University of Pardubice
Faculty of Transport Engineering

Implementation of automatic train control systems and their influence on the capacity of railway lines.

DOCTORAL THESIS STATEMENT

2024 Ing. Erik Tischer

Annotation

The dissertation focuses on the impact of the implementation of automatic train control systems on the capacity of lines. The theoretical part of the thesis analyses automatic train control systems with a focus on ETCS and its applications. In the practical part of the thesis the simulation of the different levels of the ETCS system is performed. For this simulation a three-level simulation model is used to evaluate the effect of the introduction of these systems on the capacity of the lines.

Keywords

Simulation, capacity, automatic train control, OpenTrack

Title

Implementation of automatic train control systems and their influence on the capacity of railway lines.

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CONTENT

INTRODUCTION AND AIM OF THE DISSERTATION

The analysis and evaluation of the impact of the implementation of automatic train control systems on the capacity of railway lines is one of the key research tasks in the field of railway infrastructure capacity research. However, the impact of the implementation of these systems on line capacity has not been satisfactorily described and comprehensively evaluated by the research work produced so far. This dissertation provides an overview of the automated train control systems in use, the automated train guidance systems and the analytical and simulation methods used to determine line capacity.

Based on the analysis, the aim of the dissertation would be defined. **The aim of the dissertation is 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 the implementation of this system on the capacity of the lines is sought.**

The main part of the applied part of the thesis is a three-level simulation model for train operation in different modes of automatic train control system. The outputs of the simulation model are thoroughly analyzed and described in the dissertation. On the basis of this analysis, specific conclusions are drawn to determine the impact of automatic train control systems on the capacity of railway lines. To confirm the results obtained, the thesis is further supplemented by a case study.

1 ANALYSIS OF THE STATE OF SCIENTIFIC KNOWLEDGE

Analysis of the current state of scientific knowledge is divided into three main parts, namely 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 (literature research).

Analysis of the state of the development of automatic train control systems – automatic train control systems have a significant impact on the train journey. The analysis shows that there are two dominant systems in the world, ERTMS and CBTC, each primarily targeting a different subsystem of the rail transport system. ERTMS has been developed primarily 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 the 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 results of the analysis, the author decided to focus on the ERTMS (ETCS L2 and ETCS L3) in the proposal part of the thesis.

Analysis of the state of the art in the use of simulation tools – the analysis shows that there is a large number of usable simulation tools. The basic condition for the selection of a simulation tool is the possibility of implementing an ATC system in the model. The author has decided to select a simulation tool that allows the simulation of ETCS (or CBTC). In terms of simulation details, the author 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 the purposes of this dissertation, OpenTrack software was finally chosen. This tool meets the criterion of being able to implement the ATC system in the model as well as the required detail of the simulation model. At the same time, this SW is available in the laboratory of the Department of Transport Technology and Control.

Summary of the analysis of the state of the art – the dissertation was divided into three parts. The first part refers to the analysis of regulations and standards that deal with capacity. The essential documents that are relevant are UIC Code 406 (7,8), Směrnice SŽDC SM 124 (9) and Směrnice SŽDC č. 104 (10). The second part deals with the search of scientific papers and articles that are related to the topic. A major contribution of this analysis was the development of an overview of the approaches and methods used to address the research objective of the dissertation. 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 did not 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.

