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Jozef Gašparík , Marek Vyhnanovský , Martin Vojtek , Petr Nachtigall , Milan Dedík *

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A New Methodology for Optimising Railway Line Capacity: Improving Infrastructure for Sustainable Transport

Jozef Gašparík [1], Marek Vyhnanovský [2], Martin Vojtek [3], Petr Nachtigall [4] and Milan Dedík [5,*]

1 University of Žilina, Department of Railway Transport, Univerzitná 8215/1 010 26 Žilina
2 University of Pardubice, Department of Transport Technology and Control, Studentská 95, Pardubice, Czech Republic
3 University of Pardubice, Department of Transport Technology and Control, Studentská 95, Pardubice, Czech Republic
4 University of Pardubice, Department of Transport Technology and Control, Studentská 95, Pardubice, Czech Republic
5 University of Žilina, Department of Railway Transport, Univerzitná 8215/1 010 26 Žilina
* Correspondence: milan.dedik@uniza.sk

Abstract

Sufficient capacity of railway lines is a key prerequisite for stable and sustainable transport, not only on main or high-speed lines but also on lines of regional importance that complement the network. Their indispensable role is manifested not only daily but especially in the event of incidents on the backbone network. One of the main characteristics of these support lines is that they are largely single-track. Another important characteristic is that they alternate between sections with different traffic loads, which significantly changes the capacity requirements along the whole line. In this paper, the authors focus on developing a new, widely applicable method that identifies, based on objective criteria, the sections for which it is appropriate to proceed with a partial infrastructure measure. It also defines a mathematical apparatus that can be used to determine the new infrastructure parameters required. Each measure must be dimensioned to meet future requirements for rail traffic volume. The article thus provides a new perspective on the dimensioning of appropriate measures for increasing the capacity of the railway in general.

Keywords: capacity; railway infrastructure; railway line; journey time; throughput; modernisation

1. Introduction

A major issue today is the change of the modal split. Namely, due to the environmental impact, our society would like to shift more cargo from roads to rails. However, this effort is often in stark contrast to the available (free) capacity. This will require, among other things, modernisation of the rail infrastructure, particularly electrification and increasing capacity, not only on the main corridors but also on other railway lines, which can act as diversionary routes by increasing their parameters. [1 - 4]. In cooperation with the PSOs (Public Service Obligations) and other RUs (Railway Undertakings), each infrastructure manager addresses this issue individually. Thus, there is no general approach to solving this question using an appropriate mathematical apparatus. This paper aims to provide such a systematic approach.

Although rail transport has a lower environmental impact than, for example, road transport, some aspects can still be improved. For example, the environmental cost of turnouts can be reduced by using under-sleeper pads [5]. A predictive maintenance system that uses big data and materials reuse can also help reduce negative environmental impacts [6,7]. Recycling old asphalt material from roads is also suitable for use as sub-ballast [8]. Train journeys also consume a lot of energy, but with

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electric traction, trains can reduce their energy consumption through regenerative braking [9]. All these aspects increase the sustainability of the whole system and mean that rail is even more environmentally friendly than other modes of transport.

Although high-speed lines are regarded as a means of releasing capacity on conventional freight corridors, there may be insufficient released capacity once operational due to the development of regional passenger services during the daytime. One potential solution to this issue the implementation of traffic optimisation strategies, which aim to maximise the utilisation of train capacity by passengers [10]. However, this may prove insufficient, considering the projected growth in rail traffic. It is therefore important to consider not only the construction of high-speed lines and the upgrading of existing corridors but also the development of other lines that are tangential (and mostly single-track) and have the potential to relieve the main corridors, major railway nodes and to serve as diversionary alternatives in the event of closures, emergencies, or even maintenance works on the main lines [11,12]. In such cases, re-routing can help reduce delays and improve passenger satisfaction.

At the same time, these lines can complement the high-speed network and thus increase its reach. Freight traffic will also benefit from the increased capacity of these lines, not only because of the possibility of diverting traffic and avoiding the main nodes but also through the possibility of running more freight trains with higher parameters (train length 740 metres, higher line load class). A modern infrastructure can help to ensure that rail becomes more integrated into Industry 4.0 [7]. With regard to the transport of goods, tangential rail lines can also be used to optimise the logistics chains [13].

This article aims to present a new methodology that will facilitate the selection of sections of routes that require modification to achieve the desired level of capacity utilisation. Route modifications and railway infrastructure expansions are primarily implemented when the existing capacity is inadequate to meet the demands of the transportation system. [14,15]. Usually, the initial step towards route modernisation is undertaking a feasibility study. This study addresses the development of traffic, the economic potential of the line and the possibilities for infrastructure development. However, the return on investment is difficult to compare as there is no consistency in determining future traffic or timetables [16].

