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Modelling the Traffic Prediction at the Direct Level of TMS Systems

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Abstract: The paper deals with the issue of modelling traffic prediction in operational applications of infrastructure managers to increase the quality of decision-making at the direct level of railway traffic management. First, the paper defines traffic prediction and the influences that can generate traffic conflicts. Then, it proposes an approach to modelling traffic prediction that eliminates the generated traffic conflicts and evaluates the benefits of the proposed model. The authors' proposal is based on their knowledge of the direct-level Traffic Management System (TMS) in the Czech Republic. The aim is to propose options for traffic prediction solutions to be used primarily on the railway network of the Czech Republic, but also elsewhere. The solutions are proposed with regard to their realizability in currently used computing resources.

Keywords: Traffic Management System, traffic conflict, conflict-free traffic, traffic prediction

1. Introduction

Traffic Management Systems (TMS) are used for effective railway traffic management at the level of direct transport management. [1] They enable dispatchers to have all the traffic documentation automatically registered and to communicate automatically or manually with other information systems on the railway. However, the main benefit of TMS is to make the necessary information available to the dispatchers. This means the train traffic timetable, according to which the dispatchers manage the traffic [2] and make optimization decisions based on the information available in it, leading to the elimination of traffic conflicts. This is supported by auxiliary automation functions and tools that help the dispatchers to improve the traffic prediction [3].

The traffic prediction is the state of the current daily timetable, which carries information on all approved train paths [4] in accordance with the timetable. By traffic prediction interval, the authors mean the time interval from the current time to the future of approximately 8 hours. This interval already contains almost all regular passenger and freight train paths. Based on the authors' experience, these trains should already be conflict-free at the time of their introduction due to basic timetable planning. In order to draw up the annual timetable, the infrastructure manager (Správa železnic in Czech Republic) offers technical capacity of the path, which is based on the equipment of the railway infrastructure. [5] This means that their spatiotemporal location will allow all trains to run smoothly without any interaction between them.

Ad-hoc trains ordered according to the needs of carriers can be included in the timetable at any time, even minutes before the scheduled train. The data of such an ad-hoc train is distributed by the operational TMS level, where the carrier submits the train path request. [6] This is especially typical for freight trains, which usually run on customers' demand, as stated in [7]. Unlike regularly running trains, the paths of these trains are not conflict-free and their mere presence may create traffic conflicts with other trains that are already scheduled. This brings about a set of traffic conflicts that must be resolved. Conflicts caused by some train delays are not dealt with centrally in the Czech Republic today. The research divides causes of traffic conflicts according to their mode of occurrence into uncontrolled and controlled.

Uncontrolled (randomly occurring, cannot be predicted) causes are:

- the influence of weather,
- technical faults on the train or on the infrastructure (randomly occurring),
- the driver's observance of journey times,
- deviations from normal passenger demand (extended train stays),
- the influence of external factors (emergencies, intervention of the emergency services).

Controlled causes are:

- unresolved traffic conflicts at the basic level, especially for ad hoc trains,
- the inconsistent description of the railway infrastructure,
- the impact of infrastructure restriction (construction works),
- waiting for connecting trains and regional bus connections,
- the operational dispatcher's decisions in case of emergencies and traffic deviations.

The result of resolved traffic conflicts is conflict-free traffic, which includes the planned train paths (timetable) adjusted by the amount of actual delay and also adjusted by the elimination of traffic conflicts. [8] In paper [9], a conflict-free timetable is considered essential to ensure efficient and reliable operation. Research suggests that traffic conflicts should not only be detected at stations and line tracks or occasionally at the platform edge. Besides that, conflicts at crossing points of train routes must be considered.

In the Czech Republic, one of the used TMS software is called "Graficko-technologická nadstavba zabezpečovacího zařízení (GTN)". The GTN used "Disposition Criteria" to resolve traffic conflicts in an operational manner. [3] These are tools for planning train overtaking, train crossing and waiting for the train to arrive. It allows the modelling of traffic prediction train paths, or parts of paths, to eliminate traffic conflicts.

2. Data and Methods

In this section, the research first divides traffic conflicts into several types. Next, the issue of identifying and illustrating traffic conflicts is examined and then possible solutions to the identified conflicts are proposed.