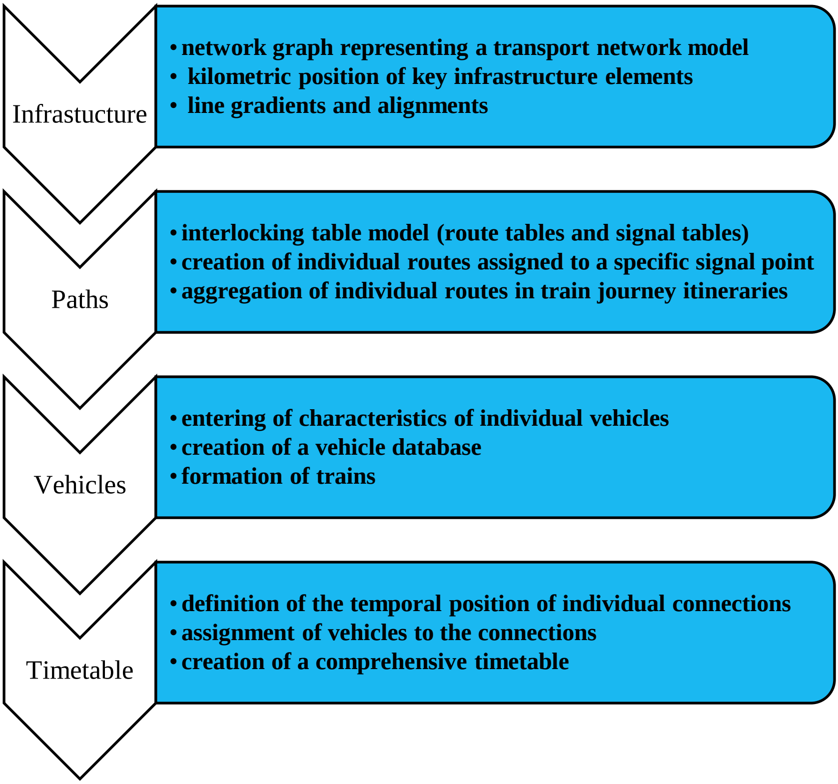
2 SELECTED RESEARCH METHODS AND SOLUTION METHOD

In order to elaborate and achieve the proposed objective of this dissertation, the following scientific methods are used: system decomposition, transport system modelling, computer simulation techniques and statistical analysis.

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. In terms of subdivision, topological, functional, factual and hierarchical decomposition can be distinguished. The basic prerequisite for the successful construction of 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 key elements of the systems from which the simulation model will be constructed and which may influence on the capacity of railway lines. These key elements are then the starting point for the selective approximation of the model being developed. This approximation is necessary for a useful model fitting, which allows to include only elements that have an impact on the evaluated indicators (12 p. 24-26).

Transport systems modelling – is a research technique that in principle replaces the real system with the system model. Depending on the details of the model, the input characteristics are approximated to the desired level of detail (13). In terms of the development of this dissertation, the model is built at the microscopic level. The construction of the simulation model takes place in four phases, these are: 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.

Schematic representation of the different stages of simulation model preparation



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Computer simulation – is a research method of working with a simulation model that represents the performance of a selected system. The model validation check is done in three steps, which are referred to as model verification, calibration and validation. The use of simulation techniques is the best tool to observe the performance of a real system. The simulation model and simulation are the core part of developing this dissertation. In this dissertation, all simulation scenarios are described in detail 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 repetition of experiment and data evaluation. Statistical analysis can be used to examine the probability of different operational scenarios. In this dissertation, the author has used the knowledge of probability theory and random variables as well as regression analysis. The above 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 be used to input delays to the model during the simulation. Regression analysis is used to compare the change in the values of each input to the output values of the simulation model (15).

