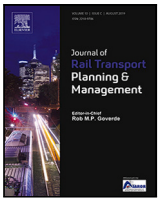
Journal of Rail Transport Planning & Management 40 (2026) 100612

Contents lists available at ScienceDirect

Journal of Rail Transport Planning & Management

journal homepage: www.elsevier.com/locate/jrtpm



Full Length Article

Optimising capacity of railway lines under ETCS Level 2 by implementing densified block sections in station areas

Tobias Müller, Tamme Emunds *, Andreas Pfeifer, Nils Nießen

Institute of Transport Science, RWTH Aachen, Mies-van-der-Rohe Straße 1, Aachen, 52074, Germany

ARTICLE INFO

Keywords:
Railway line capacity
Expected waiting times
Queueing theory
European train control system
Densified block sections

ABSTRACT

With the increased focus on sustainable transportation, railway systems are experiencing increasing capacity demands. Since the construction of new rail infrastructure is very cost intensive, infrastructure managers have a high motivation in increasing the capacity of existing railway infrastructure efficiently. With an implementation of the European Train Control System, block sections of railway infrastructure can be designed more flexible, resulting in enhancements of infrastructure capacity. In this work, we introduce the technique of implementing densified block sections in the line infrastructure and analyse their effect on the nominal capacity with the help of timetable-independent expected waiting time calculations. The results show that an implementation of those densified block sections can not only increase the nominal capacity of the railway line, but additionally save costs by reducing the necessary amount of block sections. Based on their operational constraints, suitable parameter settings for these densified block sections are identified and subsequently integrated into the strategic infrastructure layout for long-term planning.

1. Introduction

Rail transport currently suffers from a partially overaged infrastructure, declining punctuality and high capacity utilisation on main corridors as well as at critical capacity bottlenecks. In order to effectively address these challenges while considering future traffic growth, there are essentially two options. Firstly, effective capacity expansion can be achieved through the strategic development and extension of infrastructure. Additionally, digitalisation and automation of operations and capacity management also contribute to achieving the goals. A part of this solution involves the implementation of the European Train Control System (ETCS). However, the optimal design of the block layout under ETCS remains a relevant parameter for achieving capacity enhancement. In this work, we focus on ETCS Level 2 (L2) on double-track lines because it represents the most commonly used level. ETCS L2 consists of fixed blocks, which can be arranged flexibly and whose length can be less than the train length.

The capacity of the railway system depends on various influencing factors: On the infrastructure (track topology, permissible speeds, positioning of operational infrastructure, and the underlying signalling system), and the implemented operating program (UIC, 2013; Nießen, 2013). In particular, the comprehensive use of ETCS L2 serves as a key factor to increase capacity. This is analysed by Goverde et al. (2013), who demonstrated that infrastructure occupancy under ETCS L2 could be significantly improved compared to the conventional Dutch signalling system. For high-speed traffic between Vienna and St. Pölten, a simulation study showed that ETCS L2 can approximate the small train headway times as they can be achieved with ETCS L3 by utilising short block sections (Schöbel and Permiakova, 2021). Koning (2002) even highlighted that ETCS L2 provides the greater capacity benefits for

* Corresponding author.
E-mail address: emunds@via.rwth-aachen.de (T. Emunds).

https://doi.org/10.1016/j.jrtpm.2026.100612
Received 15 September 2025; Received in revised form 26 June 2026; Accepted 8 September 2026
Available online 25 September 2026
2210-9706/© 2026 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).
Open access funding enabled and organized by Projekt DEAL.

station areas compared to ETCS L3 with moving blocks. A study conducted by the UIC on the impacts of ETCS on line capacity generically demonstrated that both ETCS L2 with short block sections and ETCS L3 have high potential for capacity enhancement (UIC, 2008). Similar conclusions were reached by Nachtigall and Tischer (2023) in their investigation of an infrastructure model representing a typical layout of railway lines and stations in the Czech Republic.

As Ranjbar et al. (2022) have shown, in addition to the choice of the signalling system, block length is a crucial criterion influencing capacity. The precise positioning of signalling components has a decisive impact on railway capacity (Luteberget et al., 2019). The length of block sections under ETCS L2 is not restricted by signal visibility and alignment of the braking distance with the block length, so that a significant improvement in capacity can be expected (Landex et al., 2019). According to the authors, a capacity improvement can be achieved solely by choosing a higher ETCS level (here L2), which can be further enhanced through block optimisation. Quaglietta (2014) also emphasises that when designing the signalling layout, there is a tendency to maximise the technical efficiency of the system by shortening the length of block sections. At the same time, investment costs increase proportionally with the number of trackside equipment and their maintenance as the number of defined block sections increases (Sun et al., 2019). Therefore, the minimum costs for construction and maintenance are achieved when the number of trackside block sections is minimised, maximising the length of block sections. Thomas et al. (2008) demonstrate that larger blocks result in a significant reduction in capacity, but there is a declining return as the block size decreases.

There have already been attempts to automate or at least partially automate the optimal block layout for various signalling systems. Luteberget et al. (2019) have developed a method primarily intended for smaller scales, as in the design phase of infrastructure planning. The aim is to assist planners in the early planning stages in generating the most efficient block layout by taking the specific track plans and information on the local capacity specifications as input. Vignali et al. (2020) have developed an analytical methodology for designing railway control systems under ETCS L2, determining the optimal length of block sections based on travel time requirements with the fewest number of signal installations. The procedure requires various input parameters such as train types, braking curves, specific schedules, headways, and infrastructure features. Using the developed tool, track-specific block section lengths are calculated and the required positioning of the signal infrastructure is derived. Furthermore, block layouts are optimised in the context of energy-efficient driving. Ke et al. (2009) have proposed such an algorithm for Mass Rapid Transit Systems, though it does not meet the criteria for capacity optimisation. More recently, Grubor et al. (2024) introduced a method to partially automatically design the most capacity efficient block layout for ETCS L2 systems without signals. Their approach includes restrictions such as overhead line section breaks or railway crossings, however they focus on the optimal layout for the whole line and therefore do not consider existing, usually homogeneous, block section lengths. Contrarily, this work introduces an approach that can enhance existing signalling infrastructure by condensing block sections specifically in the areas close to railway stations, but refrains from including case-specific restrictions.

Existing methods rely on various input parameters (such as specific track plans, preliminary signalling designs, specific timetable designs, and information on rolling stock) and require complex simulation or calculation methods. Consequently, the results are specific to individual cases and applicable in the medium to short term due to the required level of information density.

With this contribution, we aim to present a method that derives generally valid specifications for the planning of block layout in proximity of railway stations. In detail, we

- describe a method to evaluate block layouts based on the estimation of expected waiting times,
- apply this method to describe the performance benefits of densifying block sections in station areas,
- and derive suggestions of standard block separation implementations for different traffic demand scenarios, that can be applied in the context of strategic infrastructure dimensioning.

While previous research has primarily focused on the optimisation of block sections along railway lines, this study specifically addresses the operational processes related to station approaches and departures. One main objective is to develop efficient block layouts in station areas while maintaining the given block division on the railway line. For this, we target the reduction of minimum headway times with the help of block compression at the transition between railway line and passing station. The introduced method allows the derivation of an efficient arrangement of densified block sections in station areas solely from the input of route characteristics and a rough train schedule. Accordingly, a microscopic analysis is required only once for the initial generation of the compressed block sections. By applying a queueing-based method to estimate expected waiting times, the introduced method reduces the need to conduct complex, case-specific simulations to evaluate operational quality.

Therefore, the objective is not to perform calculations for a specific case under predefined boundary conditions, but rather to define a strategic infrastructure layout for long-term planning in the absence of a concrete timetable. The primary objective is to support the initial planning and design of infrastructure through the definition of so-called *line standards*, which describe the technical and operational characteristics of railway lines in clusters depending on three main parameters: maximum permitted velocity, train type and capacity. Given the operational heterogeneity resulting from different maximum velocities, discrete velocity transitions, and traffic-related stops, the dimensioning of block lengths based on uniform average values is methodologically inappropriate. Instead, block lengths should be specifically tailored to the respective operational requirements. The necessary consideration of basic operational constraints can be ensured effectively and sustainably through the definition and application of suitable line standards. This approach eliminates the need for either case-specific calculations or the application of generalised design parameters that are independent of the underlying operational concept.

The remainder of this work is organised as follows: Section 2 discusses the influencing factors to the performance of a railway line. While Section 3 introduces the methodology for this work, Section 4 conducts a case study for mixed traffic railway lines and compares the performance of different infrastructure layouts. A conclusion is given in Section 5.

Table 1
List of notations.

λ	Arrival rate
λ_{max}	Maximal possible arrival rate
λ_{opt}	Optimal arrival rate
t_U	Time horizon
$\mathrm{E}T_W$	Expected waiting time
$\mathrm{E}T_{W,sum}$	Total expected waiting time
T_W^*	Waiting time threshold
n_{opt}	Nominal capacity
$z_{i,j}$	Minimum headway time
$\bar{z}$	Average minimum headway time
$\bar{t}_\mathrm{P}$	Average buffer time
p_VE	Probability of delayed arrival
$\bar{t}_\mathrm{VE}$	Average delay at entry
p_g	Probability of equal-ranking train succession
p_{pt}	Share of passenger traffic
$v_{\mathrm{max,\ train}}$	Maximum velocity of rolling stock
$v_{\mathrm{max,\ line}}$	Maximum velocity at the line
$v_{\mathrm{max,\ switch}}$	Maximum velocity at the branching switch

2. Railway line performance indicators

To assess the performance of railway lines, different performance indicators may be used. In Section 2.1 the definition of railway line capacity for this work is proposed. An outline of various railway line performance influencing factors is given in Section 2.2. Table 1 gives a summary over the used notations.

2.1. Capacity definition

While the definition of theoretical railway capacity can be described naturally as *the maximal number of trains that can traverse the infrastructure in a fixed amount of time*, more diverse types of capacity, depending on the application scope, may be distinguished (Wakob, 1985).