The first step is to analyse the existing line and its current operational status, including the timetable. This analysis is then used for the division of the line into segments with a consistent number of trains, ensuring logical continuity or prioritisation. This assessment, coupled with capacity calculations, enables the identification of critical points (segments). When lines are modernised, certain infrastructure measures must be implemented to increase the capacity. These include increasing line speed or speed at switch point areas by upgrading switches to allow higher speeds in the direction of divergence. It is recommended that these speed-related measures be implemented in any line upgrade.

In addition to the measures affecting speed, one way to increase the railway's capacity is to implement infrastructure measures. These may include, for example, the double-tracking of the line, the construction of a new passing bay, the modernisation or installation of line signalling equipment (or the increase of the number of block sections on the line). This methodology addresses which sections are to be selected for implementing these measures.

2. State of Art

Many methods can be employed to ascertain the capacity of a railway line. Capacity can be determined on line sections or in a station, where the problem is more sophisticated due to collisions of train paths in switch point areas, which are determined by the complexity of the given station [17,18]. Static models can be used to calculate station capacity. One of these is the "Kaban" tool used in Sweden [19].

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The fundamental approach is the utilisation of analytical calculations, which are founded upon the compression method. Generally, the higher the capacity utilisation, the more susceptible the line is to transmission delays between trains and poorer timetable performance [20,21].

An alternative approach is using simulation software, specifically OpenTrack, which can incorporate stochastic phenomena [22]. With the help of simulation, infrastructure planning can be as efficient as possible within the framework of possible investments [23].

Another option is to use graph theory, linear programming and polyhedral geometry [24]. However, an additional approach is using probability, for example, based on Markov chains and queueing theory [25,26]. Further option for rail capacity management is using multi-objective capacity models, which are a more comprehensive approach to the problem [27].

Alternatively, graphical methods may be designed to interact with the timetable and utilise the ratio of the timetable area to the area occupied by the train on the infrastructure element under consideration [28].

Consequently, the graphical method does not necessitate compression like the analytical method [29,30,31]. The compression can be carried out on the entire line or individual sections. This is done in different ways depending on the method used [32]. To transform heterogeneous traffic, where the train sequence is important and decisive, into homogeneous traffic, it is possible to use an equalised train, which is artificially created and whose parameters are determined by weighted parameters of different types of trains [33].

Each of these methods has its own set of advantages and disadvantages. They differ in terms of the number of input parameters, the level of knowledge required regarding the traffic on the line, and the complexity of the results. However, the analytical method has the advantage of not necessitating a detailed knowledge of numerous specifics while still enabling the attainment of a result.

There are several ways to increase the capacity of the line. One is to change the organisation, both on the part of the infrastructure manager (more staff, timetabling, rerouting in cooperation with railway undertakings) and also on the part of the railway undertakings, especially if there are more RUs. Mutual coordination can reduce dwell times, especially for freight transport, and thus increase the whole system's efficiency [34 - 37].

The other way to reach higher capacity is to upgrade the infrastructure by increasing the speed and the number of compartments on the line or using ERTMS and its benefits (in particular, ETCS L2 and higher). The number of block sections (even moving ones at a higher implementation level) can be increased using this system [38 - 40].

3. Materials and Methods

The question thus arises as to how one might determine the specific sections of the line in which infrastructure measures should be carried out in a manner that is both context-specific and coherent.

The methodology for determining journey time limits provides a framework for selecting the sections where capacity enhancement measures must be implemented.

The following inputs are employed in the calculation [30]:

A – The analysis period defines the duration of the assessment phase, which is used to ascertain the number of trains and capacity. [h]

ND9 – The ninth decile of the number of trains in the critical section represents the value of the ninth decile of the daily number of trains, ranked from highest to lowest. [-]

- **d** – The item corresponding to the ninth decile is ordered as follows. [-]

$$d = \frac{a}{10} \tag{1}$$

- **a** – The length of the observation period is defined as the number of days over which the observation is conducted. [-]

N$_{VÝHL}$ – The prospective number of trains for the period (the expected number of trains for the period). [-]

b – Unit occupation time. [min]

bn – The most unfavourable journey time is the highest journey time observed in the critical section of the sub-track. If the highest journey time differs significantly from the others, the next journey time in order from the highest is used as the reference point. [min]

n – Infrastructural capacity is defined as the number of feasible journeys that can be accommodated on a given infrastructure within a specified time period. The relation between capacity and unit occupancy time over the course of a one-hour monitoring period is pictured in Figure 1. [-]

$$n = \frac{A \cdot 60}{b} \quad (2)$$

k – Step of unit occupation time by which the unit occupation time is gradually reduced. The value of this variable can be arbitrarily small (which makes it possible to obtain a value of utilisation closer to the desired utilisation), but in the reality of railways and timetabling, values of 0.5 or 1 minute are appropriate. [min]

K$_p$ – Target capacity utilisation – targeted utilisation for a given line segment. [-]

