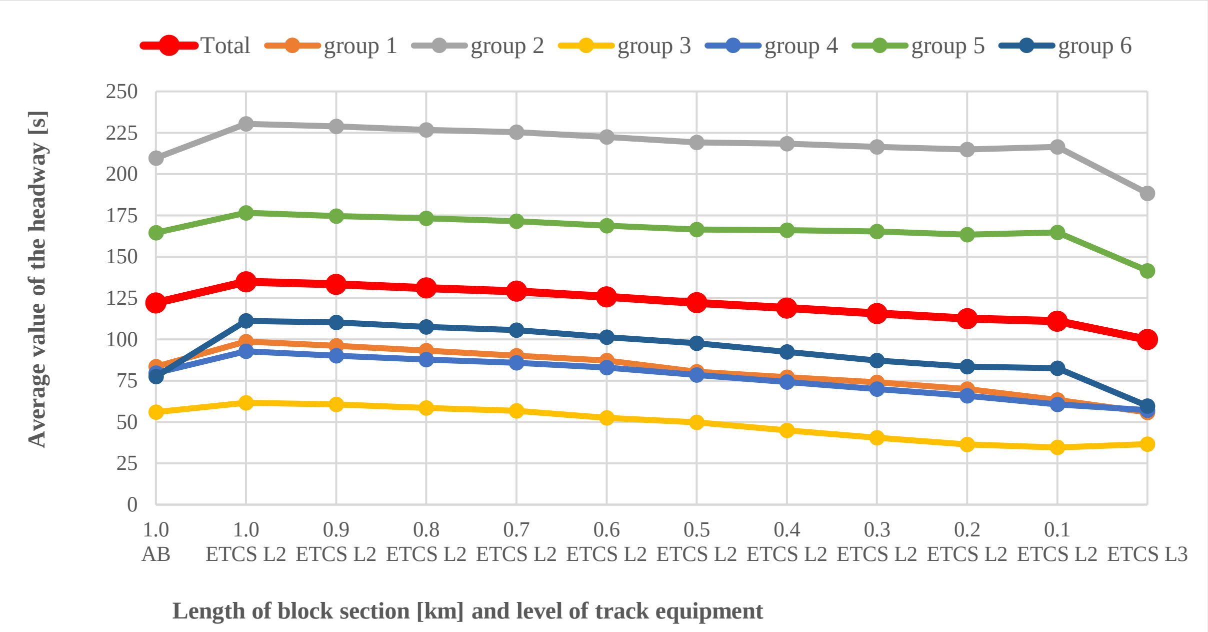

Figure 5 – Headway on different block section lengths

Evaluation of the station head simulation – second level (S) – this variant aimed to assess the behaviour of the simulation model when simulating different types of station heads. A significant output of this level of simulation is the finding that, in terms of total measured values, the deployment of ETCS L2 with benefits (at a fixed block size of 0.5 km) results in an improvement in the values of the headway period for all train groups. In total, by 6% for ETCS L2 and 21% for ETCS L3 when operating in moving blocks. It can also be considered significant that the most remarkable improvement in the values of the headway period when switching from conventional operation occurs at station headways where the switches are run in the diverging direction at lower speeds (40 km·h^{-1}; 60 km·h^{-1}). Conversely, these values may deteriorate as the speed of the turnouts increases in the diverging direction (80 km·h^{-1}; 100 km·h^{-1}). A comparison of the values achieved in the headway periods is shown in Figure 6.

