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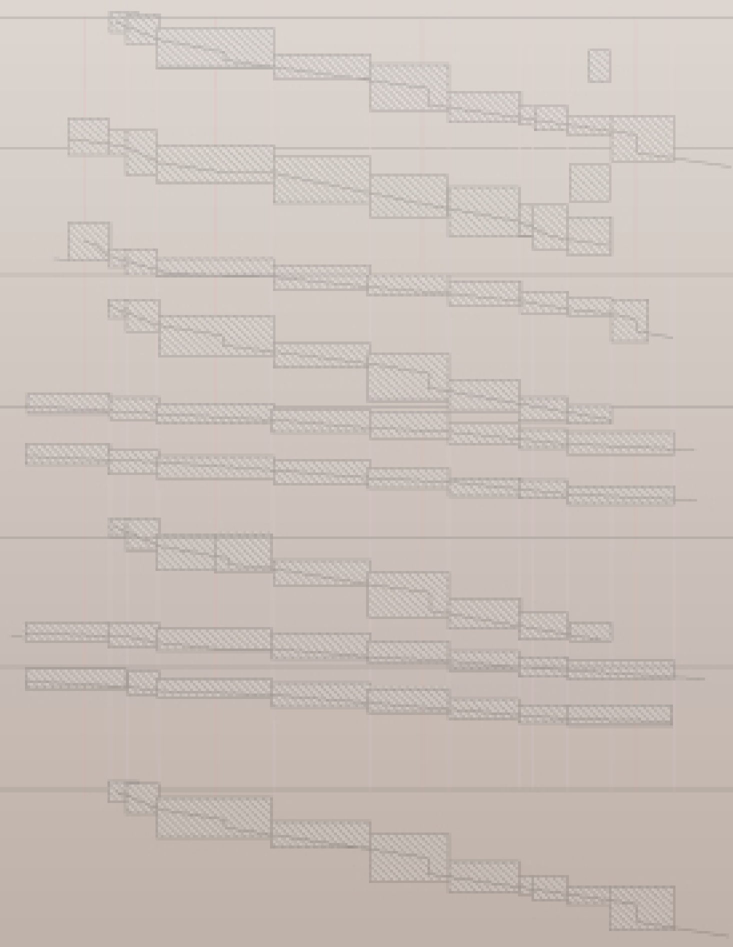
Influence of ETCS on line capacity

Generic study



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Foreword

Transport capacity of railway lines can be significantly influenced by the nature and configuration of the under laying Command-Control and Signalling (CCS) systems. In the past, different approaches have been realised in context with the various national legacy CCS systems.

For the new standardised ETCS, there is a need for a common understanding of the effect on line capacity. Thereby the influence of various application parameters, like application level, operational mode or the parametrisation of braking curves is of prime interest.

This study has been commissioned by UIC to the Institute of Transport Science of the RWTH University at Aachen, which has already been in charge of elaboration of the UIC code 406 “Capacity”. Basically, the same calculation methodology is used however with certain extensions and adaptations to the specific properties of ETCS.

As there exists no absolute value for capacity consumption, this study is investigating the effect of ETCS for typical application cases of high-speed or conventional rail service on main and secondary lines.

The methodology and the main findings of this report have been presented by the authors to a group of experts from several interested networks. The following question and answer session has confirmed the plausibility of the study results.

Encouraged by the positive echo on this study, the ERTMS Platform of UIC has decided to launch a similar research work on the influence of ETCS on the capacity of railway nodes.

Peter Winter
UIC ERTMS Programme Manager

1 Introduction

For the introduction of a new signalling system such as ETCS the influence on the capacity consumption is of high relevance. In order to assess the capacity consumption the infrastructure characteristics, transport schedules and punctuality levels have to be considered. UIC has engaged the RWTH Aachen University (Institute of Transport Science) to examine a number of typical applications of ETCS.

An important performance indicator is the line capacity consumption as defined in the UIC Code 406 “Capacity”. This document provides the basis for a common understanding of capacity and an agreed method for the calculation of capacity consumption. Since the UIC Code 406 describes only the assessment for lines with conventional signalling, this model has to be developed for ETCS in all three levels. As the UIC Code 406 does not consider the delays of the trains so the STRELE-formula (method of Schwanhäußer) is used for the assessment of the capacity consumption.

In this study both methods are used to demonstrate the influence of ETCS in its different configurations in a specific context. In order to be independent from national influencing factors, generic infrastructure characteristics are used for the assessment of the capacity consumption. A conventional main line, a high speed line and a regional line are selected as three typical infrastructure cases. For each line a specific operational programme and punctuality levels are under laid. The analysed ETCS application configuration includes Level 1 with limited supervision, Level 1, Level 2 with regular and optimised block sections and Level 3.

2 Fundamentals

2.1 Terms

Some terms have to be explained to quantify the capacity consumption of a single train movement ("train path").

2.1.1 Blocking time

An adequate model is necessary to quantify the interactions between individual train paths and to calculate the efficiency of infrastructure. In Germany the blocking-time model (derived by Happel [3] in Aachen in 1959) has been used for the purpose of modelling capacity consumption for many years. With the introduction of a software tool for computer-aided train path management, this model is also used for compiling timetables in Germany. The International Union of Railways (UIC), moreover, has started recommending the model for the use in capacity studies (cf. chapter 3.2).

The basic principle of the blocking-time sequence is the operational occupation of a block section by a train movement. A block section is demarcated by two main signals. In such a block section the occupation by a train is exclusive, meaning that only one train can be located in a block section. This is ensured by the control and safety technology. The occupation of a block section can be illustrated by the blocking time diagram (Fig. 1).