2.1 Types of Traffic Conflicts

The traffic conflicts examined in this research can be assigned to individual trains or pairs of trains. They generally relate to train movement on individual stations and line tracks. The research divides the types of detected conflicts into several basic categories, which are described below.

2.1.1 Conflict of Completeness and Consistency of Train Parameters

In this case, missing train parameters that make subsequent conflict investigation within the other categories impossible have been identified. Typical data are as follows: train length, without which it is not possible to check the correct lengths of station tracks or platforms of stopping trains, missing traction vehicles to check electrification, differentiation between passenger and freight trains, and so on. Furthermore, various data consistency checks can be added, such as train type, braking method and resistance type, etc.

In principle, these conflicts inform the user that the entered train parameters are not sufficient to identify its traffic conflicts correctly, or they themselves represent an unexpected or unauthorised combination of parameters.

2.1.2 Conflict between the Train and the Infrastructure

This group includes conflicts where the relevant train parameters do not match the infrastructure used, usually station or line tracks. Typical cases are non-compliance with the (cumulative) length of the station tracks for a stopping freight train, non-compliance with the length of the platforms for a stopping passenger train and non-compliance with the (type of) engine – diesel or electric locomotive. More specific cases may be a mismatch of transient types, a mismatch of ETCS equipment between train and track, etc. A specific problem is monitoring this type of conflict in case of lockout and other temporary restrictions. However, it is more a problem of continuous availability of this data or adding information about the temporal validity of the infrastructure data.

2.1.3 Conflict between Two Trains

This type is primarily represented by train overtaking and train crossing on the station track and on the line track (at conflicting time intervals). A similar algorithm can also be used to monitor the time interval between the start and end of the occupation of the track by a pair of trains and thus to some extent replace the methods of checking compliance with the operating intervals. A refinement of this model can be achieved by replacing track objects with smaller parts of train paths, taking into account block sections, etc.

2.1.4 Conflict between Scheduled Travel Times and Adherence to Operational Intervals

The conflict between scheduled travel times and adherence to operational intervals are two points of view. In the first case, the fact that the planned travel time differs significantly (by a selected value or ratio) from the regular travel time corresponding to the train and line parameters is considered. In the second case, it is a failure to comply with one of the traffic intervals, the travel following interval (interval between two trains in the same direction) or the electrical following interval. In addition, the recalculation of travel times and intervals may be required to adjust the time positions of the train paths when the used tracks are changed or the train is stopped.

The reason for separating the conflict issues related to the calculation of train travel times and intervals is fundamentally higher demands of these algorithms on the scope and accuracy of train and infrastructure parameter data. Furthermore, it is their high computational complexity, especially in the case of repeated and iterated recalculations in the process of conflict detecting and designing conflict resolution. The last reason is the specificity of using these calculations in the case of operational management. The recalculated theoretical or even regular travel time may not yet be transferable in a realistic and correct way to the driver's journey, with additional specificities in the case of ETCS or ATO driving. On the other hand, the observance of the different types of train running intervals is directly monitored by the signalling equipment, and an indicative forecast may only be sufficient for the traffic forecast.

2.1.5 Deadlock Conflict

Deadlocks, i.e. traffic congestion in infrastructure bottlenecks, occur when traffic density is extraordinary and may not yet exhibit conflicts at the level of the first three types in the time horizon under consideration. Alternatively, a traffic situation may appear on a linear section of infrastructure (track lines) divided into several independent spatial compartments where the interlocking system logically allows two trains to run against each other without the possibility of crossing. This type of conflict also requires significant attention, but its scope is beyond the scope of this paper. The issue of deadlocks has been addressed in [10,11].

2.2 Identification of Traffic Conflicts and their Standard Display

Within each group, you can select the range and depth of conflicts to search for. However, with their growth, the requirements for accuracy and availability of data description of train and railway infrastructure parameters, complexity and correctness of the used conflict detection algorithms and their computational complexity increase. On the other hand, the ergonomic possibilities of conflict indication in the user interface and the ability of the dispatcher to react meaningfully to the given range of information are also limiting.

An identified and still unresolved traffic conflict should be properly displayed to the user, e.g. in the form of a colour-coded circle. The type of conflict can be distinguished by the use of different colours. The colours can be combined or the one with the highest traffic priority can be displayed. Clicking on the conflict symbol opens a window with a more detailed description of the conflict, suggestions for further actions, etc. The indication of traffic conflicts in the TMS application is shown in Figure 1. Red circles indicate a conflict between two trains and purple circles indicate a conflict between the train and the infrastructure.