The UIC (2013) considers the *capacity consumption* of a timetable, describing the specific utilisation factor of the railway line by planned train journeys. By compressing the blocking time of the train journeys in the signalling blocks of the infrastructure, a compressed combined occupation time can be obtained. The concatenated occupancy rate can be determined by comparing this compressed time with the investigation period. Depending on the line and traffic mix, this concatenated occupancy rate should correspond to a value between 0.6 and 0.85.

Despite various definitions in this contribution however, the notation of *operational capacity* (sometimes referred to as *practical capacity*) is assumed. It corresponds to the maximal number of trains that can traverse the given infrastructure in a fixed amount of time, while considering the quality of operation. This number is further on referred to as the *nominal capacity* n_{opt} of the railway line. It can be described independent of a timetable with the mean arrival rate of the railway line. A queueing system models the arrival and service process of the analysed railway line (see f.e. Weik et al., 2016). The nominal capacity can be obtained with the optimal *arrival rate* $\lambda_{opt} = \frac{n_{opt}}{t_U}$, i.e. the rate in which trains are operating on the modelled railway line in the analysed time horizon t_U (Niessen and Kogel, 2014).

The operational quality of a railway line is measured by estimating the *expected waiting time* $\mathrm{E}T_{W,t}$ for a train t on the railway line. The waiting time of a train results from disturbances in the operational processes, f.e. by delayed trains. In this work, the STRELE-Method (Schwanhäußer, 1974; Weik et al., 2016) is utilised for the computation of $\mathrm{E}T_W$, see Section 3 for a detailed introduction.

An exemplary plot of the total expected waiting time $\mathrm{E}T_{W,sum}$ for different arrival rates λ is given in Fig. 1. Since the expected waiting time increases substantially with an increasing arrival rate, the maximal possible arrival rate λ_{max}, i.e. the rate corresponding to an operation without any buffer times (see Section 2.2), would yield a not tolerable amount of waiting times in the system.

To ensure a sufficient operational quality, the estimated expected waiting times of all trains $t \in T$ in a system $\mathrm{E}T_{\mathrm{W,sum}} = \sum_{t\in T} \mathrm{E}T_{\mathrm{W},t}$ can be compared to a threshold waiting time T_W^*, set by infrastructure managers (see Schwanhäußer and Schultze, 1982; DB InfraGO AG, 2022). The maximal arrival rate with an expected total waiting time $\mathrm{E}T_{\mathrm{W},sum}$ of less than the threshold hence corresponds to the optimal arrival rate λ_{opt}. This optimal arrival rate is further utilised to determine the nominal capacity n_{opt} of the railway line.

While the STRELE-Method for the determination of expected waiting times will be described in Section 3.2, the next Section discusses the influence of different parameters to the operational quality of a railway line.

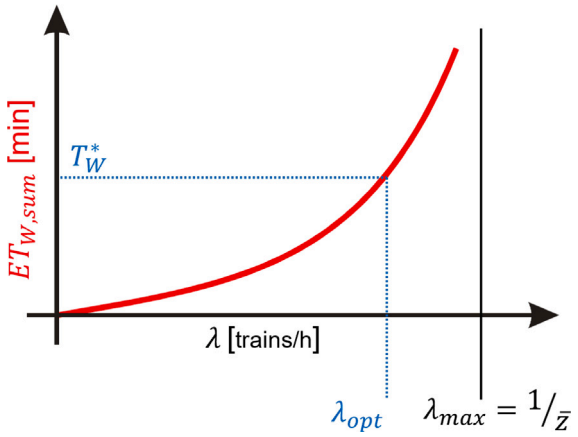


Fig. 1. Exemplary progression of the expected waiting time of all trains for an increasing arrival rate.

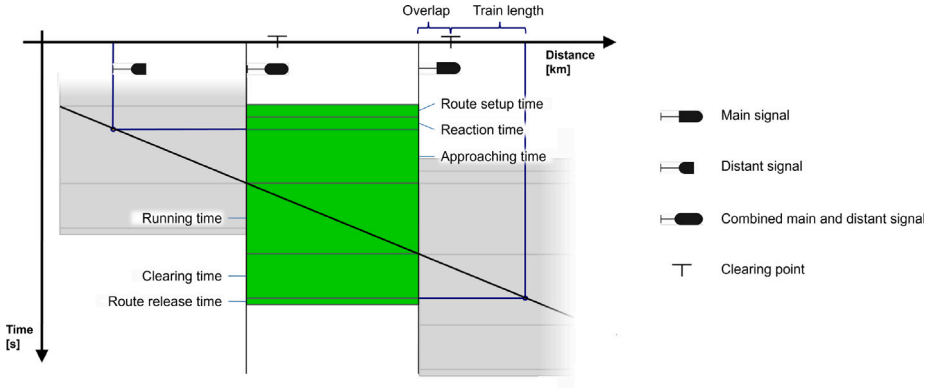


Fig. 2. Blocking time components of a block section in a main/distant signal system. Including neighbouring sections, a blocking time stairway emerges.

2.2. Influences to railway line capacity

In this section, the parameters that influence the capacity of a railway line will be discussed. One major parameter is the consumed capacity of a single train journey on the railway line.

The capacity consumption of train journeys can be described using the *blocking time* model, introduced in Happel (1959) (see also Hansen and Pachl, 2014). Due to the fundamentals of train protection, trains must keep to the distances specified by the infrastructure. A track is divided into block sections to keep trains apart. As only one train is permitted in each block section, blocking times correspond to the time, the block section is blocked for the use by other trains. The blocking times consist of different components, stated in Fig. 2 for a section equipped with conventional signalling. Obviously, the length of a block section (i.e. the distance between two main signals) significantly influences the resulting capacity consumption (see also Pachl, 2015).

The piece-wise occupation of the individual blocks on a railway line by a train journey is referred to as a *blocking time stairway* (see also Hansen and Pachl, 2014). Usually the blocking time stairway is build and further utilised for the capacity determination.

Introducing new signalling and train protection systems like ETCS L2, some modifications to the blocking time model are inescapable. Instead of a fixed distant signal, the individually calculated braking distance for each rolling-stock instance is considered and causes a broader range of approaching times.

The *minimum headway time* $z_{i,j}$ results from the sequence of two blocking time stairways.

This essential input variable for railway operations research is the shortest time in which two trains $i, j \in T$ can succeed on the analysed track section without obstructing each other. The minimum headway time therefore depends on the characteristics of the consecutive trains, for instance the maximum speed and stopping times. In principle, several distinct cases can be differentiated. If trains operate at identical speeds, the longest block section is generally the determining factor for the minimum headway time. In the case of heterogeneous speeds, required overtakings become decisive, such that braking and acceleration processes significantly influence the minimum headway time. For single-track sections, by contrast, the spacing of passing stations is the relevant parameter. All three cases described exhibit a strong dependence on the block section layout and the speed differential. These and additional Parameters that significantly influence the calculation are described in Table 2.

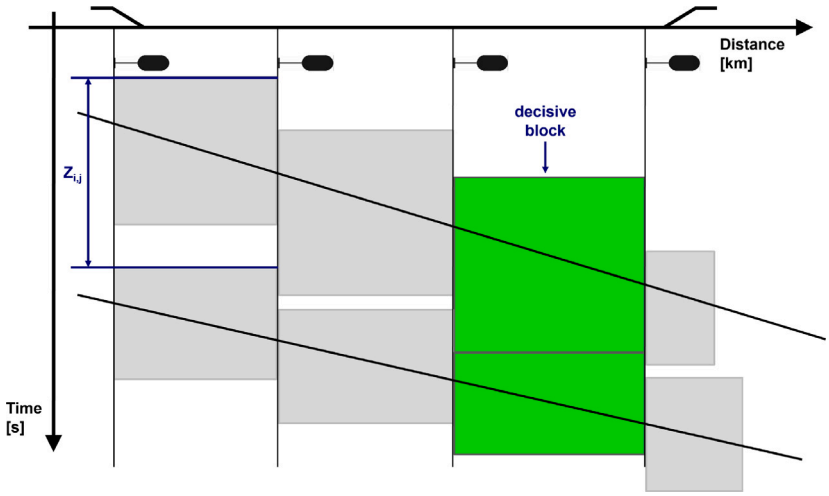


Fig. 3. The minimum headway time on a railway line.

Table 2
Parameters affecting the minimum headway times.

Parameter	Influence on minimum headway times
Block section layout	The decisive block section may be located in different areas, depending on the train sequence (see also Table 4 and Fig. 3)
Train control system	Influences to the blocking time and hence the minimum headway time
Infrastructure layout	May impose speed limits, extending the running time
Speed difference	Increases the minimum headway time in some cases, due to the necessity for faster trains to wait for the end of occupation by slower trains
Rolling stock characteristics	Influences to the driving dynamics and hence to the minimum headway time
Distance between passing stations	Leads to larger minimum headway times when enlarged

Table 3
Parameters that influence railway capacity in addition to the minimum headway time.

Parameter	Influence on railway capacity
Buffer time	The probability of knock-on delays decreases with more buffer time
Delay distribution	The higher the probability of delayed trains and the more average delay they have, the higher the amount of average waiting times per train
Priority of running services	May cause increasing expected waiting times due to passing limitations to trains of different ranks
Share of passenger traffic	More delays are admissible for freight traffic (see Schwanhäußer, 1974; DB InfraGO AG, 2022)
Single- v. double-track infrastructure	Opposing train services cause large minimum headway times for single track infrastructures

To determine the minimum headway time on a section, the blocking time stairways of these trains are compressed until they firstly intersect. The minimum headway time is then appointed at the beginning of that shared section. Fig. 3 gives an example of the minimum headway time on a railway line.

Modelling a railway line as a queueing system (see Section 3.2), the average minimum headway time $\bar{z}$ serves as the service time within the corresponding model and directly influences the capacity of the respective infrastructure.

Other influences to the capacity of a railway line contain parameters that describe the relations between multiple train journeys on the infrastructure. They are described in Table 3.

For example, the time in between the service of two consecutive train journeys is described as *buffer time* $t_{\mathrm{P},i,j}$. It corresponds to the difference $t_{\mathrm{P},i,j} = h_{i,j} - z_{i,j}$ of the actual realised headway time $h_{i,j}$ in the schedule and the theoretical minimum headway time $z_{i,j}$. Since in early planning steps no timetable can be utilised to determine the actual buffer time, the average buffer time $\bar{t}_{\mathrm{P}}$ is utilised in this work. It can be calculated as the difference $\bar{t}_{\mathrm{P}} = t_U - n \cdot \bar{z}$ between the length of the time-horizon and the sum of all minimum headway times (see also Schwanhäußer, 1974).