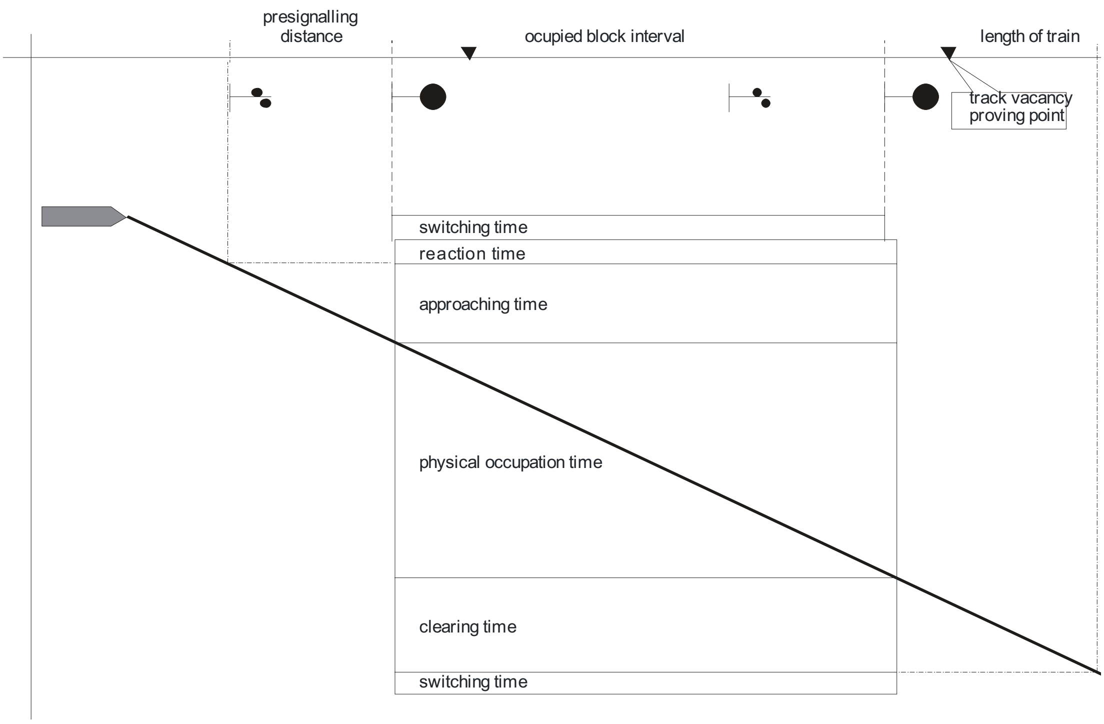


Fig. 1: Components of the blocking time

The blocking time is longer than the actual physical act of occupation. The following components are elements of the blocking time:

- Switching times for route formation and for route release. The value of this time elements depend on the interlocking.
- Reaction time for the visual perception of the distant signal. The value for conventional signalling systems is 0,2 minutes.
- Approaching time for the movement between the distant signal and the main signal A.
- Physical occupation time.
- Clearing time for passing the main signal B and the end of train reaching the track vacancy proving point (dependent on length of train).

The set of these blocking-time segments is referred to as a blocking-time sequence and indicates a train movement's capacity consumption (Fig. 2).

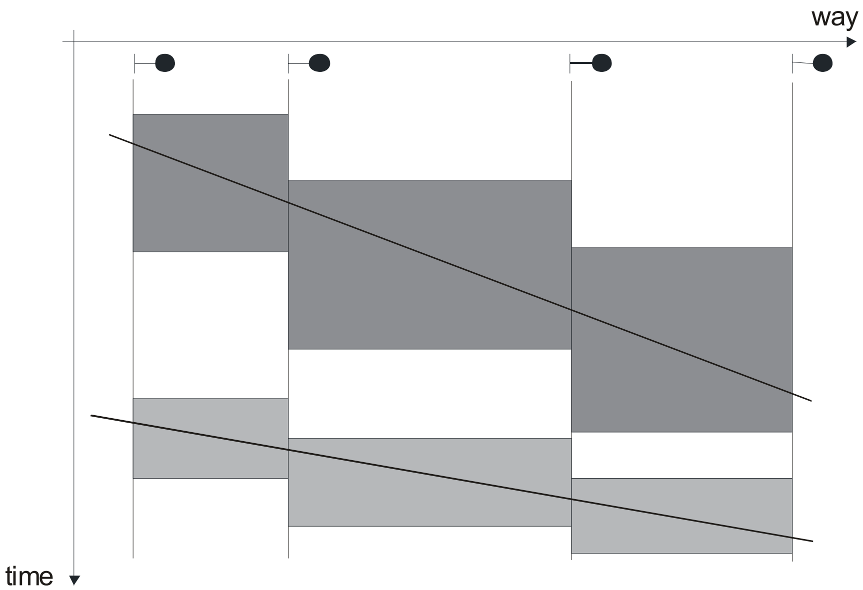


Fig. 2: Blocking-time sequences for two trains

The blocking-time sequence, which is developed for the conventional main/distant signalling system, can be adapted to modern signalling and automatic train control systems, especially for the ETCS levels which will be shown in the following sections [7].

2.1.2 Minimum headway time

The minimum headway time is the distance in time between two trains without obstructing one another. It refers to the shared line section as a connection between two nodes where it is possible to change the sequence or to cross due to overtaking facilities.

To determine the minimum headway time, the blocking-time sequence of the second train is shifted until it touches the graph of the preceding train. The minimum headway time is the period of time from the beginning of the first-train's blocking-time to the beginning of the second-train's blocking-time in the first block section (Fig. 3). It is not defined for one train but for a pair of trains.

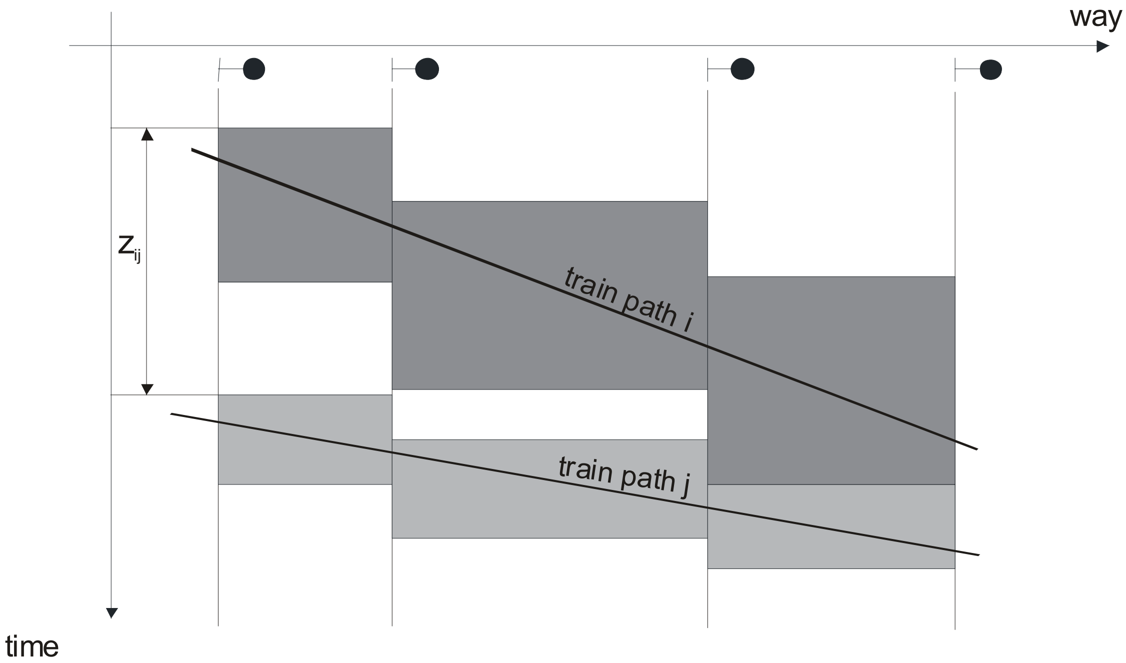


Fig. 3:Illustration of the minimum headway time

2.1.3 Buffer time

In real timetables buffer times between the blocking-time sequences are necessary to reduce the propagation of delays.