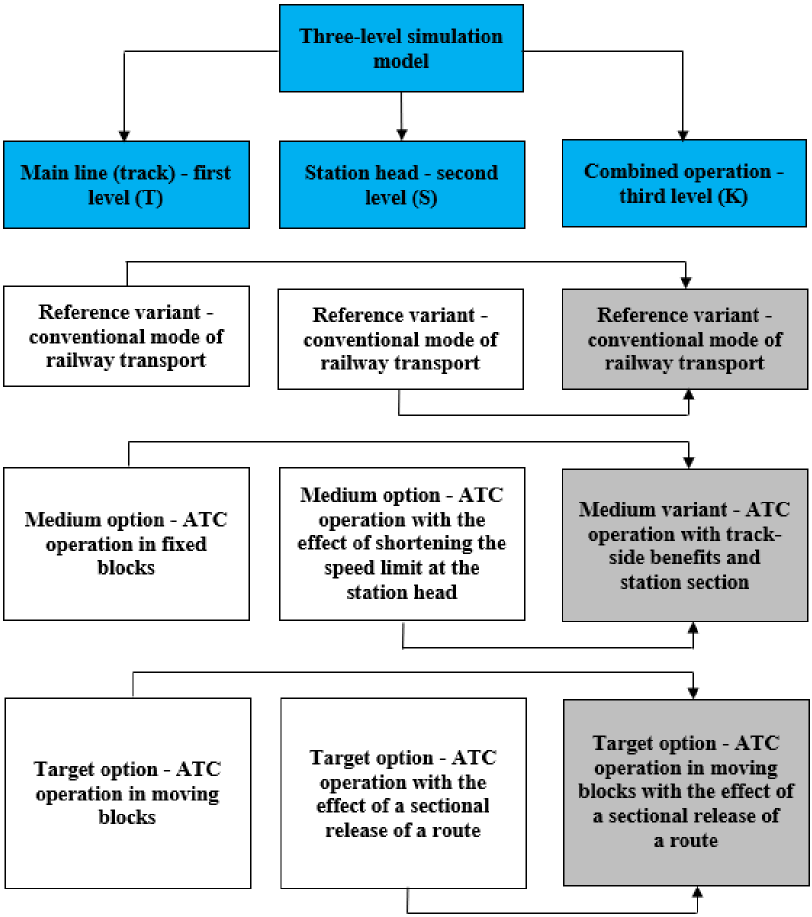
3 SOLUTION AND DESIGN OF THE SIMULATION MODEL

In this section, the author's research is described. At the same time, a simulation model for the applied part of this thesis is formulated. The model is further developed and the simulation results are continuously evaluated. In the final section, a generalization of the results is made and specific conclusions in the defined area of research are established.

Research in the ATC systems sector – during his doctoral studies, the author participated in a series of papers that investigated the issues addressed in this dissertation. These topics included: modelling of automatic metro operation, modelling of railway operation on a closed loop line, modelling of operation on a line with 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 increase in line speed and simulation of ATC systems operation. A specific list of papers and articles is given in the overview of the PhD student's publications.

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 on the basis of a number of 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.

Three-level simulation model



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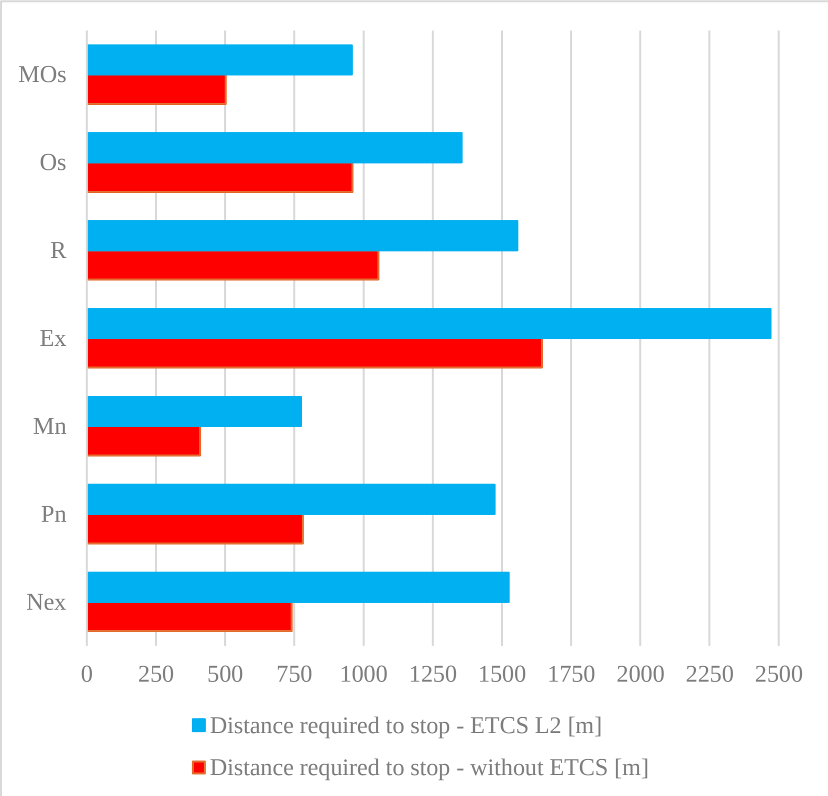
The conditions for preparation of the simulation model – the basic conditions are defined by UIC code 406 (7), Směrnice SŽDC SM 124 (9) and Směrnice SŽDC č. 104 (10). Other standards and regulations that are important to respect for the correct creation of the simulation model are: SŽ Z8 Part IV European Train Control (16), SŽ TSI CCS/MP1 Methodological Guideline Principles for the design of the ERTMS track-side part for lines with 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).