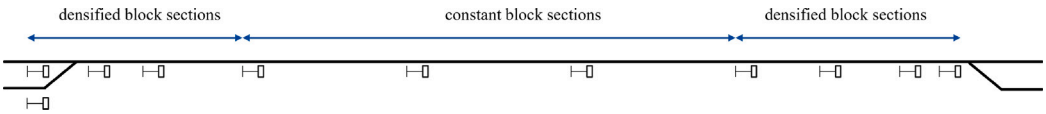


Fig. 4. Distinction of different types of block sections, here simplified for one directional track of a double-track line.

Furthermore, since a railway line is usually part of a more complex railway network, trains might not arrive on time for their allocated infrastructure utilisation slot. This can be described with the *delay distribution*, a probability distribution corresponding to the delay of a single train on arrival. Its parameters represent the *probability of a delayed arrival* p_{VE} and the *average delay* in case of a delayed entry $\bar{t}_{\mathrm{VE}}$ (see also DB InfraGO AG, 2022).

If a train is arriving with some kind of delay, conflicts with other trains may arise. Those conflicts have to be resolved, and this is assumed to be done by implementing the *priority* of a train journey. While trains with the same priority are dispatched in a first-in-first-out discipline, trains with higher priority are given precedence over trains with lower priority. Therefore, the distribution of succession between trains of the same priority and succession between trains of different priority is influencing the capacity of a railway line. In this work, this distribution is described with the parameter *probability of equal-priority train succession* p_{g}.

To facilitate different operating quality requirements for freight and passenger traffic, the share of passenger traffic p_{pt} is utilised in the determination of the threshold value T_{W}^{*} to the total expected waiting times (see Section 3.2).

Additionally, a distinction between single- and double-track lines should be made. On single-track lines, the block division is of minor importance since only the distance of passing loops and not the block division in between is of significance in the case of trains running in opposite directions. As an optimised block layout is a major aspect of the following investigations, only double-track lines are considered in the remainder of this work.

With these introduced parameters, an estimation of the expected waiting time per train can be calculated with the STRELE-Formula, described in the next section.

3. Methods

In the previous section, various key infrastructure characteristics that influence capacity have been identified. The upcoming Section 3.1 proposes a method for developing densified block sections close to railway stations. Block densification is implemented with the objective of reducing the minimum headway time. When entering and exiting a station, different acceleration and braking capacities have a significant impact on the minimum headway time, so that an improvement can be expected, especially in these areas. The greater the speed differential between two consecutive trains, the more significant the impact of block densification. Consequently, a particularly significant impact is to be expected in overtaking scenarios (see also Section 2.2). Section 3.2 describes the STRELE-method, which estimated the expected waiting times for train journeys on a railway line, utilising the in Section 2.2 introduced parameters.

3.1. Densified block sections adjacent to passing stations

It can be assumed that an overtaking will occur when there is a significant speed difference between two consecutive trains. The aim of densified block sections in station area is in this case to enable two consecutive trains with such a speed difference following within minimum timely distance. These block sections are to be distinguished from a constant block division on a whole section, as illustrated in Fig. 4. We assume a minimum block section length of 70 m, corresponding to a value where no disproportionately restrictive braking curves occur if the overlap is dimensioned accordingly. When applying ETCS L2, the length of 70 m corresponds to the standard overlap distance in Germany (DB InfraGO AG, 2023; Goers et al., 2019). The basis for this is the continuous, precise monitoring of the train, which reliably prevents the train from approaching a stop too quickly at all times. In principle, the procedure could also be carried out with a different, minimum block section length (>70 m), provided that it meets operational requirements. However, using a larger initial block section length (>70 m) would result in a lower resolution of the results, since the step size for merging the smallest block sections would increase accordingly. In the further elaboration, we therefore assume the german operational requirements (70 m).

The infrastructure in the approach area to the station up to the beginning of the switch, is initially divided into these 70-metre blocks, which are delimited by ETCS block markers. In subsequent stages, some of these block segments are merged, as such a fine granularity does not contribute to increased capacity and is therefore not efficient for block section allocation. The method assumes that block markers can be positioned arbitrarily. In reality, however, restrictions such as overhead line sectioning points or level crossings must be considered.

Next, two train movements are constructed so that their blocking time stairways intersect at the critical switch within the shared path. This achieves the minimum technically feasible headway time between these two train movements under this block division. Based on the previously defined 70-metre blocks, an analysis is conducted to determine which of these blocks can be consolidated without increasing the previously achieved minimum headway time. This consolidation can be determined based on the occupation times of the two train runs in the individual block sections.

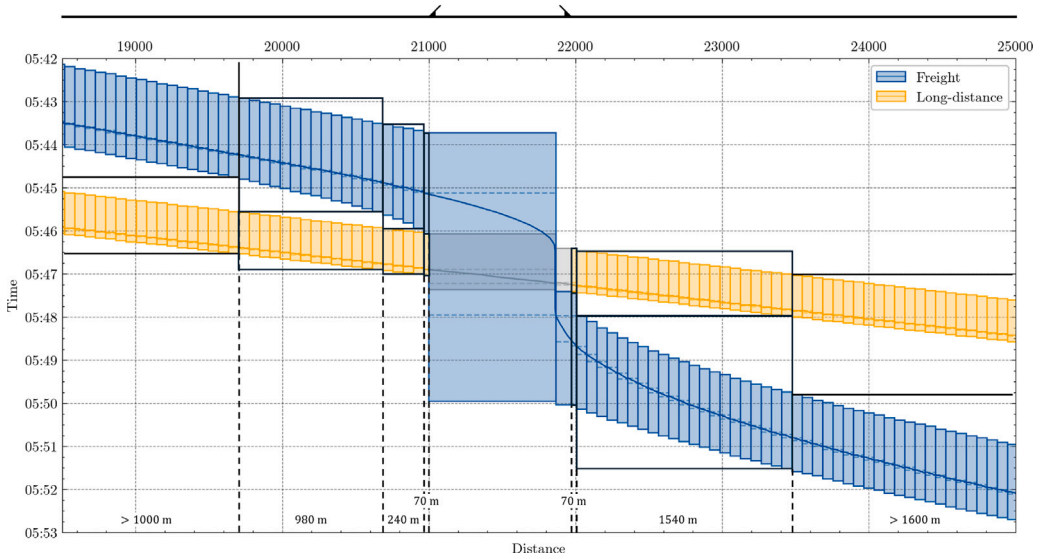


Fig. 5. Blocking time staircases for block sections of 70 m length and realisation of densified block sections through a maximal merging of these block sections without causing negative impact to the minimum headway time. The block sections in the entrance scenario are more densified than those in the exit scenario.

Preliminary investigations during this research have indicated that the entrance to a passing station usually requires more densified block sections than the exit. The block division development in the example in Fig. 5 highlights this effect, allowing for long block sections during acceleration, but requiring shorter block sections during braking. This can be explained with the fact that, due to higher braking decelerations, the braking process requires a shorter duration than the acceleration process. This difference is particularly evident for freight trains, whose braking process when utilising the maximum braking deceleration is generally significantly shorter than the corresponding acceleration process. The difference is notably smaller for rapidly accelerating passenger trains. This results in the observation that the block separation requirements determined for the entry scenario are also sufficient for the departure from a station.

In this study, it is assumed that each track can be used for train movements in both directions. Under this assumption of full bidirectional track operation, both arrivals and departures can be carried out on every track leading into and out of the station. Note that, under ETCS L2, the block layout remains permanently fixed once planned, as it requires the physical installation of track vacancy detection systems to separate block sections. Furthermore, the installation of additional track vacancy detection systems to optimise for the less restricting trajectories during accelerations seems to be ineffective in terms of fund allocation. As we assume full substitution capability of both tracks, we therefore consider only symmetric block layouts, utilising the same block lengths after and before passing station areas.

All further calculations now refer to train sequences in which a fast train (e.g. a long-distance train) follows a slow train (e.g. a freight train) of with the latter needs therefore be overtaken in a station.

When entering a station, train sequences are analysed in which the 1st train heads for the passing track via the branch of the switch and stops there. The succeeding train in contrast follows the main track and passes the station. Different stopping patterns are considered depending on the type of train services. Basically, local passenger services stop frequently, while long-distance passenger services only serve major junctions between lines. Freights only stop for passing if required.

The densified block section layout adjacent to passing stations is significantly influenced by the characteristics of the running train services, the line speed, the permitted speed in the branch track of the switches and the route setup time. This dependency on the specific train sequences results into a broad number of combinations, each with its specific optimised densified block sections in the station area. Consider an example with three different services, such as Freights, local and Long-distance services. It is assumed that each service segment is characterised by specific rolling stock. While their maximum speed may be similar due to speed restrictions on a given railway line, the braking, acceleration and stopping behaviour might differ between all three train types. Hence, the optimal block section layout depends on the chosen train combination variant. For a specific railway line, a variant is then to be selected from the train sequences that may realistically occur on this type of line. By choosing the train sequence that requires the most condensed block sections, the minimum headway time of all other possible train sequences on that line can also be improved, see also the analysis of minimum headway times in Section 4.2. This reasoning has been used to select the decisive train sequence in this work.