2.2 ETCS application levels

ETCS level 1 is a spot transmission based train control system to be used as an overlay on an underlying signalling system. Movement authorities are generated trackside and are transmitted to the train via Eurobalises. Additional Eurobalises can be placed to transmit infill information. Semi-continuous infill can be provided using Euroloop or radio in-fill. In this case, the on-board system will be able to show new information to the driver as soon as it is available and even at standstill.

ETCS level 2 and ETCS level 3 are radio based train control systems. Movement authorities are generated trackside and are transmitted to the train via Euroradio. Both Levels are based on Euroradio for track to train communication and on Eurobalises as spot transmission devices mainly for location referencing. The trackside radio block centre which provides the information to the trains knows each ETCS controlled train individually by the ETCS identity of its leading ETCS on-board equipment.

In ETCS level 2 the train detection and train integrity supervision are performed by the trackside equipment of the underlying signalling system (interlocking, track circuits etc.). In ETCS level 3 the train location and train integrity supervision are performed by the trackside radio block centre in co-operation with the train (which sends position reports and train integrity information).

2.2.1 ETCS level 1 blocking time model

ETCS level 1 shall consider the blocking time model because it refers to the conventional lineside signalling system. The balise group does not need to be located directly at the distant signal but can be positioned in rear of the distant signal. So the indication point of the worst braking train has to be considered for positioning the balise. Due to the braking curve and the indication point the approaching time increases (cf. Fig. 4).

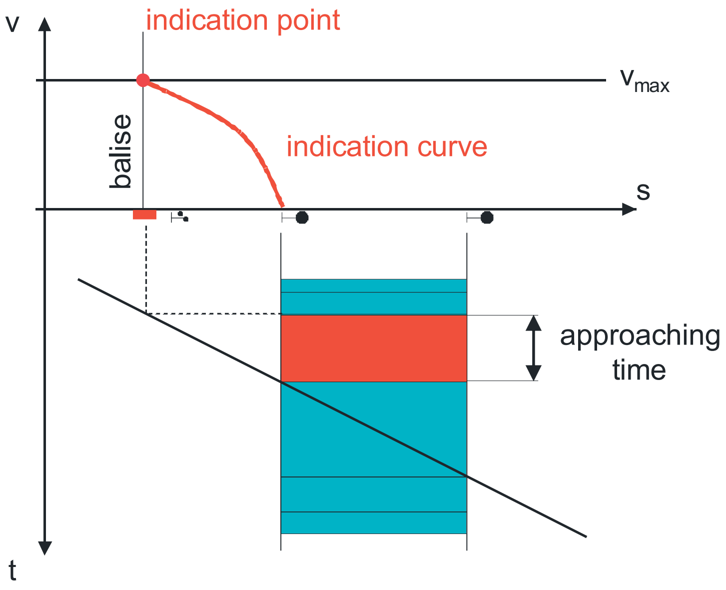


Fig. 4: Balise and approaching time

It can be noted that the balise group related to the blocking time start location may be different from one train to another as a function of the train braking parameters performances. Therefore, for some trains the blocking time reference balise group may be far in rear of the beginning of the deceleration curve. This may have an important impact on the theoretical headway performances.

2.2.2 ETCS level 2 blocking time model

Being a fixed block signalling system, ETCS level 2 considers the blocking time model but with the starting point of the blocking time is dependent directly from the indication curve (Fig. 5).

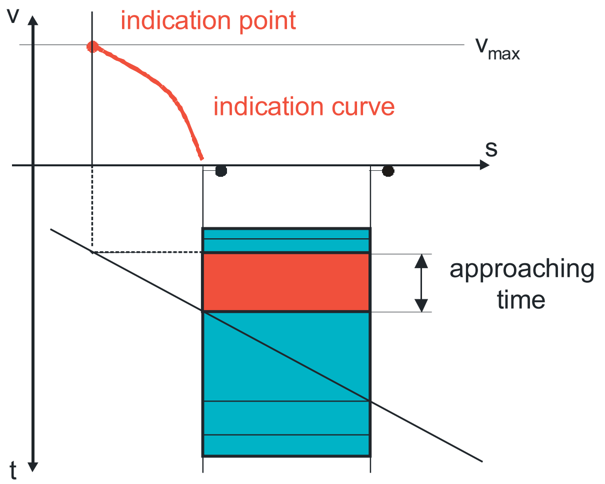


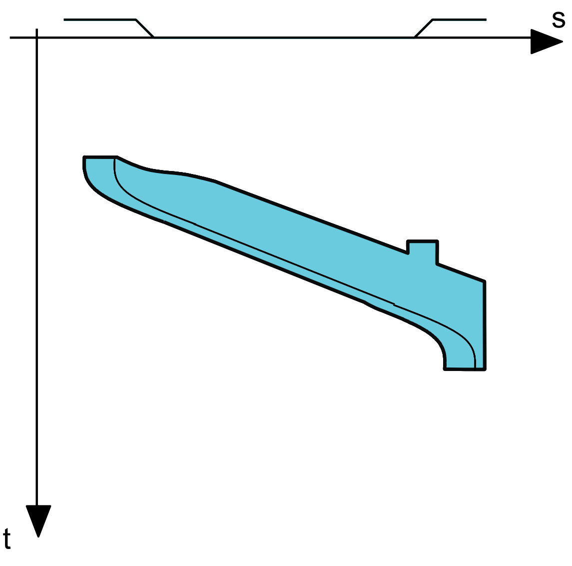
Fig. 5: ETCS level 2: Assessment of blocking times

If the movement authority is not extended the train has to diverge from its scheduled train path. The process of deceleration has to start at the indication point, which depends on the characteristics of the affected train.

2.2.3 ETCS level 3 blocking time model

As a moving block-signalling system, ETCS level 3 always provides the shortest minimum headway for all order-of-trains scenarios. Moving block operations are conditioned by a series of restrictions, leading to discrete blocking-time segments in the continuous blocking-time band. The principal restrictions are caused by sets of switch points and centenary section separators (Fig. 6).

Fig. 6: Blocking-time band (moving block)



For the purposes of modelling, the moving block can be seen as a mutation of a discretely stepped blocking-time sequence (Fig. 7). The occupation curve of the blocking-time band is determined by the braking distance currently required for the train, its cancellation curve by the train's length plus a safety margin. The blocking-time band thus constitutes the boundary function for the blocking-time sequence assuming a theoretical, infinitely dense block arrangement.