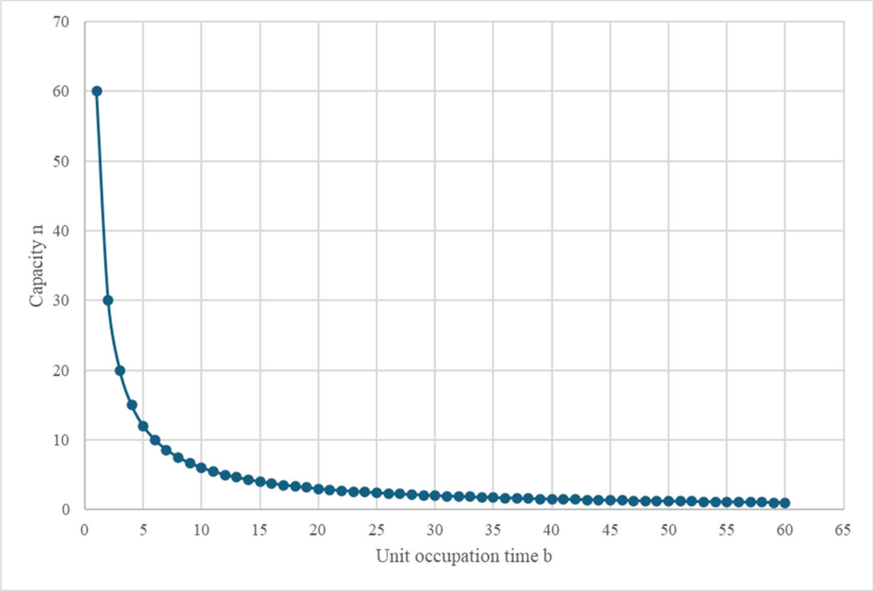

Figure 1. Dependence of capacity and unit occupancy time for a monitoring period of one hour.

4. Calculation

When examining the relationship between unit occupancy time and capacity, it was found that the percentage change in unit occupancy time between a value of b and a value of b one step k higher is the same as the percentage change in capacity for values of b one step k higher and b two steps k higher:

$$\frac{(b + k) - b}{b + k} = \frac{n_{b+k} - n_{b+2k}}{n_{b+2k}} \quad (2)$$

Which, according to the formulas and adjustments, is as follows:

$$\frac{(b + k) - b}{b + k} = \frac{\frac{A * 60}{b + k} - \frac{A * 60}{b + 2k}}{\frac{A * 60}{b + 2k}}$$

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$$\frac{k}{b+k} = \frac{b+2k}{b+k} - \frac{b+2k}{b+2k}$$

$$\frac{k}{b+k} = \frac{b+2k}{b+k} - 1$$

$$k = b + 2k - (b+k)$$

$$k = b + 2k - b - k$$

$$k = k$$

The result that k is equal to k proves that the two procedures reach the same values and are applicable.

Subsequently, the calculated values are as follows:

• **K** – Capacity utilisation - the ratio of the number of journeys to the total capacity over a specified time period. [-]

$$K = \frac{N}{n} \tag{3}$$

• **$K_{VÝHL}$** – Capacity utilisation of current infrastructure with the prospective number of trains - the utilisation of the capacity for the expected number of trains on the existing infrastructure. This formula is based on inserting the formula for capacity n into the formula for capacity utilisation K, where the reference number of trains is the prospective number of trains Nvýhl. [-]

$$K_{VÝHL} = \frac{N_{VÝHL} \cdot b_n}{A \cdot 60} \tag{5}$$

• **K_b** – Capacity utilisation for given occupation time, with the prospective number of trains – is used to calculate the capacity utilisation for different values of b, which are successive with a distance between them determined by the value of k. [-]

$$K_b = \frac{K_{VÝHL}}{\frac{b_n - b}{k} \cdot \left(\frac{b+k}{b} - 1\right) + 1} \tag{4}$$

b_{lim} – limiting journey time – a value of a journey time b in minutes, beyond which it is necessary to implement infrastructure measures. The value of this variable is defined by the relation of $\boldsymbol{K_b} \leq \boldsymbol{K_{lim}}$, which must be respected to ensure that the infrastructure meets future demands placed on it and has sufficient capacity headroom to allow for traffic development. [min]

The element $\boldsymbol{\frac{b_n - b}{k}}$ indicates the number of steps required to change from $\mathbf{b_n}$ to **b**.

The process of identifying infrastructure modifications must be divided into three steps:

- division of the line into segments,
- determination of the limiting journey time for each segment,
- identification of an infrastructure measure to increase capacity.

The individual steps are introduced in the following text.

4.1. Division of the Line into Segments

The first step of establishing an infrastructure measure is to divide the line into smaller segments, which contain several line sections connected to each other with similar traffic volume.

The route is divided into segments using a moving average. Initially, a new segment must be created, and then the 9th decile moving average values must be compared in each section with the previous one in the segment. In addition, the routing of passenger lines should also be considered in the comparison. According to this criterion, the line is divided into several segments. The procedure is illustrated in Figure 2.