It appears that continuous short block sections with a constant length of 70 m reduce the minimum headway time compared to a conventional block layout, but require huge effort in terms of infrastructure across the whole line. In such an example (see the black rectangles in Fig. 5), the blocking time staircases of the two succeeding train journeys can be compressed up to a single point

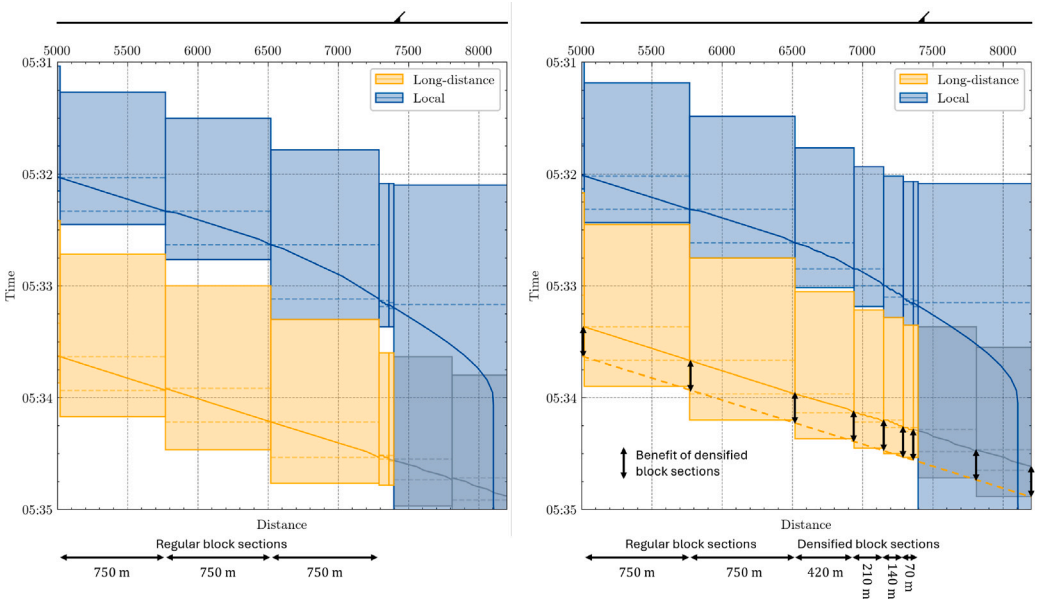


Fig. 6. Effectiveness of densified block sections compared to a continuously constant block division using the example of a 750 m block division on the line.

of contact: The block section including the switch, separating both routes. This also indicates that the respective route setup time decisively influences the minimum headway time.

Moving backwards from the switch, block sections can now be merged until the resulting blocking times of both trains interfere in that area. These merged block sections are further introduced as one combined block section. Figs. 5 and 6 emphasise that the amount of required block sections can be effectively reduced in this way without causing negative impact on the resulting minimum headway time. As explained above, the minimum block length is 70 m, which is utilised in the block section before the switch. This block section may also need an increased route setup time due to the switch immediately behind it.

By using densified block sections in the station area, the minimum headway times can be reduced whilst keeping the block division constant on the line. This effect is illustrated by the comparison in Fig. 6. This also implies that the densified block sections enable extended block sections between stations since negative effects are compensable to a certain extent, see also the results in Section 4. The upcoming Section 4 further evaluates that effect.

3.2. Determining the capacity of railway lines

The STRELE-formula according to Schwanhäußer (1974) (see also Weik et al., 2016) is one of the analytical methods used in railway operations research and is an well established method for determining the capacity of railway lines. It is based on queueing models and investigates the development of delays on a route.

With

$$\begin{aligned} ET_W = &\left(p_{VE} - \frac{p_{VE}^2}{2}\right) \cdot \frac{\bar{t}_{VE}^2}{\bar{t}_p + \bar{t}_{VE} \cdot (1 - e^{-\bar{z}/\bar{t}_{VE}})} \\ &\cdot \left[p_g \cdot \left(1 - e^{-\bar{z}_g/\bar{t}_{VE}}\right)^2 + (1 - p_g) \cdot \frac{\bar{z}_V}{\bar{t}_{VE}} \cdot \left(1 - e^{-2\bar{z}_V/\bar{t}_{VE}}\right)\right. \\ &\left. + \frac{\bar{z}}{\bar{t}_p} \cdot \left(1 - e^{-\bar{z}/\bar{t}_{VE}}\right)^2\right], \end{aligned} \tag{1}$$

it calculates the estimated expected waiting times per train on the modelled railway line.

A key input variable are the minimum headway times described earlier, in the form of the average minimum headway time $\bar{z}$, the average minimum headway time of equal ranking successions $\bar{z}_g$ and of different ranking successions $\bar{z}_V$. Furthermore, the parameters of the delay distribution, i.e. the probability of a delay at entry p_{VE} and the average delay $\bar{t}_{VE}$, are utilised. Additional influences are modelled with the average buffer time $\bar{t}_P$ and the probability of equal-ranking train succession p_g.

The model works independently of a specific timetable, but takes into account the probability of train sequences

$$p_{i,j} = \frac{n_i \cdot n_j}{n_{total}} \tag{2}$$

Table 4
Decisive block sections and influence of distance between stations for different train sequences.

Train sequence	Decisive block section	Influence of station distance
Equal speed	Longest block section	None
Slow train succeeds fast train	Block section at the beginning of the shared path	None
Fast train succeeds slow train	Block section at the end of the shared path	Yes

based on the frequency n_i/n_{total} of different trains $i \in T$ during the given investigation period in the calculation of the average minimum headway times

$$\bar{z} = \sum_{i,j \in T} p_{i,j} \cdot z_{i,j} \ , \tag{3}$$

as well as $\bar{z}_{\mathrm{g}}$ and $\bar{z}_{\mathrm{V}}$ accordingly. Note that the frequency of trains does depend on the number of trains n_{total} in a given operating program, but no specific timetable is being utilised. This operating program is hence only used to determine the probabilities of train sequences $p_{i,j}$, for the determination of the proportion of same/different rank train sets, and for the determination of the share of passenger traffic p_{pt}.

The resulting expected average waiting time $\mathrm{E}T_{\mathrm{W}}$ per train can be utilised to compare the expected total waiting time $\mathrm{E}T_{\mathrm{W},sum}$ to a threshold value T^*_{W}, corresponding to a sufficient operational quality for the railway line.

In this work, the limit value T^*_{W} to the total expected waiting times of the largest german infrastructure manager, DB InfraGO AG (2022), is utilised. It corresponds to

$$T^*_{\mathrm{W}} = 370 \cdot \exp(-1.3 \cdot p_{pt}) \ \mathrm{min}, \tag{4}$$

in 24 h. Here, the share of passenger traffic p_{pt} in the specified operating program influences the level of admissible waiting times. Note that the amount of admissible waiting time is reduced with an increasing share of passenger traffic. When the sum of expected delays $\mathrm{E}T_{\mathrm{W,sum}}$ corresponds to the limit T^*_{W}, the railway operation program is considered to be economically optimal. The associated number of running trains on the railway line is referred to as the nominal capacity n_{opt}.

This STRELE-formula is useful to analyse the impact of infrastructure design on capacity timetable independently as it considers infrastructure characteristics indirectly via the minimum headway times included in the calculation. In general, the method applies to a given infrastructure and an assumed operating program and the resulting performance is determined. Here, however, the methodology is applied to a generic infrastructure within which various parameters are varied under controlled conditions. For this purpose, different constellations of train sequences must be taken into account. Therefore, Table 4 outlines only a rough trend and is intended to illustrate the general context. Specific cases depend on a variety of factors, particularly with regard to ETCS.

Note that the distance between to stations with overtaking possibility has to be considered only in the case that a faster train succeeds a slower train. For the case of equal velocity or for instances where the first train is faster than the second train, either the longest block section or the block section at the beginning of the shared path is decisive for the minimum headway times calculation.

For calculating journey profiles and occupancy times, a travel and blocking times calculation on a microscopic infrastructure model is used to determine the required minimum headway times on a route section with a specified length. This is particularly useful as it enables considering the acceleration and braking phases around junctions and stations correctly when calculating the minimum elements.

4. Application and results

When designing railway lines, infrastructure managers need to decide the separation of block signals. In order to avoid planning from scratch, infrastructure managers may develop equipment standards that can be applied to multiple railway lines with similar demands. Such an approach is implemented in Germany through the so-called line standards. In this section, we sketch the possibility to derive idealised block sections in dependence on the operational requirements specified by the line standards , which could then be used as a planning basis for the initial design of infrastructure. The line standards are determined in accordance with the traffic code as specified in the Technical Specifications for Interoperability (European Comission, 2019) (e.g. P1_F1 high-speed mixed-traffic corridors or F3 regional freight-dedicated corridors, see also Section 4.2). Given that block separation majorly influences the nominal capacity of railway lines, infrastructure managers need to carefully evaluate the costs and benefits of block separation strategies.

For this, the implications of different infrastructure variants, with and without densifying the block sections around station areas, are evaluated for multiple demand scenarios. In the next Section 4.1, the methods from Section 3 are utilised to determine efficient infrastructure layouts for a single exemplary operating program in detail. Afterwards, Section 4.2 performs a more abstract comparison of infrastructure layouts for a variety of given operating programs.

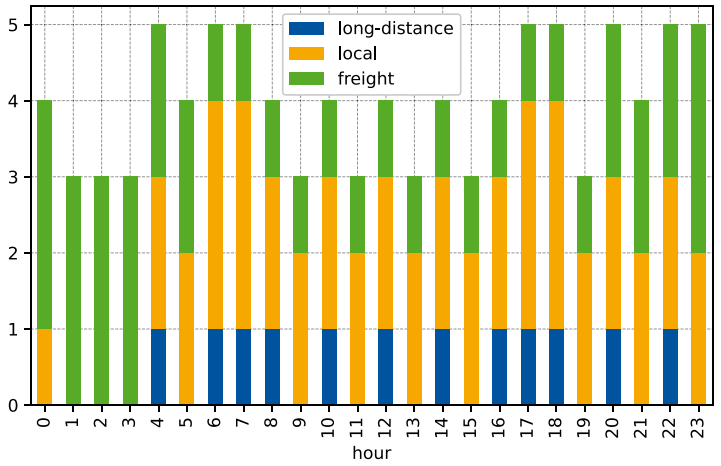


Fig. 7. Operating program of the considered railway line.

Table 5
Parameters of the considered traffic types.

Traffic type	Priority	p_{VE}	t_{VE}	$v_{max,\ train}$	Frequency in 24h
Long-distance passenger trains	3	0.5	5 min	160 km/h	12
Local passenger trains	2	0.6	4.5 min	160 km/h	45
Freight trains	1	0.6	10 min	100 km/h	39

4.1. Determination of an efficient infrastructure layout

As a first example, we consider the case of a mixed traffic railway line and evaluate the costs and benefits of infrastructure scenarios with and without densified block sections.