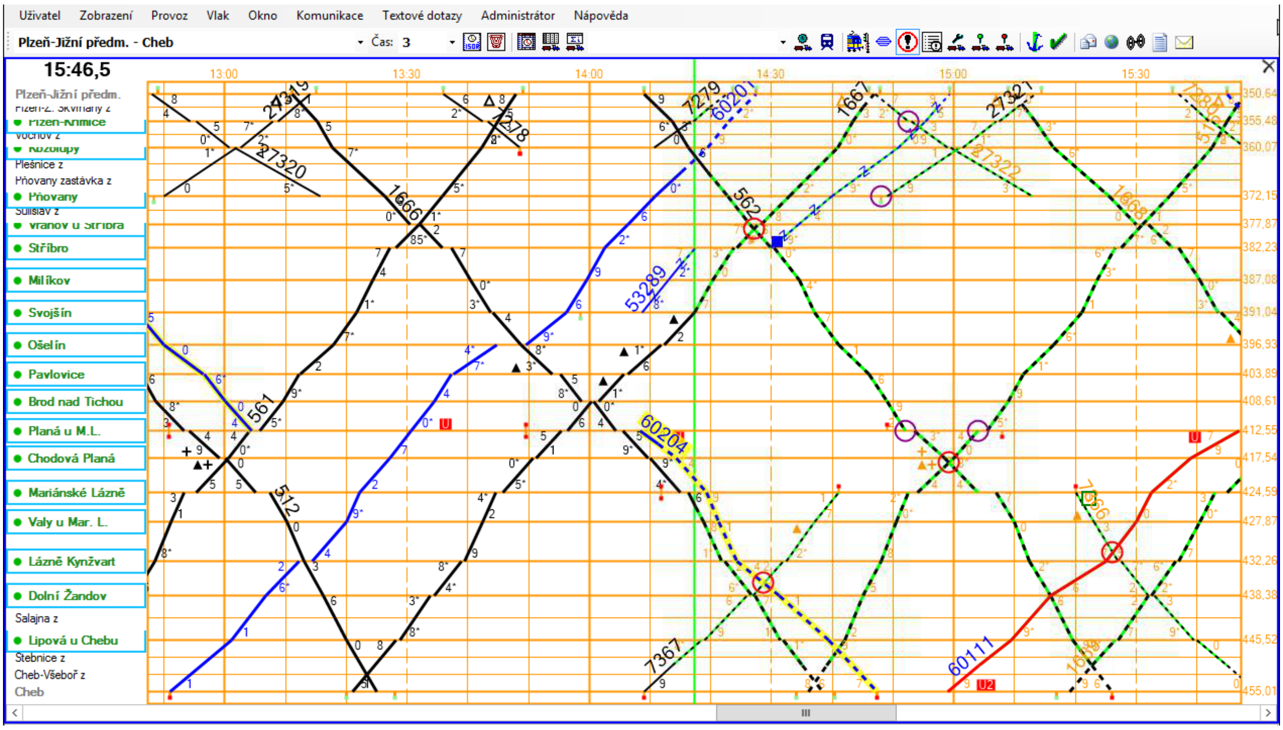

Fig. 1 The traffic conflicts display in the TMS (GTN). Source: [12]

Mathematical models can be used to find and resolve conflicts. Their problem may be their excessive computational complexity and/or lack of fidelity to the specifics of rail traffic. However, we find a simpler model useful for the conflicts of the first three types studied here. This consists of mapping train movements onto the occupancy timeline of individual track objects, typically station and line tracks. The lists are arranged according to the time of track occupation and separated for each direction of train movement. When creating the lists, it is also possible to make immediate use of the considered forecast time horizon, possible limitation to only part of the infrastructure, etc.

This creates a two-way link between trains and the infrastructure elements they use. The basic cycle of conflict identification and processing takes place not along the paths of individual trains, but along the traffic points (stations) and sections of the monitored area and their tracks. Especially in the case of conflicts of the third type, this significantly reduces the computational complexity. The first reason is the use of preprocessing of the time arrangement of the data, the second reason is the need to compare occupancy data only for neighbouring or temporally close pairs of trains. For conflicts of opposite direction travel, in principle, testing the overlap of the intervals of occupancy of the object by "temporally close" trains is sufficient, where the first disjoint pair allows the cycle to be terminated. In the case of overtaking trains, the order of occupation and track clearance is monitored. The details of the calculation are controlled more thoroughly by other parameters that can also be selected by the user.