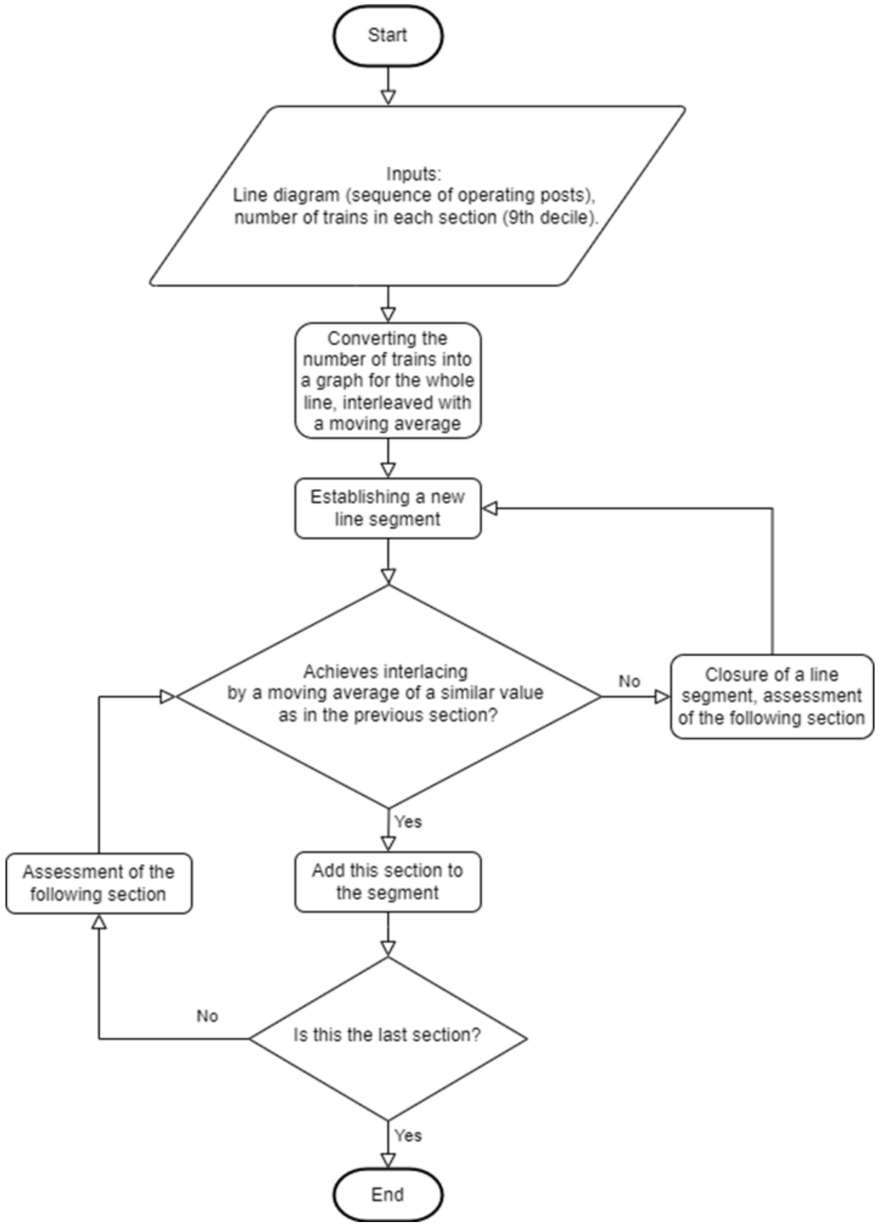

Figure 1. Diagram of segmentation.

4.2. Determination of the Limiting Journey Time for a Segment

The second step is to ascertain the limiting journey time of the given segment. The initial step is to select the segment with the highest travel time (occupancy time). If this value differs significantly from the others, the next highest in the sequence is selected.

Subsequently, this occupancy time is reduced stepwise until the desired capacity utilisation with the prospective number of trains is reached. This reduction is achieved by a gradual decrease of one step at a time.