In Fig. 7, an exemplary operating program is depicted while distinguishing between the different operating hours throughout the day as well as three traffic categories, i.e. *long-distance passenger*, *local passenger* and *freight* trains. The assumed parameters can be found in Table 5, p_{VE} and t_{VE} have been utilised as in the specifications of DB InfraGO AG (2022).

Utilising the frequencies of the different train types in the operating program, the additional parameters, required for the calculation of the STRELE-formula (Section 3.2), have been calculated. These include the average probability of delayed arrival $\bar{p}_{VE} = 0.59$, the average delay at entry $\bar{t}_{VE} = 6.8$ min and the probability of equal-ranking train succession $p_g = 0.372$. For the analysis, minimum headway times are calculated with the microscopic blocking time calculation tool *LUKS* (Janecek et al., 2020), see Hansen and Pachl (2014) for an introduction. Resulting minimum headway times for this line can be found in Appendix A.

The operating program has been tested against different infrastructure implementations, varying in the overall length of the block sections on the line. Furthermore, infrastructure variants with densified block sections and without densified block sections in station proximity have been investigated.

When designing the infrastructure with densified block sections, the approach described in Section 3.1 has been used: merging 70 m blocks into one combined block section until the maximum combined length without increased minimum headway times is obtained. Starting from the branching switch, this process could theoretically be repeated until the entire infrastructure up to the previous overtaking station consists of increasingly larger block sections. While the minimum headway time in a slow–fast train sequence would not increase, the minimum headway time for trains travelling at the same speed is significantly affected by the longest block section and would thus increase. Therefore, in this work, we have limited the maximum block section length in various infrastructures to corresponding threshold values. Upon reaching these thresholds, only blocks of appropriate length were incorporated.

For the here considered combination of traffic, the block length thresholds of 750 m, 1190 m, 2390 m, and 3800 m have been chosen. These values also correspond to the block lengths on the line outside of the densified sections in station proximity. Therefore, they have also been used as the homogeneous block lengths for infrastructure without densified block sections. Table B.15 depicts the considered densified block section lengths with their respective maximum equal block length. Note that due to a change in the restricting train sequence case, the densified block division for 750 m differs significantly from densified block divisions for the other static block lengths. In this scenario, we consider eight infrastructure scenarios, the variants with and without block densifications for line block divisions of 750 m, 1190 m, 2390 m, and 3800 m.

All infrastructure layouts feature a maximum line velocity of $v_{max,\ line} = 160$ km/h and a maximum velocity at the branching switch of $v_{max,\ switch} = 80$ km/h, see Fig. 8.

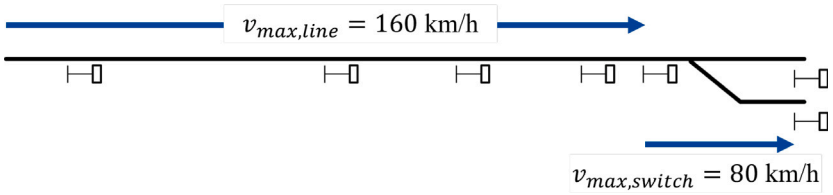


Fig. 8. Velocities in the considered infrastructure.

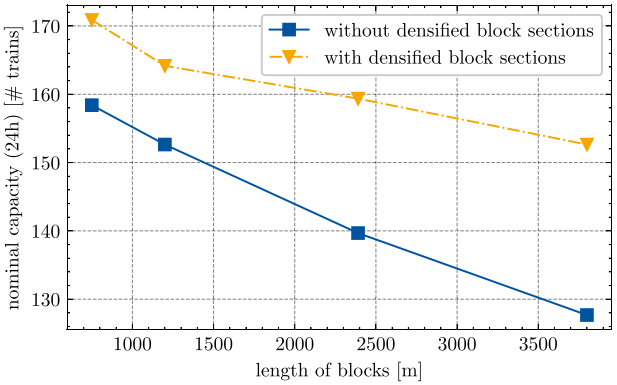


Fig. 9. Comparison of the nominal capacity by the maximum length of blocks for infrastructure with or without densified block sections in a 24 h time-span.

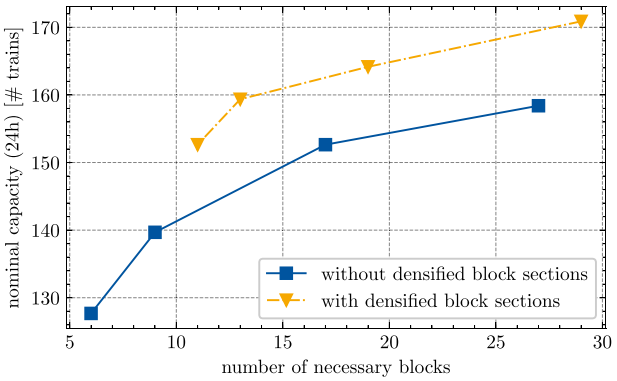


Fig. 10. Comparison of nominal capacity by the number of necessary blocks for infrastructure with or without densified block sections in a 24 h time-span.

To evaluate the capacity achieved with different lengths of the block sections, Fig. 9 depicts these values assuming the operating program in Fig. 7. We distinguish between infrastructure representations with and without densified block sections for a exemplary selected distance of the passing stations of 20 km.

The figure shows that the nominal capacity of the infrastructure without densified block sections is decreasing substantially with an increasing length of the blocking sections. While a number of ca. 159 trains in 24 h is operable with acceptable quality on the infrastructure with a homogeneous block-section length of 750 m, only 128 trains in 24 h remain operable for a homogeneous block-section length of 3800 m. This confirms the effect of smaller blocking section lengths increasing the nominal capacity, discussed in other research (see Section 1).

Accordingly, the capacity of an infrastructure layout with densified block-sections is at 171 trains in 24 h for a maximum block section of 750 m and at 153 trains in 24 h for a maximum block section of 3800 m. Hence the effect of nominal capacity reduction with increasing block section lengths can be mitigated by introducing densified block sections.

However, additional block sections do require the infrastructure manager to fund more train control system infrastructure, i.e. track occupancy detection systems. Hence, the effectiveness of additional block sections should be compared between the two infrastructure scenarios with homogeneous or with densified block section lengths.

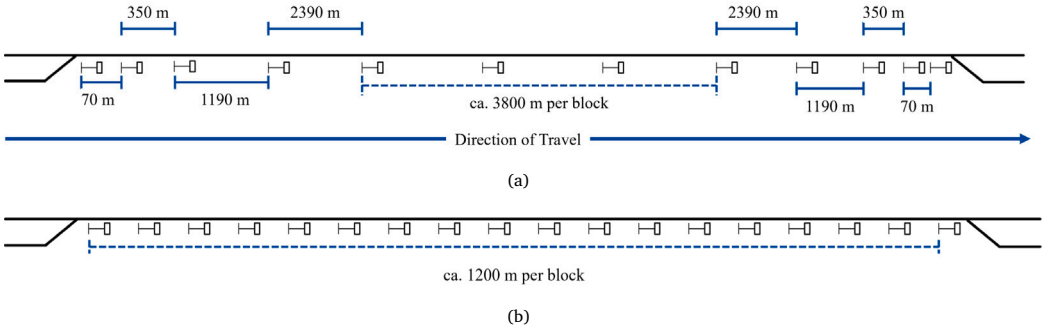


Fig. 11. Line infrastructure with an passing station distance of 20 km. (a) corresponds to a densified block sections implementation with 11 blocks and a capacity of $n_{opt} = 152$ trains. (b) shows a homogeneous block section length of 1200 m implementation with 17 blocks and a capacity of $n_{opt} = 152$ trains.

Table 6
Overview of the parameters for the considered line standards.

Line standard	Traffic amount	5 h traffic			24 h traffic			Passing distance	v_{max} Line	v_{max} Switch
		IC	RE	FT	IC	RE	FT			
P1	High	14	9	0	48	27	0	60	300	100
P1_F1	High	10	6	6	47	24	13	35	300	100
P1_F1	Mid	2	0	6	41	0	7	60	300	100
P2_F1	High	14	12	14	49	42	65	≥10*	250	100
P2_F1	Mid	7	9	6	27	30	39	30	250	100
P2_F1	Low	4	5	4	12	17	20	60	250	100
P3_F1	High	7	16	11	23	56	65	20	160	80
P3_F1	Mid	3	12	5	12	45	39	50	160	80
P3_F1	Low	0	8	3	0	28	16	60	160	80

Fig. 10 illustrates the nominal capacity in dependence of the number of block sections required for an infrastructure layout with a distance between passing stations of 20 km.

A homogeneous block section infrastructure may be already implemented with a total of 6 blocks per direction, while achieving a capacity of 128 trains. In comparison, at least 11 blocks would be required for an infrastructure with densified block sections, in return achieving a capacity of 153 trains. In order to achieve 153 trains in 24 h with homogeneous length block sections, 17 block sections would be required.

In summary, infrastructures with homogeneous block section lengths can be realised with a low number of block sections, but an implementation of densified block sections can actually decrease the number of block sections required for a given nominal capacity. Infrastructure managers may hence opt to install densified block sections, achieving the same nominal capacity with less train control system equipment.

An example for this can be found in Fig. 11 for a 20 km long sample railway line infrastructure between two passing stations. For this railway line, two different control system infrastructures are implemented, one with densified block sections up to a maximum block length of 3800 m 11(a) and the other one with a homogeneous block section length of 1200 m 11(b). In the scenario with homogeneous block section lengths, 17 blocks are necessary, while only 11 blocks are required for the implementation with densified block sections. However, both infrastructure examples correspond to the same nominal capacity of ca. 152 trains in the considered 24 h interval.

4.2. Statistical analysis

In addition to the detailed analysis of the case of a mixed traffic railway line with a medium traffic amount in the last section, this section evaluates the block section densification on a more abstract level. For this, we applied the methods to a variety of demand scenarios and infrastructure variants.