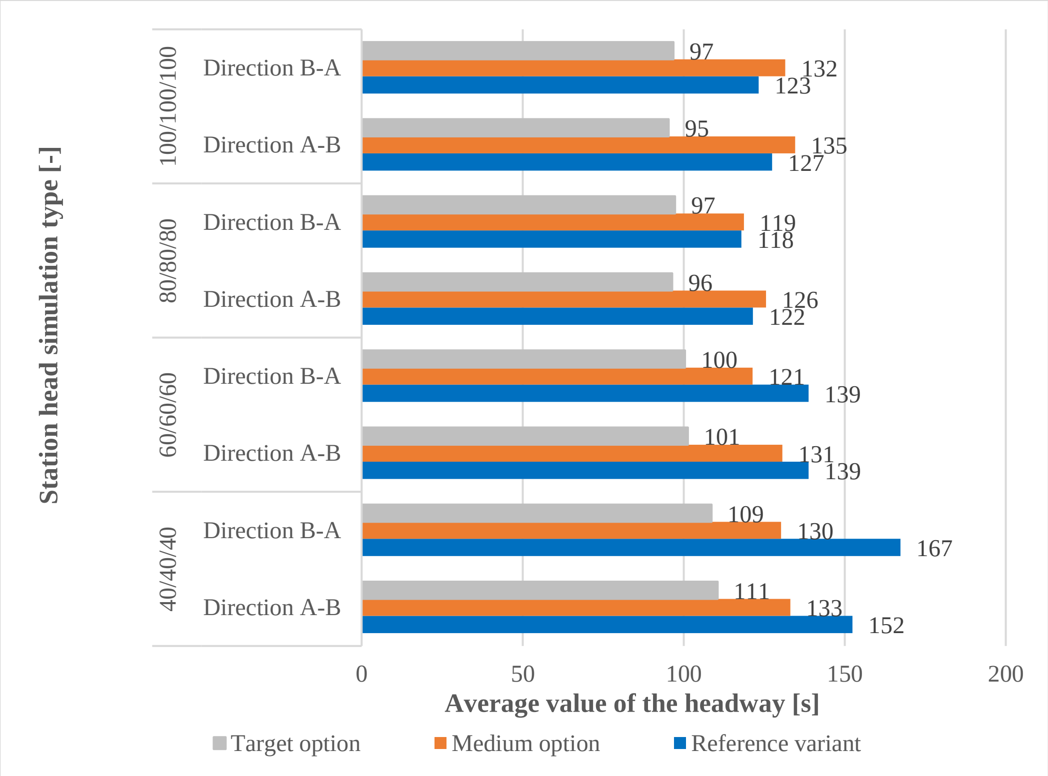

Figure 6 – Average results for each variant

Evaluation of the combined operation – third level (K) - In this section, the results of the test values and the total output delay for each simulation variant are presented. The results show that all levels of the simulation achieve overall negative values for the incremental delay, demonstrating the ability of the timetable to cope with the delays incurred. In the reference variant, the total delay increment is -3,081 s, while the transition variant achieves slightly worse values, with a total delay increment of -2,169 s. The best delay increment values in the target option are achieved at -3,247 s. The following table shows the results converted to average delay increment values by category (according to [9]). The results of the individual simulation groups are coloured yellow for the risky level of traffic quality and green for the optimal traffic quality.

	Value of the average delay increment [min]			
	Long-distance passenger transport	Regional passenger transport	Freight transport	**Total**
reference variant	0.027	-0.016	-0.139	**-0.043**
medium option	0.024	-0.015	-0.122	**-0.038**
target option	0.038	-0.033	-0.137	**-0.044**

Table 1 – Average delay increment values by train category

The delay simulation did not show a significant negative effect of the change of the train protection device on the delay increment; in the case of the transition variant, the value deteriorated by 12%; in the case of the target option, the value improved by 3%.

4. Case study

An essential condition to verify the validity of the proposed method is to test the simulation model on actual infrastructure. For this purpose, line No. 326A was selected, according to the track ratio tables (TTP), in the section Brno-Maloměřice (outside) - Rájec-Jestřebí (inclusive). In this section, there are a total of four transport stations: junction Svitava, station Adamov, station Blansko and station Rájec-Jestřebí. The method of operation is not yet in line with exclusive ETCS operation. As part of the verification operation, trainsets are deployed in ETCS L2 mode. The line is operated until 1.1.2025 in a mode with additional operational measures. Regarding the trainsets used, the author decided to use practical knowledge from the test operation of the new units No. 530 and No. 550 marked MORAVIA (in 2024, they are operated by České dráhy, a. s.). Simulations and practical measurements in the field were also carried out on the 530 unit.

Conducting field measurements – the field research was divided into two parts. In the first part, observations were made at the driver's station; in the second part, it was necessary to obtain some input materials about the signalling equipment that could not be obtained in digital form. The author was present at the driver's station during all test runs. For the detailed development of the infrastructure model, data on station, train, and track-side signalling equipment was also necessary. The complete final tables are stored directly at the station or the relevant professional administration of the railway operator. To make the simulation as close to the actual infrastructure, the author verified the construction of potential paths and fixed elements on the simulations of individual unified control places.