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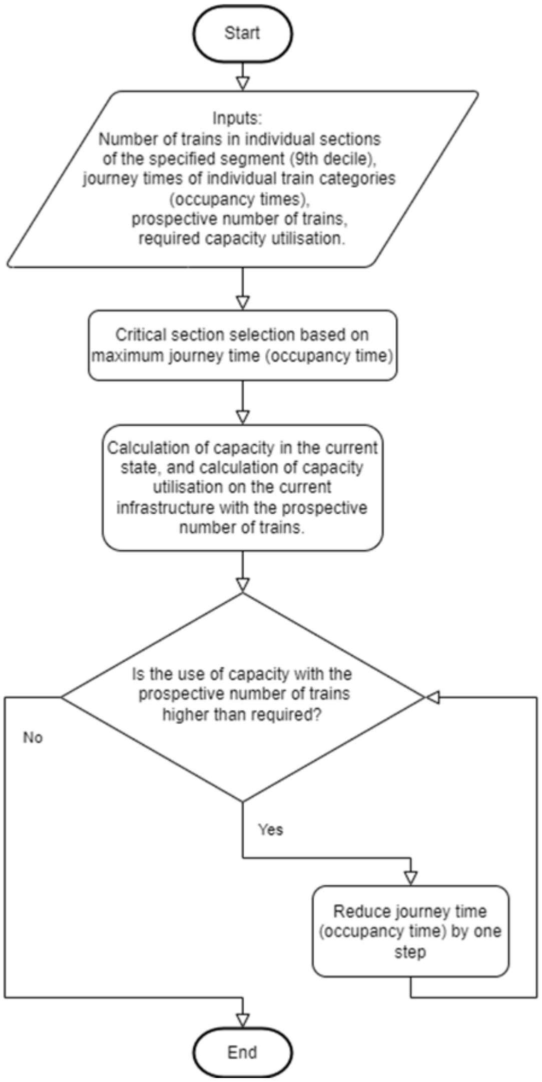

Figure 3. Diagram of determination of the limiting journey time for a segment.

4.3. Identification of an Infrastructure Measure to Increase Capacity

The final step is determining the appropriate course of action for each section.

Subsequently, the calculated limiting journey time can be compared with the current train journey times (or their average or weighted average, which may consider the diversity of traffic). If these current journey times exceed the limiting journey time, an infrastructure measure must be proposed.

For the sake of simplicity, the infrastructure measures will be divided into three categories:

- division of the track section into discrete block sections,
- division of the line with a track branching (station, passing loop),
- increasing the number of tracks (double tracking).

To ascertain the precise infrastructure measure, it is essential to consider, in addition to the magnitude of the deviation from the prescribed journey time, the potential operational concept under evaluation and the resulting tact nodes and transport facilities for tact crossing. Furthermore, the infrastructure arrangements must be modified to align with these constraints.

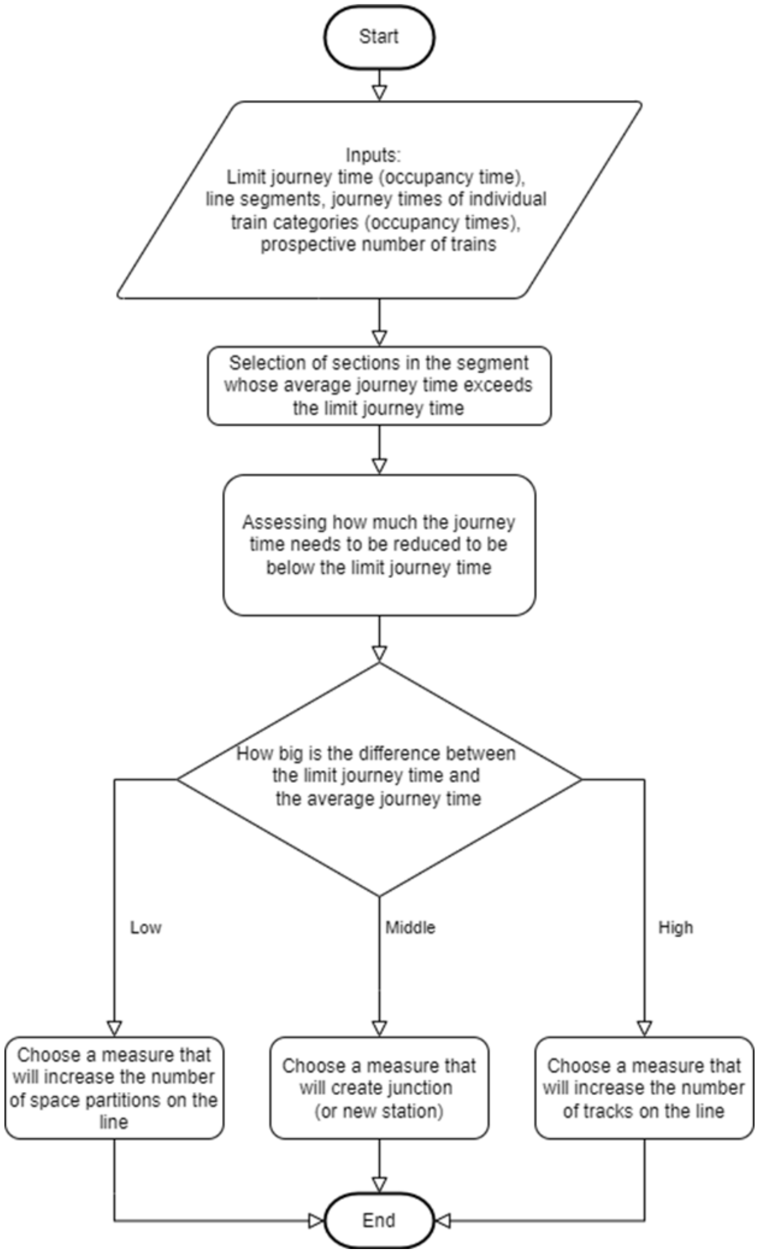

Figure 2. Diagram of identification of an infrastructure measure to increase capacity.