Modelling of speed braking curves – is one of the basic tasks of preparing traffic simulation 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 important 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, which is used in the model as the curve for service braking. EraTool, the official tool for generating braking curves, is used to model the ETCS braking curves. All considered trainsets were modelled as alpha trains. The following graph compares the distance required to stop for the braking curves modelled according to the UIC model and for the braking curves modelled by EraTool.

Braking curve comparison



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<u>The simulation process</u> – this section describes the simulation process for each part of the three-level simulation model for each level.

The simulation main line (track) - 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 is used to determine the headway. This tool tests, by means of a multiple simulation, the values of the headway. The half-interval method is then used to determine the resulting value. In order to confirm the correctness of the calculation of headway, 2352 replications were performed. Thus, each pair of trains was tested several times on each of the line models created with the corresponding size of the fixed block.

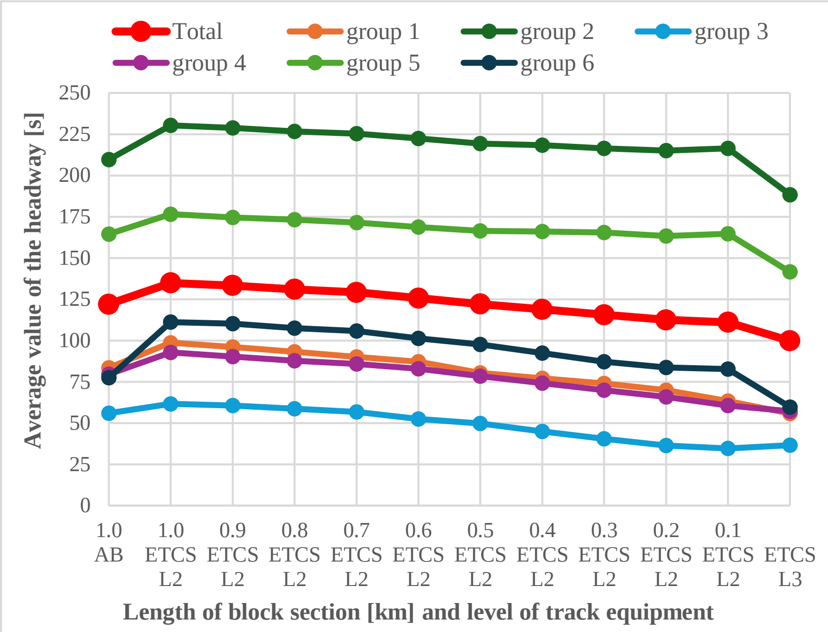
Station head simulation – second level (S) – the simulation model created for this level is built in such a way that the effect of the station head configuration and the type of ATC system used on the headway period can be observed. The station head length is determined for each of the four simulated variants. The statzion head length is determined by the design speed of the turnouts. 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 simulation 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 7056 replications were performed in this level of the model. Each pair of trains was tested on each of the twelve prepared infrastructure models.

The combined operation – third level (K) – is a model of a complete infrastucture network, which methodologically follows the two previous levels of the three-level simulation model. For the purposes of the dissertation, 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 labeled as: Station A, Station B, Station C and Station D. The individual intermediate line are always 5 km long. The station tracks have a consistent length of 800 m. The length 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. For the evaluation of the combined simulation, the delay increment method was chosen. The delay increment is defined as the difference between the input and output delay.

<u>Simulation evaluation and conclusions</u> – 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 total average headway value for a 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 the following figure.