2.3 Traffic Conflict Resolution - Modelling Conflict-free Traffic Prediction

The problem of designing and implementing conflict resolution is a degree more complex than conflict identification. Traffic conflict resolution in the form of train rescheduling is dealt with e.g. in [13]. The solution may use the Blocking-Time Theory, which is specified in [14]. In [15] is applied the Blocking-Time Theory to solve traffic conflicts. The operational traffic control system they propose consists of two sub-problems: identifying and eliminating traffic conflicts and determining operating intervals. They consider that traffic conflict occurs when two trains occupy one blocking window simultaneously. They also consider the so-called "buffer time" for each pair of trains and each section of the block, which is the minimum time between window occupancy. A detailed survey of methods for resolving prospective traffic is published in [16]. The problem of crossing trains on a single-track line and assigning station tracks to trains is addressed in [17]. In [18], the authors briefly mention the use of reserved windows for determining the consumption of railway capacity. This is elaborated in more detail in [19], where the advantages and disadvantages of reserved windows are also defined. We see this as important because the need to resolve traffic conflicts increases with increasing traffic intensity and exhausted capacity. Some lines in the Czech Republic are even running out of track capacity, as stated in the analyses [20] on the railway operator's website.

The authors have gained considerable experience in resolving conflicts within the long-term planning or train scheduling tools used in Kango-GVD. Conflict-free traffic planning in Kango-GVD or TMS is presented in [21]. There the author considers the use of the marking algorithm and

Blocking-Time Theory for the purpose of ARS (ASVC in the Czech Republic). They can be used as a starting point for designing a conflict resolution procedure for operational and direct management, but it is anticipated that they will need significant modification and subsequent testing and validation. Therefore, in this paper a rather conceptual proposal and its stages are presented.

The resolution of individual conflicts is proposed just after they have been identified. Where possible or appropriate, multiple solutions are proposed, usually with priority given to their use. In the case of conflicts between two trains, the train with the lower priority is identified and intervention is assumed to eliminate the conflict, although the variant solution may involve changing the running of the priority train. A composite function is used to determine the priority, which may take into account the type of train, penalties for stopping and delaying the train.

After gaining sufficient experience, it is possible to gradually limit the number of variant solutions to proven types, fix the parameters of the function, etc.

The research expects the main ways of resolving the identified traffic conflicts:

- Change the track to another track that is unoccupied at the required time and has the required parameters. The solution applies mainly to station tracks, exceptionally also to line tracks.
- Stop the train and wait for the necessary infrastructure to be released. A distinction is made as to whether it is just an extension of the train's stay, or whether it is also stopping a passing train. In long-term planning, only the occupation of the station tracks was extended and, if the extension of the stay was not possible, the train stay was extended at the previous stations. It is a subject to consideration whether a stop on the line track at the entrance signal can be considered.
- "Dynamic" conflict resolution by linking the train running order by Disposition Criteria. The automatic calculation of traffic prediction thus stably maintains a conflict-free train timetable. At first glance, this is more of a computational traffic prediction tool, but if the dispatcher or functional ARS (Automatic routes setting) system respects this prediction, it is an effective and currently already used conflict elimination tool.

To resolve traffic conflicts, it is considered that passenger trains with a published timetable must not leave the passenger boarding station earlier than the timetable. To resolve traffic conflicts, the authors consider that passenger trains with a published timetable must not leave the passenger boarding station earlier than the timetable. Furthermore, when solving traffic conflicts, it is necessary to consider the operating intervals (defined in the Czech Republic in [22]), which must not be violated.

The research considers the application of traffic conflict solution to have two phases.

In the first phase of implementation, it is assumed that a suitable solution to individual conflicts will be chosen and implemented by a dispatcher. The dispatcher is automatically presented with a set of alternative solutions together with a tool for previewing the traffic situation after the solution has been accepted. The operator either confirms one of the variants or returns to the previous state. The phase is a first step to verify the correctness of the proposed algorithms and the reactions of their users. The gained experience will allow us to move on to the next stages. It will also be very important to obtain a data base for the eventual use of AI methods. Relevant data will be the structure of the identified conflicts, the solutions chosen by users, the order and hierarchy of the resolved conflicts. Collecting this data in a suitably designed format can be a significant asset in itself. The block diagram of the proposed methodology is shown in Figure 2.