In instances where the permitted journey time is exceeded significantly, it is recommended that double-track or multiple-track alignment, or the line splitting by traffic with track branching, be considered. In such cases, it is essential to consider the spatial conditions to ensure the feasibility of constructing a station or a second track, while also aligning with the investment capabilities of the infrastructure manager.

In the event of a lower exceedance of the limiting value or the inability to implement alternative infrastructure measures, it is recommended that the line section be divided into additional block compartments. This approach will be particularly beneficial when coupling trains of the same direction.

5. Results

This procedure has been applied to the Havlíčkův Brod - Jihlava - Znojmo line, potentially relieving the Brno node. However, it is necessary to modernise and electrify the line to increase its capacity, which will enable the transfer of part of the freight traffic not only from the Havlíčkův Brod - Brno - Břeclav branch but also from other modes of transport to this line. Modernizing the infrastructure can significantly increase operational safety and significantly save traffic management staff.

Critical points were identified through an analysis of traffic and infrastructure. At these locations, measures were proposed to improve the existing condition, rendering the line suitable for future needs.

The average number of trains in each section was determined based on the ninth decile of train counts from 2019 to 2023 (each year between 1 January and 31 March). This is shown in Table 1 and Figure 5, where the graph is interlaced with the moving average.

Table 1. 9th Decile of the number of all trains in each section

Section / year	2023	2022	2021	2020	2019	Average
Havlíčkův Brod						
	70	75	75	80	55	**71**
Šlapanov						
	70	70	75	80	55	**70**
Dobronín						
	70	75	80	80	55	**72**
Jihlava						
	50	50	45	55	45	**49**
Louka nad Jihlavou						
	50	50	45	55	45	**49**
Bransouze						
	50	50	45	55	45	**49**
Okříšky						
	24	25	25	25	25	**24.8**
Stařec						
	24	25	25	25	25	**24.8**
Kojetice na Moravě						
	24	25	25	25	25	**24.8**
Jaroměřice nad Rokytnou						
	24	25	25	25	25	**24.8**
Moravské Budějovice						
	30	30	30	35	25	**30**
Grešlové Mýto						
	30	30	30	35	25	**30**
Šumná						
	30	30	30	35	25	**30**
Olbramkostel						
	30	30	30	35	25	**30**
Znojmo						

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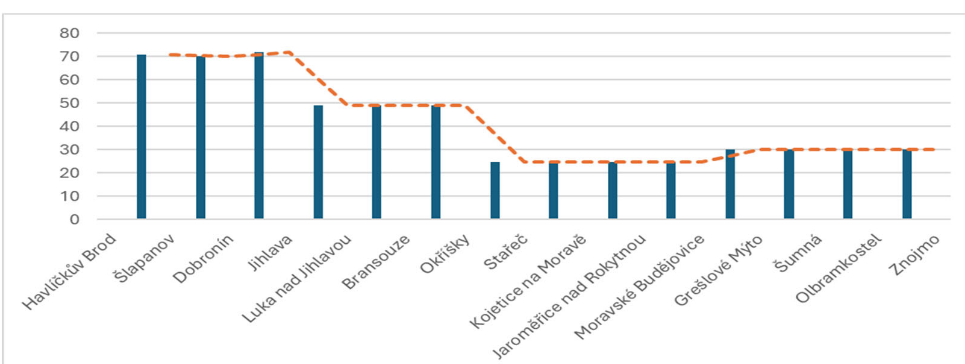

Figure 5. Average 9th decile interlaced with moving average (2019-2023).

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Table 2 presents the journey times of trains between stations in both directions. The data has been classified into three categories: passenger trains (Os), fast trains (R) and regular freight trains (Pn; journey times of Pn 62331/62330, running with the 742 series).

Table 2. Journey times [min] on the original infrastructure.

Direction / category	Znojmo			Havl. Brod			Average	Limiting journey time
	Os	R	Pn	Os	R	Pn		
Havlíčkův Brod								
	9	7	12.5	9.5	7.5	10	**9.3**	
Šlapanov								**5**
	8	6	12.5	8	6	8	**8.1**	
Dobronín								
	9	6	13	8.5	6.5	10	**8.8**	
Jihlava								
	11.5	11.5	13	12.5	10	16.5	**12.5**	
Louka nad Jihlavou								
	10.5	7.5	8.5	11.5	7.5	10.5	**9.3**	
Bransouze								
	9	7.5	13	9	8	8.5	**9.2**	**8**
Okříšky								
	10	7.5	14	9.5	8	10	**9.8**	
Stařec								
	6.5	5.5	9.5	6.5	5.5	13.5	**7.8**	
Kojetice na Moravě								
	8	7	9.5	9	7	13.5	**9.0**	
Jaroměřice nad Rokytnou	9	7.5	8.5	8.5	7	7	**7.9**	**9**
Moravské Budějovice								
	12.5	9.5	11.5	12.5	9	19	**12.3**	
Grešlové Mýto								
	7	6	12	7	6.5	9	**7.9**	
Šumná								
	6.5	6	7.5	7	6	14.5	**7.9**	
Olbramkostel								
	13.5	12	12	14	12	29	**15.4**	
Znojmo								

Source: Authors based on data [29].