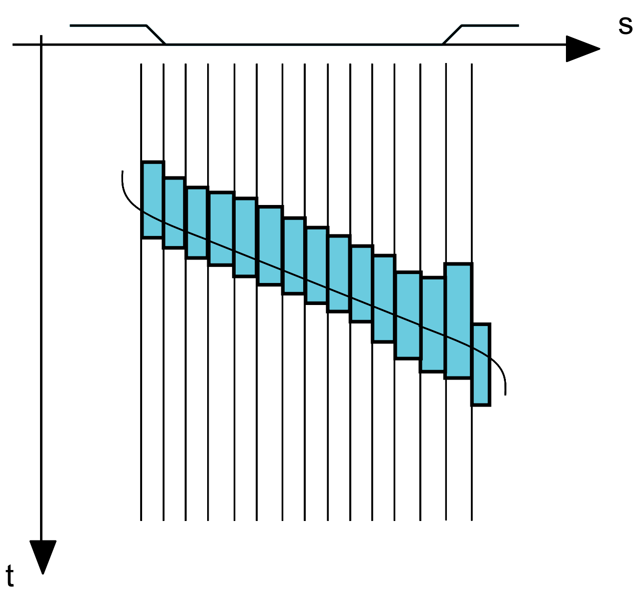


Fig. 7: Graduated blocking-time band

For the purpose of practicable efficient calculations it is possible, when modelling the absolute braking distance, to overlay an "almost infinitely dense" layout of ETCS level 2 marker boards, at distances of approx. 50 m. This approach results a very finely graduated blocking-time sequence that represents a very good approximation of the blocking-time band. In principle, the blocking-time band model can also be applyed for running at a relative braking distance. As this technology is not currently playing any part in practical discussions and in any case does not have any impact on efficiency, reference is made to the relevant publications for detailed discussion thereof.

2.3 SPURPLAN Tool

The modelling of the infrastructure is basic for the analysis of capacity consumption. With the tool SPURPLAN, which was developed at the Institute of Transport Science at RWTH Aachen University [1], links and nodes of the relevant network are created. In SPURPLAN the infrastructure data is a node-rated digraph. This is a directed graph, whose nodes contain the track attributes and the links represent the track. Interlocking routes in every station exist in SPURPLAN.

2.3.1 Infrastructure

In SPURPLAN the elements of the infrastructure are attributed to the stations. The elements of the infrastructure are defined as follows:

- Switches/Points, crossings,
- Signals: distant and main signals, rear-integrity proving points,
- Speeds,
- stopping place for passenger and freight trains,
- stations: beginning, middle and end,
- Gradients,
- other infrastructure elements: braking distance, etc.

Every infrastructure element is characterised by its type, name, position, value and the corresponding station. In addition they have a univocal direction.

2.3.2 Interlocking routes

In addition to the infrastructure elements, interlocking routes are compulsory. An interlocking route is a defined and in interlockings associated route from the beginning of a station to the stopping place or the end of the station.

2.4 ANKE Tool

The tool ANKE (Analytische Netzkapazitätsermittlung, analytic network capacity assessment) is used for the calculation of waiting times [6]. The infrastructure has to be decomposed into single-channel service systems, so called single-channel components section route nodes (SRN). These are automatically separated on the basis of the infrastructure graph. For the calculation of the minimum headway time alternative routes are automatically analysed for the determination of overtaking and crossing sections. Afterwards the scheduled and unscheduled waiting time can be determined. The scheduled waiting time is generated during the timetable construction process, where train paths have to be moved to solve conflicts. The unscheduled waiting time arises during operation because of delayed trains. For the quantification of the scheduled waiting time queuing, theoretical models are being used. For the calculation of the unscheduled waiting time during operation (secondary delay) probability theoretical models are being used. Without an existing schedule only the train mix and the probability of train sequences will be considered.

3 Calculation of capacity consumption

3.1 STRELE-formula (Method of Schwanhäußer)

By application of the queuing theory a direct interrelation between operating quality and capacity of a railway infrastructure can be assessed. The (theoretical) capacity n_{max} of a railway infrastructure is the number of trains that can be processed with specification of a defined route and safety standards, but with an unlimited storage capacity in front of the infrastructure.

Waiting times and delays grow to infinity in an n_{max}-scenario. Regarding this, only operations with a considerably reduced number of trains are possible on a railway line. The optimal capacity n_{opt} is the number of train paths reducing the average waiting times and average delays to an expected value in conformity with the market expectation ($ET_{W,zul}$ – "level of service", cf. Fig. 8). Average waiting times are used as a quality measure with reference to the capacity of a railway line. Quality can be defined for timetable construction process and for operational process.

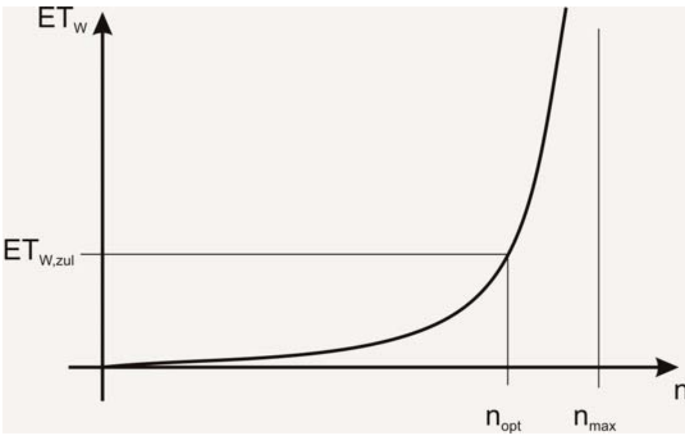


Fig. 8: Relation between train number and waiting times

The timetabling capacity $n_{max,tt}$ [trains/unit of time] of railway infrastructure is the maximal number of train paths that can be scheduled without conflicts within a reference period t_U. The temporal and quantitative demand patterns and the protection-system conditions shall be respected. Normally, there is lost capacity between two train paths, due to the constraints during the timetable construction process (for example regular-interval traffic).The timetabling capacity corresponds to scheduled waiting times as a suitable quality measure, whereas the operating capacity corresponds to unscheduled waiting time. Scheduled waiting time arises during timetabling if it is necessary to remove train paths from the slot desired by the train operating company (TOC) in order to solve paths conflicts.

The operating capacity $n_{max,op}$ [trains per unit of time] is the number of trains that can operate on a railway infrastructure within a reference period t_U as commercial services. This value corresponds to secondary delays (or unscheduled waiting times) as a suitable quality measure. Secondary delays are likewise a capacity-dependent quality indicator.