In detail (Table 6), we performed an analysis on 112 scenarios, varying rolling stock (see also Table B.13), traffic demand, passing distance, maximum permissible speed on the line or at the switch, and crucially the block separation (in terms of whether densified block sections have been used and the block length on not condensed sections of the line).

For this, we distinguish between traffic codes (European Comission, 2019) to generate scenarios for different mixed traffic lines. Note that multiple passing distances have been considered for the scenarios of P2_F1 with high traffic load, as this majorly influences

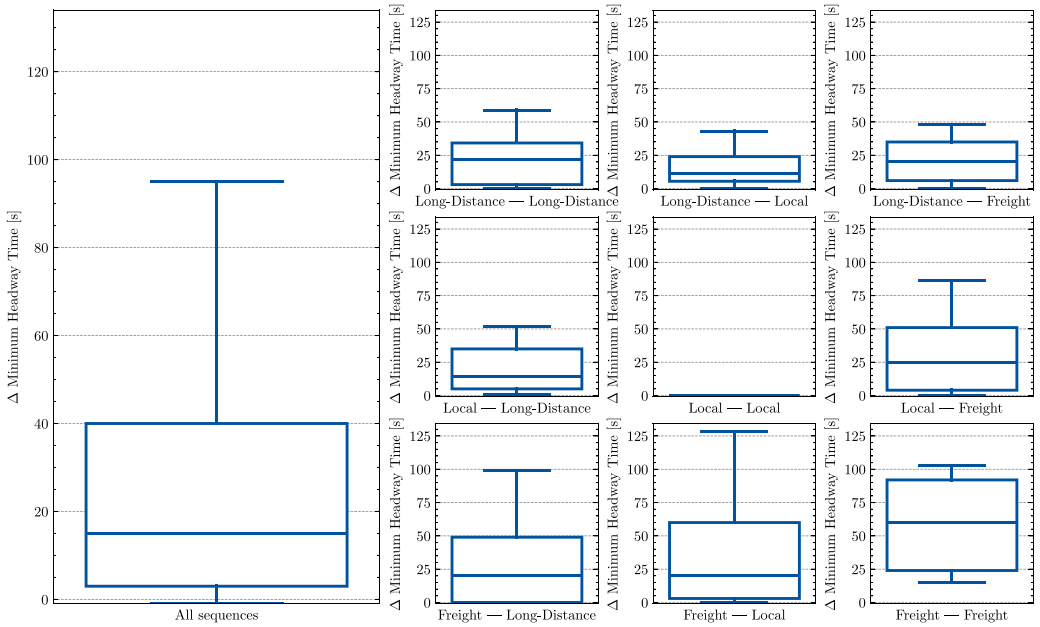


Fig. 12. Statistical analysis of the difference in minimum headway times, when densifying blocks in station proximity.

Table 7
Statistical parameters of the minimum headway time difference (in s) for the scenarios with and without densifying blocks in station proximity.

Scenario	n	$n_{<0}$	min	max	std	median	mean
ld-ld	56	0	0.0	59.0	18.35	22.0	22.11
ld-lo	56	0	0.0	43.0	12.13	11.5	14.43
ld-fr	53	0	0.0	131.0	28.82	20.0	26.36
lo-ld	56	0	1.0	52.0	15.72	14.0	18.75
lo-lo	56	0	0.0	12.0	3.31	0.0	1.04
lo-fr	53	0	0.0	134.0	32.34	25.0	32.36
fr-ld	53	3	−1.0	131.0	37.94	20.0	32.47
fr-lo	53	0	0.0	128.0	33.98	20.0	36.85
fr-fr	53	0	15.0	103.0	31.64	60.0	60.49
Total	489	3	−1.0	134.0	30.37	15.0	26.88

Abbreviations: ld = Long-distance trains, lo = Local trains, fr = Freight trains.

the minimum headway time and therefore nominal capacity in such heterogeneous traffic demand scenarios. The assumed block sections lengths for cases with condensed blocks in station proximity can be found in Tables B.14 and B.15.

Given the block layout for all 112 scenarios, the minimum headway times could be computed. In Fig. 12, these are compared for each train sequence in every scenario-pair with the same block length on the open line but either with and without densified block sections in station proximity. Note that stops at both ends of the evaluated line section have been assumed for every freight train, while passenger trains are considered to run through.

The box plots illustrate the statistical distribution of the reductions in minimum headway time resulting from block densification in station proximity. Note that the box plots in Fig. 12 are grouped based on traffic sequences, even though different rolling stock units have been assumed for different traffic types, based on the evaluated standard scenario (see Table B.13).

The statistics of the minimum headway time comparison are listed in Table 7. Over all sequences, the minimum headway time could on average be reduced by 26.88 s with a standard deviation of 30.37 s. Only 3 out of 489 sequences show an increase in minimum headway time, all of them within the scenarios where Long-Distance trains follow Freight trains. The maximum difference for these cases was 1 s, which may also result from numerical precision, as this value corresponds to the resolution of the obtained headway data.

However, the influence of block densification varies between traffic sequences. Standard deviations of up to 37.94 s indicate substantial variability in the reductions of minimum headway times even within individual traffic sequences. While sequences where two local trains follow each other experience almost no difference for the considered block separations, sequences with a leading passenger train show moderate improvements. The largest reductions occur in sequences with a leading freight train, particularly in the fr-fr case with a median reduction of 60 s and a standard deviation of 31.64 s.

Table 8
Overview of efficient infrastructure layouts per line standard.

Line standard	Traffic load	Block length line [m]	Densified blocks	Number of blocks	Quality factor
P1	High	2980	with	32.0	0.98
P1_F1	Mid	2980	without	20.0	0.12
P1_F1	High	1670	without	21.0	0.94
P2_F1	Low	2980	without	20.0	0.59
P2_F1	Mid	2980	without	10.0	0.87
P2_F1	High	500	with	24.0	0.94
P3_F1	Low	5900	without	10.0	0.31
P3_F1	Mid	3800	without	13.0	0.90
P3_F1	High	750	with	32.0	0.94

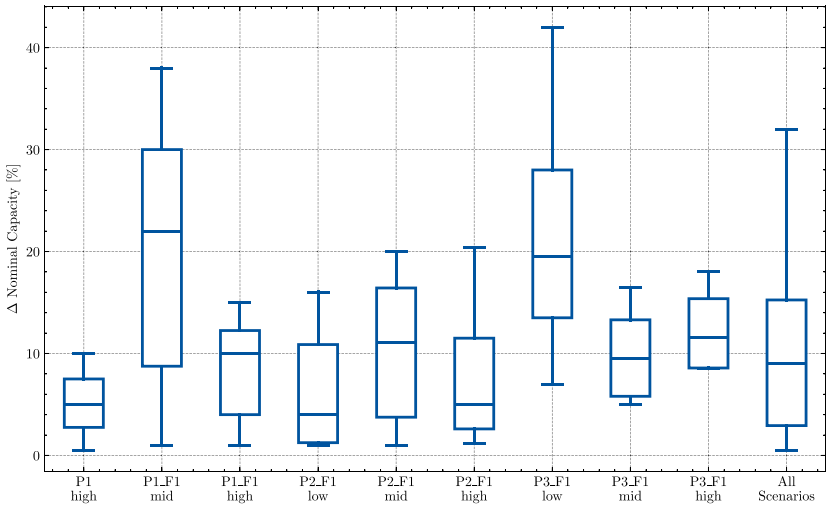


Fig. 13. Increase in % of nominal capacity for a time horizon of 24 h when implementing densified block sections in station proximity.

From the minimum headway times, expected waiting times could be computed with the formula from Section 3.2. To select an efficient block separation, the expected waiting times have been compared to the limit value of each scenario. This comparison has been done for a peak traffic period of 5 h. The corresponding quality factors can be found in Table C.16, together with information on the required number of blocks. For every traffic demand scenario, an infrastructure manager may select the infrastructure variant with the least number of blocks as the most cost-efficient one out of all variants with low-enough expected waiting times (this corresponds to quality factors smaller than 1.0).

Table 8 gives an overview of these selections. With the described procedure, the densified block sections would be implemented in 3 of the 9 scenarios. Note that this might not correctly represent the benefit of densified block sections as other parameters, such as the distance between passing stations, can influence the number of blocks.

Another evaluation criteria might be the nominal capacity. For a time horizon of 24 h, Fig. 13 highlights the capacity increase of infrastructure layouts with densified block sections compared to layouts with homogeneous block separation.

The amount of additional capacity depends on the considered scenario. A median increase of ca. 9% can be achieved over all scenarios. The highest increase could be obtained for the line standards P1_F1 (medium load) and P3_F1 (low load), with a median increase of ca. 20%–22%. For these two demand scenarios, the box plots show a high variability with peak relative capacity improvements of over 38%–40%. Other line standards experience less variability, reaching up to 20% increase at most. Noteably, results for the line standard P1 without freight traffic have the lowest variability and minor improvements with a median of 6%.

In summary, infrastructure managers need to carefully evaluate whether an implementation of densified block sections actually decreases the necessary number of blocks, and with it presumably also construction costs. However, when applied, block densifications can significantly increase the capacity of a railway line. The here discussed scenario of densifying block separation in station proximity might be particular suitable for upgrade scenarios, where a railway line currently equipped with homogeneous block section lengths needs to satisfy higher traffic demands.

5. Conclusion and discussion

In this work, a novel approach for planning efficient railway control system infrastructure has been introduced: By implementing densified block sections before and after passing stations, the capacity of a railway line infrastructure can be increased significantly.

The detailed capacity calculations have been performed with the help of microscopic running time calculations, where smaller block section lengths lead to smaller minimum headway times. In the applied methodology, an expected waiting time is calculated with the help of queuing theoretical formulas for every infrastructure scenario. By comparing it to threshold values, the nominal capacity of the analysed railway line can be specified. Furthermore, realisations of the introduced densified block sections have been analysed on multiple railway line scenarios with mixed traffic and compared to infrastructure layouts with homogeneous block section lengths, yielding convincing gains of the nominal capacity. Based on the number of necessary blocks for every infrastructure layout with enough capacity, standard block separation implementations have been suggested for the considered line standards. The results show that a densification of block infrastructure is not efficient in every case. However, given that the here discussed block densification scenarios can easily be performed on top of already existing homogeneous block divisions, infrastructure managers might decide to implement block densification to upgrade a railway line, when necessary to fulfil increasing capacity demands.