Comparison of achieved journey times – the actual simulation was carried out on a simulation model, where itineraries correspond precisely to the real journey of trains Os 4732, 4746, 4741 and 4757. The initial simulation results were compared with the timetable, and then the model was calibrated so that the achieved journey times corresponded to the established timetable. Corresponding values were achieved by setting the maximum available power utilisation and maximum speed to 95% and 98% in the case of train delay in the simulation. Subsequently, the individual train routes were re-simulated.

The results of the comparison of journey times confirm that, in terms of compliance with the timetable, a risky phenomenon is compliance with journey times when the train stops at the stop Babice nad Svitavou. In other cases, the journey times were always observed, while the total deviation of the journey times determined by the simulation from the journey times set by the timetable is 12.6% for train Os 4732, 14.4% for train Os 4746 and 14.1% for trains Os 4741 and 4757. The total deviation of journey times is 13.8%. Since the deviation of journey times, except for the section ŽST Blansko – Blansko město stop, does not exceed 0.5 minutes, the results of the simulation model can be considered valid.

In all cases, the simulation results and the recording of the actual train run confirm the validity of the values obtained by the simulation. The overall deviation of the journey times from the actual train journeys from the journey times determined by simulation is 11.3% for train Os 4732, 9.2% for train Os 4746, 9.5% for train Os 4741 and 12.6% for train Os 4757. The total variation in journey times is 10.6%. This deviation may be due to the individual driving control of the train by the driver. In addition, the ATO system was used to guide the train on the run of train Os 4757. In both cases, neither the driver nor the ATO system is making maximum use of the unit's power or the braking curve limits.

Comparison of tachographs of simulation and real train running – it is evident from the tachographs that in real train running when the driver controls braking, the curve of the actual train running does not copy the curve generated by the simulation model in the initial braking phase. This is mainly because the driver does not follow the limit (identical to the Indication curve) displayed on the DMI. In addition, a deviation at the stopping point is visible. This is mainly due to the driver stopping at the usual stopping point, whereas the simulation model assumes a stop before the platform end level. The following figure shows the track tachograph junction Svitava – railway station Adamov.