It is possible to express timetable service capacity or operational service capacity in form of capabilities of traffic flows in dimensions trains per unit of time with the help of the trains' capacity utilisation rate. Models and formulas of the queuing theory allow the establishment of a connection between the characteristic performance quantity (trains per unit of time) and the quality measure (waiting time). By means of queuing theory, the general rules of services in transport and message systems are described and analysed. Thereby, it is possible to assess the consistency between performance and quality measures. The main focuses of queuing theory are on the formation of queues and congestions.

A queuing model consists of four main components: arrival process, service process, service station and waiting area.

The arrival process describes the structure of the input stream of demands, primarily characterized by the period of time between two customers or demands (inter-arrival interval t_A). The inter-arrival interval can be understood as a random variable. The main information on the service process is the average service time t_B, which can also be understood as a random variable.

The service times of the service channel line section are the decisive minimum headway times of this line section. Minimum headway times refer to a common route of trains i and j and have to be determined for each overtaking section separately. An overtaking section is limited by stations, in which a sequence change between trains i and j are possible. The possibility of the sequence change is not only influenced by technical parameters (e.g. track length), but also by commercial constraints (is the sequence change from the commercial point of view permitted?).

$$Z = \begin{pmatrix} z_{11} & z_{12} & \cdots & \cdots & z_{1n} \\ z_{21} & z_{22} & \cdots & \cdots & z_{2n} \\ \vdots & \vdots & \ddots & & \vdots \\ \vdots & \vdots & & \ddots & \vdots \\ z_{n1} & z_{n2} & \cdots & \cdots & z_{nn} \end{pmatrix}$$

z_{ij} Minimum headway time for the trains i and j

A line can be divided into overtaking sections allowing fast high-ranking trains to overtake slow low-ranking trains. In addition to this it has to be respected that passenger trains can only be overtaken in combination with a regular stop for passenger change. During the overtaking process, the low-ranking train has to be stopped in the overtaking station and has to wait until the high-ranking train has passed. Resulting from the division into overtaking sections, the length of the shared train run is reduced. This leads to smaller minimum headway times. It is necessary to consider acceleration and braking operations.

Waiting times within sufficiently dimensioned stations have no effect on the capacity of the adjacent lines in principle. On a line a determinative minimum headway time can be identified for each succession of two trains. The decisive minimum headway time of each pair of trains results from the maximum of their minimum headway times on all overtaking sections.

For the capacity assessment of line sections one can take advantage of the correlation between the number of trains and unscheduled waiting times (operational process). The delays at entry, brought forward into the line sections, as well as primary delays, generated on the line section itself, induce new secondary delays on the line section.

Secondary delays arise from threading trains into the line section. Schwanhäußer derived the following formula for the calculation of average secondary delays (equivalent to unscheduled waiting times) on line sections [5]:

$$ET_W = \left(p_{VE} - \frac{p_{VE}^2}{2}\right) \cdot \frac{\bar{t}_{VE}^2}{\bar{t}_P + \bar{t}_{VE}\left(1 - e^{-\bar{z}/\bar{t}_{VE}}\right)} \cdot \left(p_g \cdot \left(1 - e^{-\bar{z}_g/\bar{t}_{VE}}\right)^2 + (1 - p_g) \cdot \frac{\bar{z}_v}{\bar{t}_{VE}} \cdot \left(1 - e^{-2\cdot\bar{z}_v/\bar{t}_{VE}}\right) + \frac{\bar{z}}{\bar{t}_P} \cdot \left(1 - e^{-\bar{z}/\bar{t}_{VE}}\right)^2\right)$$

with

- $\bar{t}_p$ average buffer time,
- $\bar{z}$ average determinative minimum headway time,
- $\bar{z}_g$ average determinative minimum headway time of equal-ranking successions of trains,
- $\bar{z}_v$ average determinative minimum headway time of different-ranking successions of trains,
- $\bar{t}_{VE}$ average delay at entry,
- p_{VE} probability of delay at entry and
- p_g probability of the occurrence of an equal-ranking succession of trains.

The sum of the waiting times ΣT_W is the product of the average secondary delays ET_W and the reference period t_U:

$$\sum T_W = ET_W \cdot t_U$$

According to given quality measures, acceptable unscheduled waiting times can be defined. The acceptable sum of unscheduled waiting times, which leads to a satisfying operating quality is for example in Germany

$$ET_{W,zul} = 0{,}257 \cdot e^{-1{,}3 \cdot p_{RZ}}$$

p_{RZ} proportion of the passenger trains

The average determinative buffer time $\bar{t}_{P,erf}$ results from the limitation of the acceptable sum of unscheduled waiting time according to the following equation of the STRELE-formula:

$$\left(p_{VE} - \frac{p_{VE}^2}{2}\right) \cdot \frac{\bar{t}_{VE}^2}{\bar{t}_P + \bar{t}_{VE}\left(1 - e^{-\bar{z}/\bar{t}_{VE}}\right)} \cdot$$

$$\left(p_g \cdot \left(1 - e^{-\bar{z}_g/\bar{t}_{VE}}\right)^2 + (1 - p_g) \cdot \frac{\bar{z}_v}{\bar{t}_{VE}} \cdot \left(1 - e^{-2 \cdot \bar{z}_v/\bar{t}_{VE}}\right) + \frac{\bar{z}}{\bar{t}_P} \cdot \left(1 - e^{-\bar{z}/\bar{t}_{VE}}\right)^2\right) = 0{,}257 \cdot e^{-1{,}3 \cdot p_{RZ}}$$

This equation has to be resolved to the time $\bar{t}_P$ (only numerically solvable). The result corresponds to the buffer time necessary for reaching a satisfying operating quality, thus $\bar{t}_P = \bar{t}_{P,erf}$.

3.2 Calculation of capacity consumption in UIC Code 406

The capacity consumption calculation method suggested in UIC Code 406 “Capacity” is based on blocking times / blocking time sequences (cf. chapter 2) as capacity consumption model [4]. Therefore, the focus must be on interactions between different train paths and their influence on the capacity of railway infrastructure.

Obviously there cannot be a capacity problem for the first “constructed” train path on a railway infrastructure.

If there is no overlapping of blocking-time sequences, a second train movement can take place without hindrance. Any overlapping of blocking-time sequences constitutes a timetabling error. The minimum distance between two trains with specified speed profiles is referred to as minimum headway time z_{ij}. In cases where the blocking-time sequences of any two trains just touch in the graphical representation, the minimum headway can be gauged from the blocking-time elements comprising the first block section jointly negotiated. In practical timetabling, buffer times t_P between blocking-time sequences are provided to make it less likely that delays are passed on from one train movement to the next.