Cells highlighted in green indicate the most unfavourable journey time. In the case of the Olbramkostel - Znojmo section, the second highest value was chosen because the highest value (marked in red) was too different from the others.

Based on the algorithm described, Table 3 shows the inputs used to calculate the limiting journey time output values.

Table 3. Inputs and outputs of the calculation.

Segment	Prospective number of trains for a given period	Capacity in current state (with most unfavourable journey time)	Capacity utilisation	The most unfavourable journey time	Target capacity utilisation	Future capacity utilisation	**Limiting journey time**
	$N_{výhl}$	n	$K_{výhl}$	b_n	K_p	K_b	b_{lim}
Havl. Brod – Jihlava	27	19,2	140 %	12,5	60 %	56 %	**5**

Jihava – Okříšky	16	14,55	110 %	16,5	55 %	53 %	**8**
Okříšky - Znojmo	13	17,14	75 %	14	50 %	49 %	**9**

From these values, the mean and limiting journey times were calculated, resulting in 5 minutes in the Havlíčkův Brod - Jihlava section, 8 minutes in the Jihlava - Okříšky section and 9 minutes in the Okříšky - Znojmo section.

The specified journey time limit was exceeded in the following sections: Havlíčkův Brod - Stařeč, Moravské Budějovice - Grešlové Mýto and Olbramkostel - Znojmo.

From an analysis of the 9th decile values, it is evident that the most significant adjustments must be made in the Havlíčkův Brod - Jihlava section, due to the flexibility of the Havlíčkův Brod and Jihlava interchanges. Therefore, it is proposed that this section should be fully double-tracked.

It is similarly important to consider the Jihlava-Okříšky section. In light of the proposed operational concept and the anticipated increase in freight transport, it is suggested that two passing bays (Kosov and Rokštejn) be established, along with a double-track extension of the Okříšky station. This latter point is also regarded as a tact node for crossing and connecting links.

In the remaining section, Okříšky - Znojmo, the number of trains is not as high, and the modifications to the line may not be as significant as in the previous sections. It is therefore proposed that the line be divided into two spatial sections in these sections (Okříšky - Stařeč and Moravské Budějovice - Grešlové Mýto). In the section Olbramkostel - Znojmo, given the lengthy journey times, the Mašovice passing bay is proposed to be constructed. Figure 6 presents a current and proposed line diagram illustrating the type of station interlocking and track-side signalling equipment.

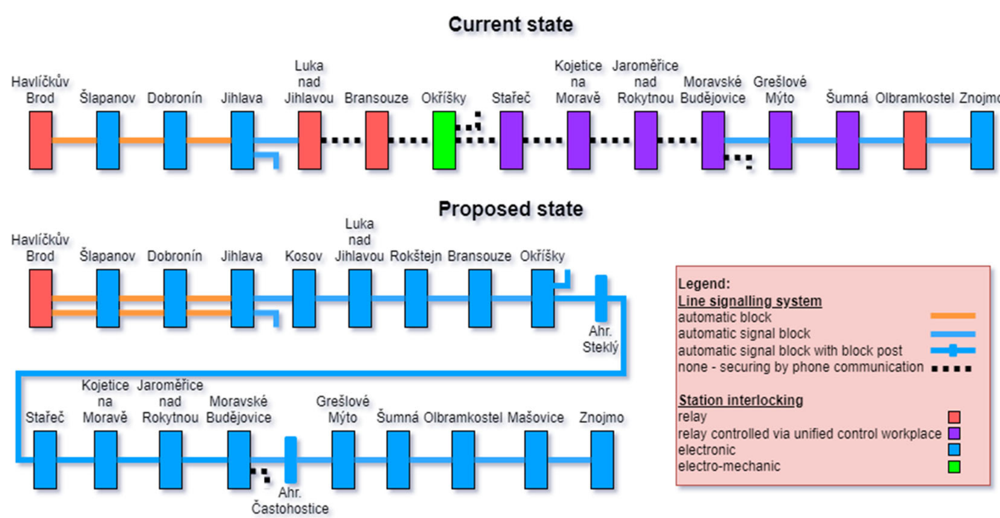

Figure 3. Line scheme.