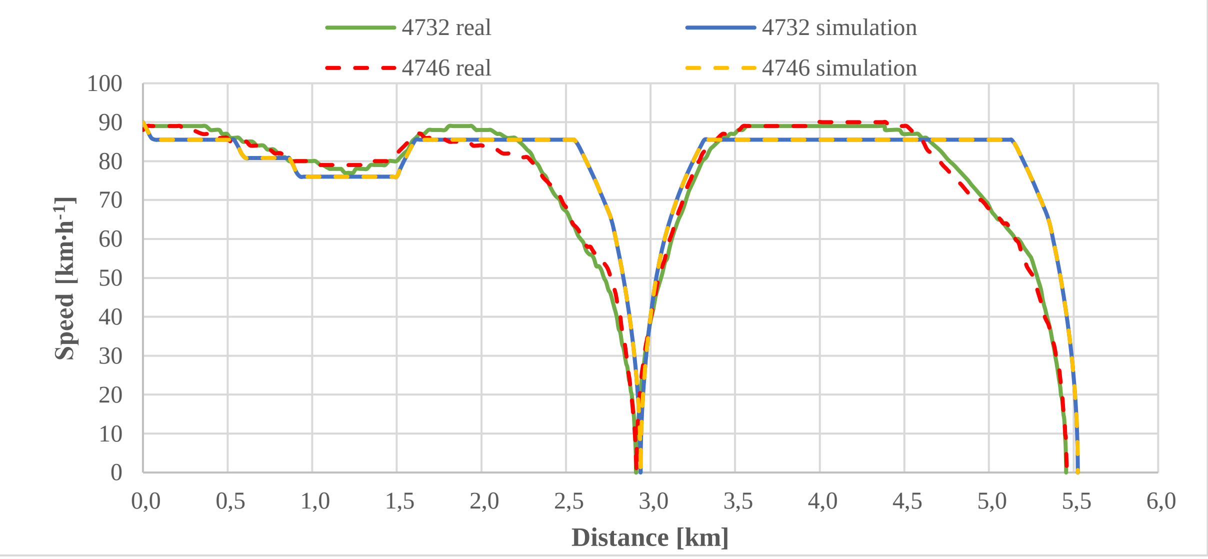

Figure 7 – Tachograph from the case study

The simulation results were compared with the results of actual measurements in terms of achieved travel times. It was confirmed that the maximum deviation of the achieved journey times for individual test runs ranged between 9-15%. Furthermore, the driving behaviour on individual tachographs was investigated, where it was possible to observe the deviation of the actual train running from the simulation. In this comparison, it was found that the driver needs to make maximum use of the limits of the braking curves in his driving, and especially at the start of braking, there is a noticeable deviation from the simulation. The applicable maximum power and maximum speed level were tested by repeating the simulations and comparing them with the already established timetable.

Conclusion

Based on the dissertation thesis [25], this article deals extensively with the operation of automatic train control systems. The author has described a comprehensive theoretical introduction to automatic train control systems. Based on the analysis, he also decided to continue the research on the impact of the introduction of ERTMS on line capacity. This was a logical step, as the introduction of ERTMS is currently a very topical issue in the Czech Republic. The authors decided to use simulation modelling of traffic at the microscopic level to accomplish the research.

The authors proposed the simulation model to verify the influence of track capacity on the deployment of automatic train control means by simulation. Based on a set of experiments, the authors have successively developed a three-level simulation model that can be used to assess the natural effect of these systems comprehensively. Based on the evaluation of the results of the three-level simulation, it was possible to draw concrete conclusions that describe the impact of the implementation of automatic train running control systems on the capacity of the railway lines.

During the research, the complexity of the whole problem became apparent, and it was necessary to focus further research on some areas, as others could no longer be covered. This includes, for example, the simulation of the impact of automatic train control and CBTC systems on railway line capacity, as well as the simulation assessment of the suitability of each system according to the type of operation of the railway infrastructure. Another crucial scientific issue is the design of a system that combines the advantages of all the systems applied so far in automatic train control. Efficient management of traction energy is also an essential aspect of automation, where the train runs interact with each other as part of the optimisation process. It is, therefore, necessary to describe the impact of such systems on railway line capacity in the future. The automation of traffic management and how the infrastructure is operated also affects line capacity, and it is desirable to describe the impact of the introduction of such modifications on line capacity in this area as well. The above topics can be investigated as part of the follow-up scientific work in the training facility.

This article proposes one of the possible approaches to assess the capacity of a given part of the railway infrastructure. The stated objective of the thesis, i.e. the design of a simulation model for train operation under the supervision of automatic train control systems, has been fully met. Based on a detailed analysis of the current state of scientific knowledge and the author's research, a three-level simulation model for capacity assessment of railway lines equipped with ETCS at L2 and L3 levels was developed.

The three-level simulation model allows for assessing the influence of automatic train control systems at three levels. In the first level, the simulation main line (track) - first level (T) is assessed separately, where it was crucial to determine the influence of the length of the created fixed blocks on the size of the subsequent gap in the given section, followed by the impact of the ETCS L3 deployment and the operation in moving blocks partitions. At the next level, station heads are considered. In the third level, the simulation is performed on a complex railway line model in which ETCS deployment's impact on timetable adherence quality is studied. The three-level simulation model found that, when considering a wide line, a shortening of the fixed blocks to a length of 0.5 km is required to obtain equivalent values of the headway time when changing the line protection from the automatic block to ETCS L2. An overall summary of the change in the specified parameters is given in the following table.

Level of simulation model	**ETCS L2 Indicator value change [%]**	**ETCS L3 Indicator value change [%]**
Mainline (track) - first level (T)	0	18
Station head – second level (S)	6	21
Combined operation – third level (K)	-12	3

Table 2 – Simulation results

The author concluded that using ETCS can positively impact railway line capacity if the potential of ETCS L2 with benefits is exploited and equipment modifications are implemented to allow operation in shortened block compartments.

Acknowledgement

The work was supported as part of the sustainability of the project "Cooperation in Applied Research between the University of Pardubice and companies in the Field of Positioning, Detection, and Simulation Technology for Transport Systems (PosiTrans)" (No. CZ.02.1.01/0.0/0.0/17 049/0008394) supported by ERDF.

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