There are various impacts influencing the capacity of a railway network. For the capacity analysis and comparison, one has to consider different operational requirements, dispatching strategies, priority rules, speeds, block distances, train control systems and signalling equipment. Furthermore the traffic mix, the degree of interoperability and the interferences between track capacity and train capacity change because of the implementation of new technologies. By using the minimum headway time all of these impacts are considered precisely (no estimation necessary), because each single impact is taken into account in the calculation of the minimum headway times. All of these effects are "compressed" into the minimum headway times between two individual train paths, which can be handled easily for further calculations on railway infrastructure capacity consumption.

The proposed procedure for the determination of the railway lines' capacity consumption in UIC Code 406 is the method of compression. With the compression all blocking time sequences of a line section within the investigation period are pushed together up to the (theoretical) minimum headway. This procedure can also be used if in place of a concrete timetable, the train-mix and the minimum headway times are given.

The figures 9 and 10 show the method of compression for an investigation period of 60 minutes. In Fig. 9 the original timetable is represented, Fig. 10 shows the compressed timetable with the condensed blocking time sequences. In this example the occupation time begins at 7:00 and ends at 7:33. Thus here the minimum occupation time within the investigation period amounts to 33 minutes.

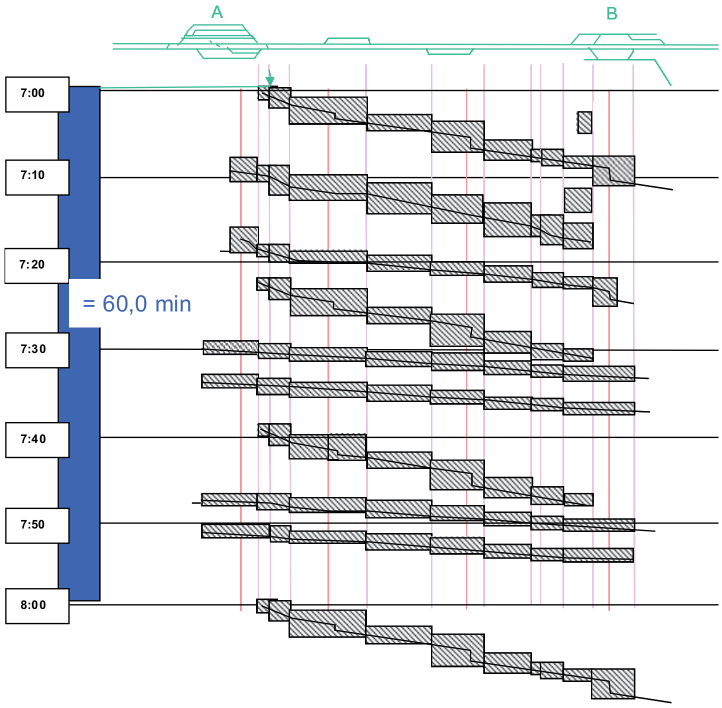


Fig. 9: Original timetable

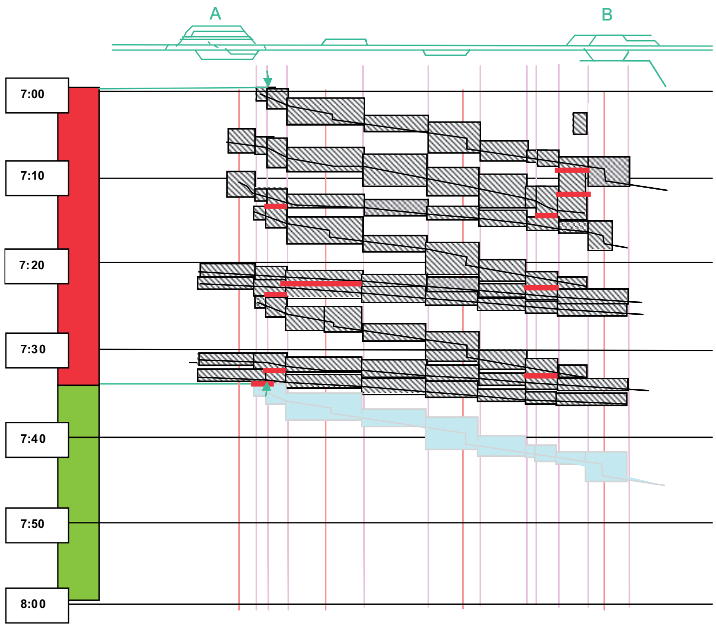


Fig. 10: Compressed timetable

For the calculation of capacity consumption it is necessary to consider time reserves for timetable stabilization (buffer times) and for maintenance requirements apart from the minimum occupation time. The remaining time slice is the unused capacity. A part of this unused capacity cannot be used otherwise due to the market requirements. No further train paths can be inserted in this time window. The second part of the unused capacity represents still available capacity, which could be marketed in the form of further train paths. Fig. 11 shows the different times slices from which capacity consumption and the unused capacity of a railway line can be determined. The total consumption time k consists of the time slices A, B, C and D:

$$k = A + B + C + D$$

with

- k total consumption time [min]
- A infrastructure occupation [min]
- B buffer time [min]
- C supplement for single-track lines [min]
- D supplements for maintenance [min]

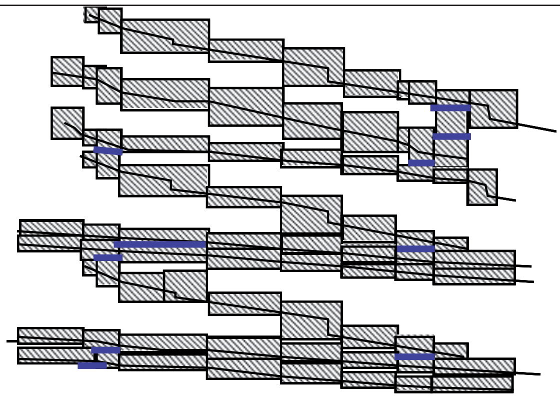
I	Capacity conumption	**A**	(minimum) infrastructure occupation 
		B	buffer time
		C	supplement for single-track lines
		D	supplement for maintenance
II	Unused Capacity	**E**	usable capacity
		F	lost capacity

Fig. 11: Determination of capacity consumption

Capacity consumption K is defined as

$$K = \frac{100 \cdot k}{t_U}$$

with

K capacity consumption [%]

t_U chosen time window [min]

UIC specifies a guideline for standard values of infrastructure occupation time A in order to achieve a satisfying operating quality. These values are indicated as a function of the type of line and the infrastructure use.

Type of line	Peak hour	Daily period
Dedicated suburban passenger traffic	85%	70%
Dedicated high-speed line	75%	60%
Mixed-traffic lines	75%	60%

Tab. 1: UIC's recommended values for infrastructure occupation

With this method of calculating the capacity consumption the optimal number of trains is only depending on average minimum headway times. Buffer times are neglected. This method is equivalent to the determination of an acceptable infrastructure occupancy rate.