The local line Moravské Budějovice - Jemnice is currently operated under simplified control according to the SŽ D3 regulation, where safety is ensured by telephone communication between the driver and the dispatcher. As passenger traffic on the line is only operated on weekends and seasonally, and freight traffic is organised regularly (but with only one pair of trains), it is proposed that this type of control be maintained. In the long term, however, it would be advisable to modernise and secure this line as well, preferably by introducing remote control and transferring the operation to SŽ D1 regulation, as well as on the rest of the line. This will also increase safety and capacity on this branch line [41].

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The journey time limit has facilitated the identification of sections of the line where it is appropriate to implement infrastructure measures to enhance capacity. In the case of the Havlíčkův Brod–Znojmo line, the implemented modifications resulted in a notable increase in capacity, from the initial 14 journeys in the peak period to 22 journeys.

The aforementioned increase in capacity, in conjunction with other related infrastructure modifications (including alterations to station configurations, the extension of station tracks, an increase in line speed and electrification), have rendered this line a fully-fledged diversionary alternative to the Brno node.

Modernizing signalling equipment has also permitted the implementation of remote traffic control across the entire section, reducing CZK 17.488 million per annum in personnel costs. This equates to CZK 140,000 per kilometre of line [42].

4. Discussion

This methodology provides valuable insights into optimising railway network performance, focusing on the limitation of journey time and its utilisation and the factors that influence them. The methodology outlined within this study emphasises the significance of accurately determining limiting journey times as a critical component in evaluating railway operations.

The analysis emphasises that infrastructure enhancements, including track upgrades, improved signalling, and station layouts, can lead to substantial improvements in performance. Furthermore, incorporating advanced technologies, such as ERTMS and automated train operation systems, will likely offer significant gains in operational efficiency and reliability.

The applicability of this method is contingent upon the condition that the line under consideration is not divided into multiple block sections. If the line is segmented into several sections, the method is deemed incompatible due to the complexity inherent in integrating train bundling. Nevertheless, under circumstances where trains on such a line do not frequently undergo bundling and, for instance, trains intersect at each station, particularly during periods of peak traffic, the implementation of this method becomes feasible (a scenario that is analogous to the Havlíčkův Brod - Jihlava segment). The method's merits lie in its simplicity and potential for universal application on single-track lines. In the future, examining the problem of existing tangent lines and attempting to upgrade them to release capacity around agglomerations would be advisable.

Finally, while the present study focuses chiefly on the technical aspects of railway system optimisation, it underscores the significance of collaboration among various stakeholders, including railway operators, infrastructure managers and regulatory bodies. Effective coordination across these groups is imperative for implementing pragmatic solutions aligned with long-term transportation objectives.

In conclusion, the study provides a solid foundation for improving railway network efficiency, focusing on the determination of limiting journey times and identifying key areas for enhancement. While further research is needed to refine these strategies, the study provides valuable insights that can guide the future optimization of railway systems, balancing technical improvements with broader operational and policy objectives.

5. Conclusions

This article proposes a robust analytical framework for evaluating and enhancing railway line performance, with a particular emphasis on assessing journey times and identifying opportunities for efficiency improvements. Utilising a data-driven approach, the methodology facilitates a comprehensive understanding of the factors influencing overall operational performance. It underscores the significance of precise data collection and the employment of analytical techniques to identify areas necessitating attention, thereby contributing to the optimisation of service delivery. The methodology is comprised of three constituent elements:

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- Segmentation of the Railway Line - the initial step in this process is the division of the railway line into segments, with the basis of this division being the similarity of traffic volumes. This segmentation uses a moving average, with each segment comprising several connected line sections. This division is of crucial importance to identify areas in which infrastructure improvements are most required.
- Determination of Limiting Journey Times - the subsequent stage of the process is to calculate the limiting journey times for each segment. The segment with the longest journey time (occupancy time) is identified first. The second-longest value is chosen if there are significant differences in journey times. This limiting time is progressively reduced to achieve the desired capacity utilisation for the expected number of trains. Based on this, the maximum acceptable travel times are determined for each segment.
- The identification of infrastructure improvements - the methodology has been developed to facilitate the identification of critical sections of the railway line where infrastructure improvements are necessary. These improvements may include dividing the track into discrete block sections, adding track branches such as stations or passing loops, or increasing the number of tracks. These measures are proposed for sections where journey times exceed the limiting value, ensuring that the railway system can meet future demands effectively and efficiently.

The approach is of significant value to railway operators and planners, providing insights that can inform strategic decisions to enhance the railway network's capacity, reliability, and sustainability. It underscores the necessity for continual assessment and adaptation to ensure that the system can meet growing demands and maintain efficiency in the long term. In essence, this methodology promotes a more effective use of resources, ensures better management of railway operations, and contributes to developing a well-functioning transportation network that benefits operators and passengers alike.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/doi/s1, Figure S1: title; Table S1: title; Video S1: title.

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