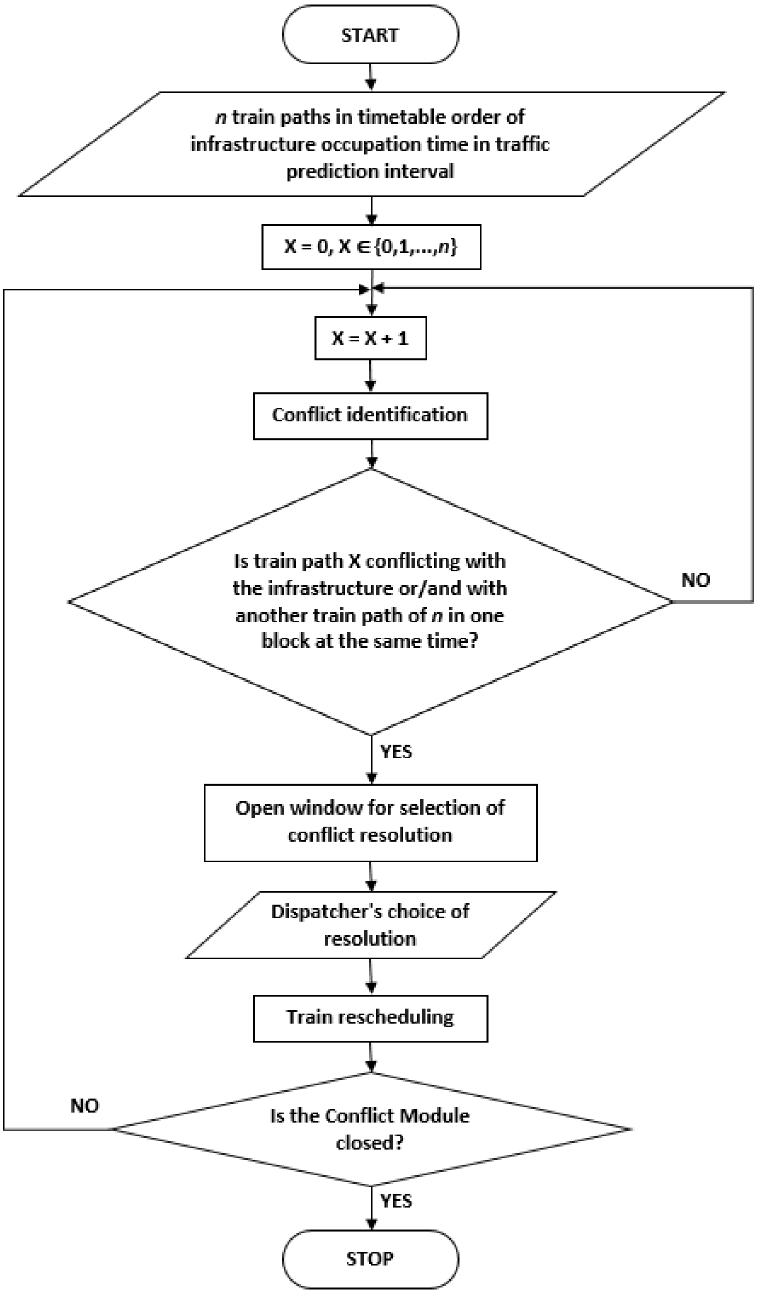

Fig. 2 The block diagram of the proposed methodology. Source: authors

In the next phase, it is expected that conflict resolution will be gradually automated. The application of a heuristic method is considered, which will not include the consistent calculation of the tree of all possible solution sequences of the identified conflicts. A correct hierarchization of the solution order will be crucial instead. Unacceptable solutions (e.g., an electric train cannot run on a track without electric traction lines, a stopping passenger train cannot run on a track without a platform.) must be eliminated primarily. Conflicts can be resolved only after this correct track assignment. In order to optimize and make these algorithms efficient, a number of parameters will need to be identified and set correctly, such as the size and overlap of the time windows of the traffic situation calculation, the extent of control of the occurrence of secondarily generated conflicts (after the solution has been accepted, the possibility of user intervention, tools against looping or excessive computational demands...). The scope and complexity of this task is the reason why we will not or cannot currently specify the exact extent of these stages.