Additionally, there is no explicit interrelation between capacity and quality, as this method is independent of delays or train priorities. The method can be used for the calculation of a rough benchmark of capacity consumption, but not for an estimation of railway infrastructure's performance. By means of UIC Code 406 there is no explicit method to determine the level of service. UIC Code 406 is based on expert's opinion. Corresponding to the STRELE-formula the average determinative buffer time $\bar{t}_{P,erf}$ can be calculated with the equation:

$$\bar{t}_{P,erf} = \frac{\bar{z} \cdot (1 - \rho_{zul})}{\rho_{zul}} = \frac{A \cdot (1 - \rho_{zul})}{N_{vorh} \cdot \rho_{zul}}$$

with

ρ_{zul} recommended value for the infrastructure occupation of UIC Code 406,
N_{vorh} existent number of trains.

3.3 Equivalent buffer time

The two methods – STRELE-formula and UIC Code 406 – assume a hindrance-free driving curve of a train. The time between the distant and the main signal is the approaching time. During this time the model assumes that the train does not brake. That means the following block section is duly cleared by the previous train so that the following train run is not affected.

For scheduling, a hindrance-free driving curve makes sense. For operation, the influences of the automatic train control with infill functionality (balise, loop, GSM-R) needs a different treatment. If the train is slowed down due to a slower leading train, the effects of the infill have an impact on capacity. If the following block section is occupied the train must brake down between the distant and the main signal. With the infill the train can get the information to accelerate if the next block section is cleared. The influence of the infill, described in [7], is expressed by the additional buffer time $t_{P,add}$ when comparing a train control system with another one.

With regard to the equivalent buffer time the optimal number of trains can be calculated with the formula:

$$N_{opt} = \frac{t_U}{\bar{z} + \bar{t}_{P,erf} - \bar{t}_{P,add}}$$

with

$\bar{t}_{P,add}$ equivalent buffer time.

3.4 Comparison of the STRELE-formula with UIC Code 406

The input parameters for both methods are the minimum headway time and the equivalent buffer time. In addition the STRELE-formula needs the average delay and the probability of delay at the entry of the line. With the acceptable sum of unscheduled waiting times the necessary buffer time can be calculated. The UIC Code 406 needs the recommended value for infrastructure occupation to calculate the necessary buffer time.

4 Analysis

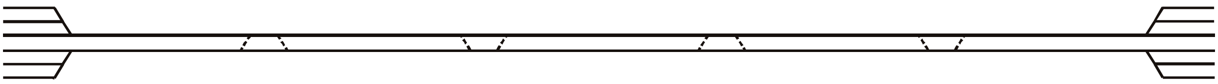
4.1 Modelling of infrastructure and scheme for operation

The infrastructure model has to be adapted for the different ETCS levels. ETCS level 1 has a spot and ETCS level 2 and 3 have a continuous injection of information. For all ETCS levels the braking model according ERTMS-Users Group Model "Description of the brake curve calculation" Version 6K is used [2].

4.1.1 Configuration of track layout

Three different configurations of track layouts will be analysed for this capacity study. The relevant parameters of the track layouts for high-speed line, conventional main line und regional line are described below.

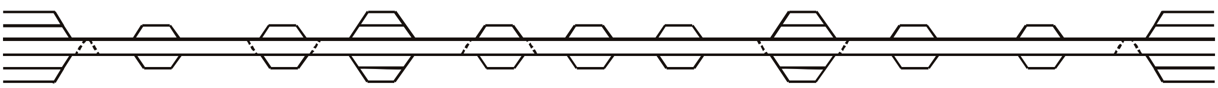
4.1.1.1 High-speed line



Speed	300 km/h
Distance of overtaking stations	In the distance of published stops
Length of block section	5 km
Total length of the line	approx. 100 km
Station at the beginning and end of the line	Large station with discharging lines of different categories
no en route stations	
Entrance/Exit speed	100 km/h

Fig. 12: Track layout high-speed line

4.1.1.2 Conventional main line



Speed		160 km/h
Distance of overtaking stations		In the distance of published stops
Length of block section		3 km
Total length of the line		approx. 100 km
Station at the beginning and end of the line		Large station with discharging lines of different categories
Totally nine en route stations, thereof		
	Two	Large stations normally without discharging lines
	Seven	Overtaking stations without discharging lines
Entrance/Exit speed		80 km/h

Fig. 13: Track layout conventional main line

4.1.1.3 Regional line

Speed	80 km/h
Distance of crossing stations	15 km
Length of block section	without block sections
Total length of the line	approx. 100 km (single-track line)
Station at the beginning and end of the line	Large station with discharging lines of different categories
Totally four en route stations	crossing stations
Entrance/Exit speed	50 or 40 km/h

Fig. 14: Track layout regional line

4.1.2 Scheme for operation

The utilisation of the infrastructure and the scheme for operation of these three categories are given below.

Abbreviation	Description	Example
HST	High Speed Train	ICE, TGV, Thalys, …
EC	EuroCity	IC, EC, …
REX	Fast Regional Train	RE, TER, REX, …
R	Slow Regional Train	RB, R, …
IRC	Inter-Regional Cargo Train	IRC, …
RC	Regional Cargo Train	RC, …

Tab. 2: Train categories

Train	Length [m]	Speed [km/h]	Brake percentage	Brake position	Coaches	Weight [t]	Train
HST	400	300	220	R + Mg			passenger
EC	320	200	220	R + Mg	11		passenger
REX	180	140	145	R	6		passenger
R	50	100	145	R			passenger
IRC	500	100	80	P		1250	freight
RC	500	90	80	P		1000	freight

Tab. 3: Characteristic of trains

4.1.2.1 High-speed line

Infrastructure utilisation		
	120 trains/day per direction	
	only long-distance passenger transportation	
Scheme for operation		
	train type	**number of trains (per day)**
	HST	80
	Stop at the beginning and end of the line	
	EC	40
	Stop at the beginning and end of the line	

Tab. 4: Scheme for operation high-speed line

4.1.2.2 Conventional main line

Infrastructure utilisation		
	150 trains/day per direction	
	50 long-distance passenger transportation, 40 short-distance passenger transportation, 60 freight transportation	
Scheme for operation		
	Train type	**number of trains (per day)**
	HST	20
	Stop at the beginning and end of the line	
	EC	30
	Stop at the beginning and end of the line	
	REX	20
	Stop at the beginning and end of the line and at all large stations of the line	
	R	20
	Stop everywhere	
	IRC	40
	RC	20

Tab. 5: Scheme for operation conventional main line

4.1.2.3 Regional line

Infrastructure utilisation		
	50 Trains/day (totally)	
	40 short-distance passenger transportation, 10 freight transportation	
Scheme for operation		
	Train type	**number of trains (per day)**
	REX	5 per direction
	Stop at the beginning and end of the line and every second possibility for stopping at the line	
	R	15 per direction
	Stop everywhere	
	RC	5 per direction

Tab. 6: Scheme for operation regional line

4.1.3 Stop time

The global stop time is 1 minute for all trains.