Graph of average values of headway



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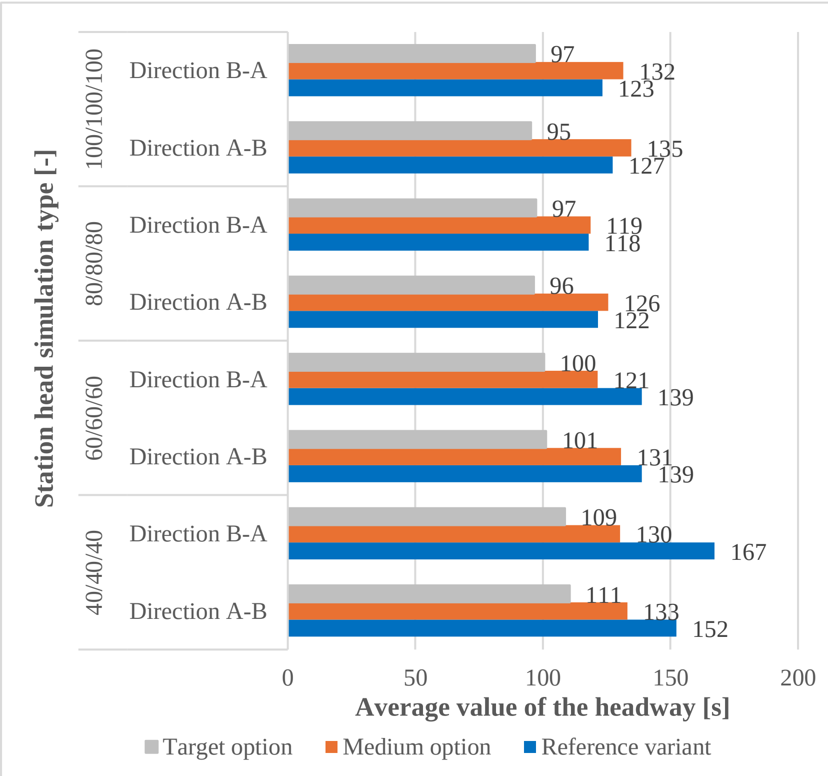
Evaluation of the station head simulation – second level (S) – the aim of this variant was to assess the behaviour of the simulation model when simulating different types of station heads. An important output of this level of simulation is the finding that, in terms of total measured values, the deployment 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 greatest 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 the following figure.

Graph of average results for each variant



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Evaluation of the combined operation – third level (K) - in this section the results with test values and the results of 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 -3081 s, while the transition variant achieves slightly worse values, with a total delay increment of -2169 s. In the target option, the best delay increment values are achieved -3247 s. When converted to average delay increment values by category (according to RIA SM124), the results are shown in the following table. The results of the individual simulation groups are coloured yellow for the risky level of traffic quality and green for the optimal traffic quality.

Average delay increment values by train category

	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**

Source: *author*

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 – ETCS L2 TRAFFIC SIMULATION MODEL ON REAL INFRASTUCTURE

An important condition to verify the validity of the proposed method is to test the simulation model on real 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. In terms of the method of operation, it is not yet a line with exclusive ETCS operation. As part of the verification operation, trainsets are deployed which are operated in ETCS L2 mode. The line is operated until 1.1.2025 in a mode with additional operational measures. In terms of 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.

<u>Conducting field measurements</u> – 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, it was also necessary to provide the necessary data on station, train and track-side signalling equipment. The complete final tables are stored directly at the station or at the relevant professional administration of the

railway operator. In order to make the simulation as close as possible to the real infrastructure, the author also verified the construction of possible paths and fixed elements on the simulations of individual unified control place.