For more homogeneous operating programs, further research may be required as other factors could exert more significant influences on corresponding railway systems. While this study has categorised train services into only three different traffic types, a greater diversity is anticipated from the rolling stock utilised in practice. Moreover, the introduced infrastructure layouts correspond to ideal environmental conditions, facilitating the design of block sections with optimal lengths. In practical applications, however, the positioning of block sections may be subject to other constraints, preventing them from achieving the same level of optimisation. Additionally, this work assumes the same branching switch for every stopping route; in practice, this may vary depending on factors such as passenger or freight station requirements. Nonetheless, the conducted data analysis provides a robust approximation for understanding fundamental principles and offer valuable insights that can guide further refinement and adaptation to specific real-world scenarios. In particular, the suggested block separation standards might be a helpful orientation for infrastructure managers when designing train control system infrastructure for railway lines.

Under the specified conditions, a deployment of densified block sections not only increases capacity but also significantly reduces the number of block sections required, thereby decreasing the funds needed for installation. By implementing densified block sections before and after passing stations, infrastructure managers are setup to improve the nominal capacity effectively. Additionally, building upon the proposed standards for efficient block separation on different traffic demand scenarios, infrastructure managers may be enabled to formulate broad infrastructure standards as starting points for infrastructure planning on mixed traffic lines.

CRediT authorship contribution statement

Tobias Müller: Conceptualization, Methodology, Investigation, Visualisation, Writing – original draft. **Tamme Emunds:** Conceptualization, Investigation, Visualisation, Writing – original draft. **Andreas Pfeifer:** Conceptualization, Project administration, Writing – original draft. **Nils Nießen:** Conceptualization, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors thank Mr. Michael Schedel, Mr. Erwin Hilbrich and their colleagues at DB InfraGO AG for the great collaboration and the opportunity of applying the described theory in a practical project.

This work is partially funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – 2236/2.

Appendix A. Minimum headway times

The sample railway line from Section 4 has been modelled within a microscopic model for the different block lengths on the open line of 770 m, 1200 m, 2400 m and 3800 m and either with or without densified block sections in station proximity. With this model, the minimum headway times for all sequences of long-distance, local and freight trains could be computed. Tables A.9 (770), A.10 (1200), A.11 (2400) and A.12 (3800) show the results.

Table A.9
Minimum headway times on an infrastructure with block length 770 m.

	Densified			Not densified		
	Long-distance	Local	Freight	Long-distance	Local	Freight
Long-distance	01:42	01:20	02:55	02:07	01:33	03:10
Local	01:23	02:27	02:43	01:37	02:39	03:03
Freight	07:04	06:53	02:52	07:15	07:13	03:33

Table A.10
Minimum headway times on an infrastructure with block length 1200 m.

	Densified			Not densified		
	Long-distance	Local	Freight	Long-distance	Local	Freight
Long-distance	01:51	01:31	02:58	02:22	01:43	03:18
Local	01:39	02:39	02:48	01:47	02:39	03:13
Freight	07:04	07:04	03:07	07:25	07:24	03:57

Table A.11
Minimum headway times on an infrastructure with block length 2400 m.

	Densified			Not densified		
	Long-distance	Local	Freight	Long-distance	Local	Freight
Long-distance	02:08	02:02	02:58	02:58	02:11	03:46
Local	02:00	02:39	02:48	02:14	02:39	03:41
Freight	07:04	07:04	03:33	07:53	07:52	04:54

Table A.12
Minimum headway times on an infrastructure with block length 3800 m.

	Densified			Not densified		
	Long-distance	Local	Freight	Long-distance	Local	Freight
Long-distance	02:39	02:35	02:58	03:36	02:45	04:19
Local	02:32	02:39	02:48	02:44	02:39	04:14
Freight	07:05	07:05	04:15	08:26	08:25	05:54

Appendix B. Further scenario data

See Tables B.13–B.15.

Table B.13
Overview of the rolling stock utilised for performance investigations.

Traffic type	Traffic abbreviation	Vehicle	Traffic code	Comment	Speed [km/h]
Long-Distance	IC	BR 407 (x2)	P1	ICE 3, high-speed traffic	320
Long-Distance	IC	BR 412	P2	ICE 4 (13-car train), mixed traffic, design speed 250 km/h	265
Long-Distance	IC	BR 193	P3	Locomotive-hauled long-distance train	200
Local	RE	BR 462 (x2)	P3	Siemens Desiro HC, double-deck multiple unit, local traffic	160
Freight	FT	BR 193	F1	Full train	100

Table B.14
Densified block division at the station for the standards P1, P1_F1 and P2_F1.

Densified block division before and after a station	Block division line (between densified sections)
350 – 140 – 70 - Switch	350
700 – 350 – 140 – 70 - Switch	700
1110 – 700 – 350 – 140 – 70 - Switch	1110
1250 – 1110 – 700 – 350 – 140 – 70 - Switch	1250
1670 – 1250 – 1110 – 700 – 350 – 140 – 70 - Switch	1670
1880 – 1670 – 1250 – 1110 – 700 – 350 – 140 – 70 - Switch	1880
2450 – 1880 – 1670 – 1250 – 1110 – 700 – 350 – 140 – 70 - Switch	2450
2980 – 2450 – 1880 – 1670 – 1250 – 1110 – 700 – 350 – 140 – 70 - Switch	2980

Table B.15
Densified block division at the station for the standard P3_F1.

Densified block division before and after a station	Block division line (between densified sections)
420 – 210 – 140 – 70 - Switch	420
750 – 420 – 210 – 140 – 70 - Switch	750
1190 – 350 – 70 - Switch	1190
2390 – 1190 – 350 – 70 - Switch	2390
3800 – 2390 – 1190 – 350 – 70 - Switch	3800
5900 – 3800 – 2390 – 1190 – 350 – 70 - Switch	5900

Appendix C. Full results

See Table C.16.

Table C.16
Results overview.

Traffic code	Traffic amount	Passing distance [km]	Block length line [m]	Number of blocks	Densified block sections	Quality factor	Nominal capacity [trains]
P1	High	60	350	174	Yes	0.98	23.2
P1	High	60	350	171	No	0.98	23.1
P1	High	60	1100	60	Yes	0.95	23.5
P1	High	60	1100	55	No	1.03	22.8
P1	High	60	2980	32	Yes	0.98	23.2
P1	High	60	2980	20	No	1.17	21.7
P1_F1	High	35	350	103	Yes	0.82	23.8
P1_F1	High	35	350	100	No	0.83	23.7
P1_F1	High	35	500	74	Yes	0.82	23.8
P1_F1	High	35	500	70	No	0.84	23.5
P1_F1	High	35	1100	38	Yes	0.76	24.5
P1_F1	High	35	1100	32	No	0.89	23.0
P1_F1	High	35	1670	28	Yes	0.82	23.8
P1_F1	High	35	1670	21	No	0.94	22.5
P1_F1	High	35	2450	24	Yes	0.83	23.7
P1_F1	High	35	2450	14	No	1.01	21.9
P1_F1	High	35	2980	23	Yes	0.84	23.5
P1_F1	High	35	2980	12	No	1.06	21.6
P1_F1	Mid	60	350	174	Yes	0.10	20.6
P1_F1	Mid	60	350	171	No	0.10	20.4
P1_F1	Mid	60	500	124	Yes	0.10	20.6
P1_F1	Mid	60	500	120	No	0.10	20.2
P1_F1	Mid	60	1100	60	Yes	0.09	21.2
P1_F1	Mid	60	1100	55	No	0.11	19.6
P1_F1	Mid	60	1670	43	Yes	0.10	20.6
P1_F1	Mid	60	1670	36	No	0.11	19.1
P1_F1	Mid	60	2450	35	Yes	0.10	100.8
P1_F1	Mid	60	2450	24	No	0.12	92.4
P1_F1	Mid	60	2980	32	Yes	0.10	99.2
P1_F1	Mid	60	2980	20	No	0.12	90.4
P2_F1	High	10	350	31	Yes	0.95	40.8
P2_F1	High	10	350	29	No	0.98	40.2
P2_F1	High	10	500	24	Yes	0.94	40.9
P2_F1	High	10	500	20	No	1.02	39.8
P2_F1	High	15	350	46	Yes	1.29	36.3
P2_F1	High	15	350	43	No	1.33	35.8
P2_F1	High	15	500	34	Yes	1.28	182.0
P2_F1	High	15	500	30	No	1.37	35.4
P2_F1	High	15	1100	19	Yes	1.28	36.4
P2_F1	High	15	1100	14	No	1.59	33.6
P2_F1	High	20	350	60	Yes	1.71	32.8
P2_F1	High	20	350	57	No	1.76	32.4
P2_F1	High	20	500	44	Yes	1.70	32.8
P2_F1	High	20	500	40	No	1.81	32.1

(*continued on next page*)

Table C.16 (*continued*).