3. The Using Conflict-free Traffic Prediction Timetable (Result and Discussion)

Optimized (conflict-free) traffic prediction supports quality in traffic management and decision-making of dispatchers, as a result of which the "optimal" train path provides for its smooth running (minimization of starts and stops, reduction of real travel times). This is followed by other benefits, which the research divides into:

- benefits for the infrastructure manager - support for traffic management, transfer of conflict-free traffic prediction to other systems, more efficient planning,
- benefits for the carrier - saving traction energy, less wear and tear on vehicle parts while minimising acceleration and deceleration of the train,
- benefits for customers (especially in passenger transport, use of more accurate train positioning),
- benefits for track capacity - according to [23], traffic prediction modelling is a low-cost tool for increasing track capacity. All the above mentioned parties benefit from increased runway capacity.

Customers (passengers, freight customers) will benefit mainly from more accurate train positioning and traffic prediction, which specifically means:

- better solution of connecting trains in case of delays of some train connections (While waiting times are nowadays set by service guidelines, from the operational point of view it will be possible to extend these waiting times ad-hoc if there is additional time margin that does not affect the operational concept on the related adjacent railway network.),
- prerequisites for better decision-making conditions for regional integrated transport systems dispatchers (Regional dispatchers often decide about the delay of a connecting train, often due to waiting for a delayed connection of a main bus line. Nowadays the decision-making of regional dispatchers is often intuitive due to the lack of relevant information. Tools for the modelling traffic prediction will make their decision-making more sophisticated and improve the final transport conditions for passengers.),

- waiting of connecting train for alternative bus transport, because in some cases connections from the main line transport have a high priority,
- a more sophisticated solution to the problem of delays of periodic train connections with an impact on other periodic train connections, thus solving the problem of the "cyclical transfer of delays" between connections,
- better consideration of the expected delay in the train's stay at a station, for example due to the loading or unloading of a large number of bicycles or the boarding or alighting of a wheelchair user, especially if these anticipated conditions are announced in advance and the dispatcher has an overview of this, which allows them to make sophisticated decisions,
- reduction of actual travel times (benefits in passenger and freight transport for full trains and higher category freight trains).

4. Conclusion

In this paper, the authors focus on the identification and resolving of traffic conflicts. The identification step is necessary to ensure conflict-free prospective transport in real time, given the fact that the announced train transport plan is affected by a number of influences that cause deviations from the plan in train operation (train delays). The research first identifies all these influences and then divide the identified traffic conflicts into several types. The method of finding traffic conflicts for a single or a pair of trains provides the advantage of transparency in the search for a solution, each conflict is solved by the same set of rules. Furthermore, the computation of the results can be performed in real time. The disadvantage of this solution may be the situation where the solution selected by the dispatcher may not be optimal from a global point of view, but suboptimal. They then propose a method to resolve these conflicts using traffic prediction modelling. Given the problem's scope, the paper sets only a framework solution, which will be further elaborated on. The goal is to find an automated traffic conflict solving system that will resolve continuous traffic conflicts in real-time and thus keep the traffic prediction conflict-free.

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References

[1] Abdulsalam Hamid, H., Nicholson, G.L. & Roberts, C. (2020). Impact of train positioning inaccuracies on railway traffic management systems: framework development and impacts on

TMS functions. IET Intelligent Transport Systems 14(6), 534-544. DOI: 10.1049/iet-its.2019.0503.

[2] Správa železniční dopravní cesty, state organization. (2014). SŽDC D7 Regulation for operational traffic control.

[3] Polach, V. (2021). Expansion of ASVC on the Czech Railways (In Czech). In Conference on Signaling and Safety Technology in Railways, 4-6 October 2021 (pp. 162-166). Olomouc, Czech Republic: Správa železnic, state organization. ISBN 978-80-907189-3-7.

[4] Správa železnic, state organization. (2022). SŽ D1 Traffic and signalling regulations for lines not equipped with a European Train Control System by Corrigendum No 1 from 1 July 2022.

[5] Správa železnic, state organization. (2023). Network Statement 2025.

[6] Nachtigall, P. & Škárek, M. (2016). Railway infrastructure capacity management for ad-hoc trains on the SŽDC network. Acta Polytechnica CTU Proceedings 2016 (5), 44-46. DOI: 10.14311/APP.2016.5.0044.