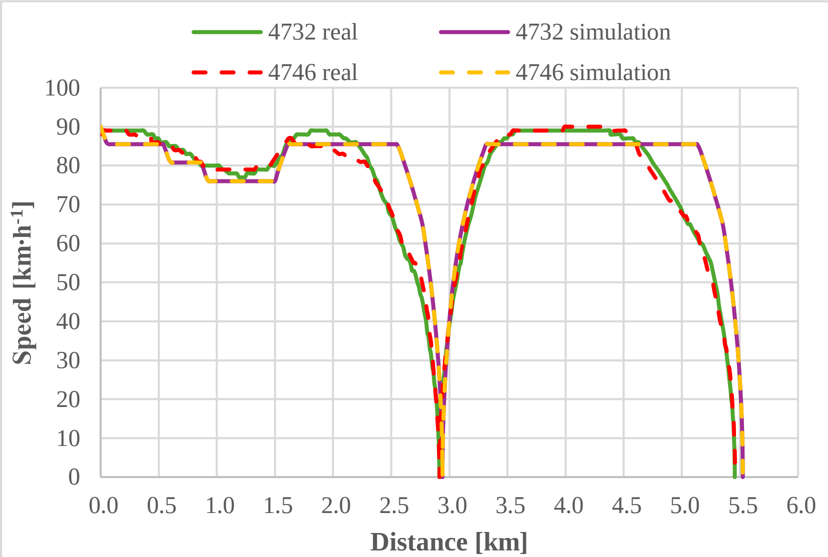
<u>Comparison of achieved journey times</u> – the actual simulation was carried out on a simulation model, where itineraries (Itineraires) were created that correspond exactly to the real journey of trains Os 4732, 4746, 4741 and 4757. The initial simulation results were compared with the timetable and 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 set timetable, a risky phenomenon is the 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, with the exception of the section ŽST Blansko – Blansko město stop, does not exceed 0,5 minutes (journey times are always rounded to the nearest 0,5 minutes), the results of the simulation model can be considered valid.

In all cases, the results of the simulation and the recording of the actual train run confirm the validity of the values obtained by 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 power of the unit 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 braking is controlled by the driver, the curve of the real train running does not copy the curve generated by the simulation model in the initial braking phase. This is mainly due to the fact that 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. The complete tachographs are presented in the dissertation

Tachograph for the direction Svitava – Rájec-Jestřebí



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The simulation results were compared with the results of real 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 does not make maximum use of the limits of the specified braking curves in his driving and especially at the start of braking there is a noticeable deviation from the simulation. By repeating the simulations and further comparison with the already established timetable, the level of applicable maximum power and maximum speed was tested.

5 CONCLUSION

This thesis deals extensively with the operation of automatic train control systems. The author has described a comprehensive theoretical introduction to automatic train control systems. On the basis of the analysis carried out, 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 author decided to use simulation modelling of traffic at the microscopic level to accomplish the aim of the thesis.

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

In the course of the research, the complexity of the whole problem became apparent in the individual parts of this dissertation and the need to focus further research on some areas that this dissertation could no longer cover. 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 important scientific issue is the design of a system that combines the advantages of all the systems applied so far in the field of automatic train control. Efficient management of traction energy is also an important aspect of automation, where the train runs interact with each other as part of the optimisation process. It is therefore essential to describe the impact of such systems on railway line capacity in the future. The automation of traffic management and the way in which the infrastructure is operated also has an impact on line capacity, and it is desirable to describe the impact of the introduction of such modifications on line capacity in this area as well. All of the above topics can be investigated in the future as part of the follow-up scientific work in the training facility.

The dissertation thesis 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. On the basis of a detailed analysis of the current state of scientific knowledge and the author's own 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 to assess the influence of automatic train control systems at three different 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 influence 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 the impact of ETCS deployment on the quality of timetable adherence is studied. Through the three-level simulation model, it was found that, when considering a wide line, a shortening of the fixed bolcks to a length of 0.5 km is required to obtain equivalent values of the headway time when changing the line protection from automatic block to ETCS L2. An over-all summary of the change in the specified parameters is given in the following table.

Summary of the most important simulation results

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

Zdroj: *autor*

The author concluded that the use of ETCS can have a positive impact on railway line capacity if the potential of ETCS L2 with benefits is exploited and equipment modifications are implemented to allow operation in shortened blocks compartments.

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3. **NACHTIGALL, Petr, Jaromír ŠIROKÝ, Josef BULÍČEK a Erik TISCHER.** *Improving single-track railway line capacity using extended station switch point area*. Journal of Rail Transport Planning & Management. Vol. 24. 2022. doi.org/10.1016/j.jrtpm.2022.100354.

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11. **NACHTIGALL, Petr a Erik TISCHER.** *Calculation of the minimal lenght of the high-speed line.* Acta Polytechnica CTU Proceedings. 2021. Vol. 31, July, p. 30-35. (Scopus)

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In 2019-2022 involvement in the scientific team within 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), registration No.: CZ.02.1.01/0.0/0.0/17_049/0008394.**