P2_F1	High	20	1100	24	Yes	1.70	32.8
P2_F1	High	20	1100	18	No	1.59	30.7
P2_F1	High	20	1670	19	Yes	1.39	35.3
P2_F1	High	20	1670	12	No	2.36	29.5
P2_F1	High	25	350	74	Yes	2.22	29.9
P2_F1	High	25	350	71	No	2.30	29.6
P2_F1	High	25	500	54	Yes	2.21	30.0
P2_F1	High	25	500	50	No	2.36	29.4
P2_F1	High	25	1100	28	Yes	2.22	30.0
P2_F1	High	25	1100	23	No	2.72	28.2
P2_F1	High	25	1670	22	Yes	1.83	32.0
P2_F1	High	25	1670	15	No	3.07	27.3
P2_F1	High	25	2450	20	Yes	2.32	29.6
P2_F1	High	25	2450	10	No	3.65	26.2
P2_F1	High	25	2980	20	Yes	2.41	29.3
P2_F1	High	25	2980	8	No	4.11	25.5
P2_F1	Mid	30	350	89	Yes	0.64	26.3
P2_F1	Mid	30	350	86	No	0.65	26.2
P2_F1	Mid	30	500	64	Yes	0.53	143.0
P2_F1	Mid	30	500	60	No	0.54	28.3
P2_F1	Mid	30	1100	33	Yes	0.64	26.3
P2_F1	Mid	30	1100	27	No	0.71	25.2
P2_F1	Mid	30	1670	25	Yes	0.56	27.9
P2_F1	Mid	30	1670	18	No	0.76	24.5
P2_F1	Mid	30	2450	22	Yes	0.65	26.2
P2_F1	Mid	30	2450	12	No	0.82	23.8
P2_F1	Mid	30	2980	22	Yes	0.65	26.2
P2_F1	Mid	30	2980	10	No	0.87	23.2
P2_F1	Low	60	350	174	Yes	0.50	17.0
P2_F1	Low	60	350	171	No	0.50	16.9
P2_F1	Low	60	500	124	Yes	0.50	17.0
P2_F1	Low	60	500	120	No	0.51	16.9
P2_F1	Low	60	1100	60	Yes	0.50	17.0
P2_F1	Low	60	1100	55	No	0.53	16.6
P2_F1	Low	60	1670	43	Yes	0.46	17.6
P2_F1	Low	60	1670	36	No	0.55	16.3
P2_F1	Low	60	2450	35	Yes	0.50	17.0
P2_F1	Low	60	2450	24	No	0.57	16.0
P2_F1	Low	60	2980	32	Yes	0.50	16.9
P2_F1	Low	60	2980	20	No	0.59	15.8
P3_F1	High	20	750	32	Yes	0.94	34.9
P3_F1	High	20	750	27	No	1.12	32.5
P3_F1	High	20	1190	20	Yes	1.03	33.5
P3_F1	High	20	1190	17	No	1.23	31.4
P3_F1	High	20	2390	13	Yes	1.12	32.6
P3_F1	High	20	2390	8	No	1.71	27.9
P3_F1	High	20	3800	11	Yes	1.25	31.3
P3_F1	High	20	3800	5	No	2.02	26.5
P3_F1	Mid	50	750	72	Yes	0.61	24.4
P3_F1	Mid	50	750	67	No	0.67	23.4
P3_F1	Mid	50	1190	45	Yes	0.65	23.8
P3_F1	Mid	50	1190	42	No	0.70	23.0
P3_F1	Mid	50	2390	26	Yes	0.67	23.4
P3_F1	Mid	50	2390	21	No	0.79	22.0
P3_F1	Mid	50	3800	19	Yes	0.70	23.0
P3_F1	Mid	50	3800	13	No	0.90	20.8
P3_F1	Mid	50	5900	16	Yes	0.78	22.0
P3_F1	Mid	50	5900	8	No	1.13	19.1
P3_F1	Low	60	750	86	Yes	0.21	20.9
P3_F1	Low	60	750	80	No	0.23	20.2
P3_F1	Low	60	1190	54	Yes	0.22	20.5
P3_F1	Low	60	1190	50	No	0.23	20.0
P3_F1	Low	60	2390	30	Yes	0.22	20.5
P3_F1	Low	60	2390	25	No	0.25	19.4
P3_F1	Low	60	3800	22	Yes	0.22	20.5
P3_F1	Low	60	3800	16	No	0.26	18.8
P3_F1	Low	60	5900	18	Yes	0.23	20.0
P3_F1	Low	60	5900	10	No	0.31	17.5

Data availability

Data will be made available on request.

References

DB InfraGO AG, 2022. Richtlinie 405 Fahrwegkapazität.

DB InfraGO AG, 2023. Richtlinie 819 LST-anlagen planen - ETCS level 2 ohne konventionelle signalisierung (l2os).

European Comission, 2019. Technical specification for interoperability relating to the 'infrastructure' subsystem of the rail system within the European union: Comission regulation (EU) 2019/776.

Goers, H., Reinhart, P., Weiß, R., 2019. Knoten stuttgart - ETCS als träger für leistungs- und qualitätssteiegerung.

Goverde, R.M., Corman, F., D'Ariano, A., 2013. Railway line capacity consumption of different railway signalling systems under scheduled and disturbed conditions. J. Rail Transp. Plan. Manag. 3 (3), 78–94. http://dx.doi.org/10.1016/j.jrtpm.2013.12.001.

Grubor, N., Crespo, A., Oetting, A., Kretschmer, E., Bachmann, V., 2024. Ansatz zur teilautomatisierten kapazitätsoptimierten Blockteilung von ETCS L2oS-Bereichen. Eisenbahntechnische Rundsch. 2024–12, 28–35, (german only).

Hansen, I., Pachl, J., 2014. Railway Timetabling and Operations: Analysis, Modelling, Optimisation, Simulation, Performance, Evaluation. Eurail Press.

Happel, O., 1959. Sperrzeiten als grundlage für die fahrplankonstruktion. Eisenbahntechnische Rundsch. 8 (2), 79–90.

Janecek, D., Weymann, F., Schaer, T., 2020. LUKS - integriertes Werkzeug zur Leistungsuntersuchung von Eisenbahnknoten und -strecken. Eisenbahntechnische Rundsch. 01+02/2020, 25–32, (german only).

Ke, B.-R., Chen, M.-C., Lin, C.-L., 2009. Block-layout design using MAX–MIN ant system for saving energy on mass rapid transit systems. IEEE Trans. Intell. Transp. Syst. 10 (2), 226–235. http://dx.doi.org/10.1109/TITS.2009.2018324.

Koning, J.A., 2002. Comparing the performance of ERTMS level 2 fixed block and ERTMS level 3 moving block signalling systems using simulation techniques. WIT Trans. Built Environ. 61.

Landex, A., Wittrup, L., Jokiranta, A., Musto, M., 2019. ERTMS/ETCS level 2 capacity benefits on the city lines of the helsinki region. Väyläviraston Julk.

Luteberget, B., Johansen, C., Steffen, M., 2019. Synthesis of railway signaling layout from local capacity specifications. In: ter Beek, M.H., McIver, A., Oliveira, J.N. (Eds.), Formal Methods – the Next 30 Years. In: Lecture Notes in Computer Science, vol. 11800, Springer International Publishing, Cham, pp. 121–137. http://dx.doi.org/10.1007/978-3-030-30942-8_9.

Nachtigall, P., Tischer, E., 2023. Simulation assessment of the headway under the ETCS L3. Acta Polytech. CTU Proc. 43, 81–85. http://dx.doi.org/10.14311/APP.2023.43.0081.

Nießen, N., 2013. Waiting and loss probabilities for route nodes. In: International Conference on Railway Operations Modelling and Analysis (RailCopenhagen).

Niessen, N., Kogel, B., 2014. Eisenbahninfrastruktur ökonomisch planen. Z. Für Verkehrswissenschaft 85, 194–213, (german only).

Pachl, J., 2015. Das Sperrzeitenmodell in der Fahrplankonstruktion. Anwendung-Spezialfälle-Alternativen. Springer Vieweg, ISBN 978-3-658-11127-4, german only).

Quaglietta, E., 2014. A simulation-based approach for the optimal design of signalling block layout in railway networks. Simul. Model. Pr. Theory 46, 4–24. http://dx.doi.org/10.1016/j.simpat.2013.11.006.

Ranjbar, V., Olsson, N.O., Sipilä, H., 2022. Impact of signalling system on capacity – comparing legacy ATC, ETCS level 2 and ETCS hybrid level 3 systems. J. Rail Transp. Plan. Manag. 23, 100322. http://dx.doi.org/10.1016/j.jrtpm.2022.100322.

Schöbel, A., Permiakova, O., 2021. Enhancing capacity on ETCS level 2 lines in Austria. In: Road and Rail Infrastructure VI. In: International Conference on Road and Rail Infrastructure, University of Zagreb Faculty of Civil Engineering, pp. 1111–1117. http://dx.doi.org/10.5592/CO/cetra.2020.982.

Schwanhäußer, W., 1974. Die Bemessung der Pufferzeiten im Fahrplangefüge der Eisenbahn (Ph.D. thesis). Verkehrswissenschaftliches Institut der Rheinisch-Westfälischen Technischen Hochschule Aachen.

Schwanhäußer, W., Schultze, K., 1982. Ermittlung von qualitätsmaßstäben für die berechnung der leistungsfähigkeit eines streckenabschnittes und entwicklung eines rechenverfahrens zur ermittlung von endverspätungen: Forschungsarbeit für die deutsche bundesbahn. (work not formally published, german only).

Sun, W., Newton, D., Cox, S., 2019. Signalling the layout-automatic design of the optimum ETCS L2 track sections. In: World Engineers Convention (2019: Melbourne, Australia). Engineers Australia Melbourne, pp. 217–231.

Thomas, P., Fisher, D., Sheikh, F., 2008. Evaluation of the capacity limitations and suitability of the European traffic management system to support automatic train operation on main line applications. In: Allan, J., Arias, E., Brebbia, C.A., Goodman, C., Rumsey, A.F., Sciutto, G., Tomii, A. (Eds.), Computers in Railways XI. In: WIT Transactions on The Built Environment, WIT PressSouthampton, UK, pp. 193–202. http://dx.doi.org/10.2495/CR080201.

UIC, 2008. Influence of ETCS on line capacity. UIC, Paris.

UIC, 2013. Code 406 - capacity: 2nd edition.

Vignali, V., Cuppi, F., Lantieri, C., Dimola, N., Galasso, T., Rapagnà, L., 2020. A methodology for the design of sections block length on ETCS L2 railway networks. J. Rail Transp. Plan. Manag. 13, 100160. http://dx.doi.org/10.1016/j.jrtpm.2019.100160.

Wakob, H., 1985. Ableitung eines generellen wartemodells zur ermittlung der planmäßigen wartezeiten im eisenbahnbetrieb unter besonderer berücksichtigung der aspekte leistungsfähigkeit und anlagenbelastungn: Dissertation. (Aachen, german only).

Weik, N., Niebel, N., Nießen, N., 2016. Capacity analysis of railway lines in Germany – A rigorous discussion of the queueing based approach. J. Rail Transp. Plan. Manag. 6 (2), 99–115. http://dx.doi.org/10.1016/j.jrtpm.2016.06.001.