[7] Pachl, J. (2024). Railway Timetabling and Capacity (Edition 1.0). Braunschweig: Technical University Braunschweig. DOI: 10.24355/dbbs.084-202407090800-0.

[8] Mladenovic, S., Veskovic, S., Branovic, I., Jankovic, S. & Acimovic, S. (2016). Heuristic based real-time train rescheduling system. Networks - An International Journal 67(1), 32-48. DOI: 10.1002/net.21625.

[9] Hansen, I.A. (2011). Railway operations modelling and analysis: An introduction to the special issue. Transportation Planning and Technology 34(4), 297-299. DOI: 10.1080/03081060.2011.577149.

[10] Li, F., Sheu, J.-B. & Gao Z.-Y. (2014). Deadlock analysis, prevention and train optimal travel mechanism in single-track railway system. Transportation Research Part B: Methodological 68, 385-414. DOI: 10.1016/j.trb.2014.06.014.

[11] Mazzanti, F., Spagnolo, G.O., Della Longa, S. & Ferrari, A. (2014). Deadlock Avoidance in Train Scheduling: A Model Checking Approach. In 19th International Conference, FMICS 2014, 11-12 September 2014 (pp. 109-123). Florence, Italy: Springer International Publishing Switzerland.

[12] TrafficSWing GTN (TMS CZ). Software.

[13] Toletti, A., Laumanns, M. & Weidmann, U. (2019). Coordinated railway traffic rescheduling with the Resource Conflict Graph model. Journal of Rail Transport Planning & Management 15, 14. DOI: 10.1016/j.jrtpm.2019.100173.

[14] Hansen, I.A. & Pachl, J. (2014). Railway Timetabling and Operations, second ed. Hamburg, Germany: DVV Media Group GmbH, Eurailpress.

[15] D'Ariano, A. & Pranzo, M. (2004). A real-time train dispatching system based on the blocking time theory. In Proceedings of the 8th TRAIL Congress and Knowledge Market 2004, Selected Papers P2004/1, 23 November 2004 (pp. 129-152). Rotterdam, Netherlands: DUP Science, Delft.

[16] Cacchiani, V., Huisman, D., Kidd, M., Kroon, L., Toth, P., Veelenturf, L. & Wagenaar, J. (2014). An overview of recovery models and algorithms for real-time railway rescheduling. Transportation Research Part B 63, 15–37. DOI: 10.1016/j.trb.2014.01.009.

[17] Yang, F., Yang, Y., Ni, S., Liu, S., Xu, Ch., Chen, D. & Zhang, Q. (2023). Single-track railway scheduling with a novel gridworld model and scalable deep reinforcement learning. Transportation Research Part C 154, 36. DOI: 10.1016/j.trc.2023.104237.

[18] Büker, T., Graffagnino, T., Hennig, E. & Kuckelberg, A. (2019). Enhancement of Blocking-time Theory to Represent Future Interlocking Architectures. EasyChair Preprint 897, 219-240. DOI: 10.29007/J33N.

[19] Pachl, J. & White, T. (2004). Analytical Capacity Management with Blocking Times. In Transportation Research Board: 83rd Annual Meeting, 11-15 January 2004 (pp. 1-14). Braunschweig: Technical University Braunschweig. DOI: 10.24355/dbbs.084-200611210100-0.

[20] Správa železnic, state organization. (2025, March). Railway capacity analyses. Retrieved March 27, 2025, from https://provoz.spravazeleznic.cz/Portal/ViewArticle.aspx?oid=2250512

[21] Vicherek, T. (2011). Principles of Traffic Intelligence in Automatic Train Route Setting (In Czech). In InfoTrans 2011, 28 April 2011 (pp. 153-160). Pardubice, Czech Republic: Universtiy of Pardubice.

[22] Správa železniční dopravní cesty, state organization. (2013). SŽDC Directive No. 104 Operating intervals and subsequent intermediate periods.

[23] Lüthi, M., Nash, A., Weidmann, U., Laube, F.B. & Wüst, R. (2007). Increasing Railway Capacity and Reliability through Integrated Real-Time Rescheduling. In 11th World Conference on Transport Research, 24-28 June 2007 (pp. 1-17). Berkeley, USA: Institute for Transport Planning and Systems, ETH Zurich. DOI: 10.3929/ethz-a-005704019.