4.1.4 Indication point

The indication point is the point where the process of deceleration of a train has to start in case of no extension of the movement authority. The indication point for each train and the position of the balise, depending on the decisive indication point, will be defined according to the ERTMS-Users Group Model Version 6K [2].

The indication curve depends on the braking distance via Service Brake Deceleration (SBD) or Emergency Brake Deceleration (EBD), 4 seconds reaction time, service brake equivalent time Tbs and if necessary on emergency brake equivalent time Tbe. The location of the indication point depending on the availability of service brake and the length of the overlap are shown in Tab. 7. Vp is the initial speed.

	Large overlap	Small overlap	No Overlap
Service brake available	(brake distance via SBD from Vp to zero) + Vp * (Tbs + 4)	Somewhere between large and no overlap	(brake distance via EBD from Vp to zero) + Vp * (2 * Tbs + 4 + Tbe)
Service brake not available (emergency brake)	(brake distance via SBD from Vp to zero) + Vp * (Tbs + 4)	Somewhere between large and no overlap	(brake distance via EBD from Vp to zero) + Vp * (Tbs + 4 + Tbe)

Tab. 7: Calculation of the indication point

4.1.4.1 Braking distance via SBD or EBD

In the calculation of the first line of intervention two situations are distinguished:

- If service brake intervention is available, the ETCS onboard shall calculate the first line of intervention (FLOI) as the minimum of the SBI1 curve and SBI2 curve.
- If service brake intervention is not available, the ETCS onboard shall calculate the first line of intervention (FLOI) as the minimum of the SBI1 curve and EBI curve.

For the calculation it is assumed that the two input parameter A_gradient and T_traction are zero. A_gradient is zero because there is no gradient at these generic lines. If a gradient exists, the influence of the downhill-slope force has to be considered iteratively. T_traction is the traction time according to the EBI curve and depends on T_traction_cut_off, T_implemented and T_audible. T_traction_cut_off is the time interval between the traction cut off by ETCS onboard and the moment the acceleration due to traction is guaranteed to be zero. This generic study assumes that the train does not brake during acceleration so that T_traction_cut_off hence T_traction is zero. If a train brakes during acceleration, the intersection between the deceleration and the acceleration curve must be calculated and T_traction has to be considered adequately.

According to this the distance for the braking point can be calculated as follows:

distance via EBI	= distance via EBD + v · Tbe
distance via SBI1	= distance via SBD + v · Tbs1 with Tbs1 = 0
distance via SBI2	= v · Tbs2 + distance via EBI
	= v · Tbs2 + distance via EBD + v · Tbe

The SBD is the Service Brake Deceleration with

A_expected = A_brake_service + A_gradient

and the EBD the Emergency Brake Deceleration with

A_safe = kv · kr · A_brake_emergency + A_gradient.

A_brake_service and A_brake_emergency are calculated according to the brake percentage conversion model.

4.1.4.2 Service/Emergency brake equivalent time

The service brake equivalent time Tbs and the emergency brake equivalent time Tbe depend on the brake position P or G, the train length and the characteristic of the passenger or freight train.

Tbs = T_brake_service
Tbe = kt · T_brake_emergency

4.1.4.3 Correction factors for the calculation

kv shall be a speed dependent and kr a train length dependent correction factor for deceleration, defined as national values. Both are given as step functions and the value of the product of these two variables as a basis for this study is given in Tab. 8.

Speed [km/h]	kv · kr
0 – 155	0,89
155 – 200	0,77
200 – 250	0,72
250 – 300	0,64
> 300	0,59

Tab. 8: Correction factors kv and kr

kt is a correction factor for the build up time defined as a national value. For this study the value is 1,11.

4.1.5 System reaction time

The following different system reaction times between the ETCS levels occur. They depend on the transmission and processing times of the components

- Lineside Electronic Unit (LEU),
- Driver-Machine-Interface (DMI, formerly known as MMI),
- European Vital Computer (EVC),
- RBC.

These values are considered in the calculation of the minimum headway times.

	mean value for ETCS level 1 [sec]
LEU	0,7
EVC + DMI	1
Summation	1,7

	mean value for ETCS level 2 [sec]
interlocking to RBC	0,05
RBC	1,5
RBC to train	1,1
EVC + DMI	1
Summation	3,65

	mean value for ETCS level 3 [sec]
Train integrity	4
Train 1 to RBC	1,1
RBC	1,5
RBC to train 2	1,1
EVC + DMI	1
Summation	8,7

Tab. 9: System reaction time for the different ETCS levels

4.1.6 Values of the braking calculation

The relevant input parameters for calculating of the braking distance are shown in Tab. 10.

Train	Length [m]	Speed [km/h]	Brake percentage	brake position	Train
HST	400	300	220	R + Mg	passenger
EC	320	200	220	R + Mg	passenger
REX	180	140	145	R	passenger
R	52	100	145	R	passenger
IRC	500	100	80	P	freight
RC	500	90	80	P	freight

Tab. 10: Relevant parameters for the calculation of the braking distance

The results and the specific parameters for the different infrastructure configuration are shown in the following sections. For each train the braking distance l [m] is calculated according to the ERTMS-Users Group Model Version 6K. With this value the average deceleration a_b [m/s²] is derived.

4.1.6.1 High-speed line

The brake percentage conversion model of the ERTMS-Users Group Model Version 6K is limited to maximum speed of 200 km/h. On the high-speed line the maximum speed is 300 km/h. According to this the brake percentage conversion model cannot be used. For railcar train-set a speed dependent deceleration as a step function exists. In this study the current deceleration of the ICE 3 with steps for the SBD and the EBD is used for the high-speed line (cf. Tab. 11).

SBD		EBD	
v [km/h]	a [m/s²]	v [km/h]	a [m/s²]
0 – 160	1,1	0 – 56	1,24
160 – 165	1,025	56 – 110	1,54
165 – 175	0,875	110 – 130	1,56
175 – 180	0,8	130 – 165	1,47
180 – 210	0,7	165 – 170	1,35
210 – 300	0,6625	> 170	1,07
> 300	0,65		

Tab. 11: Deceleration of the ICE 3

Hence the following values arise for the high-speed line with consideration of the correction factors if the service brake is available:

Service brake available					
Train	Speed [km/h]	SBI1 (with overlap)		SBI2 (without overlap)	
		l [m]	a_b [m/s²]	l [m]	a_b [m/s²]
HST	300	5729,0	0,606	6636,9	0,523
EC	200	2402,9	0,642	2680,6	0,576

Tab. 12: Braking distance for the high-speed line (service brake available)

Relevant for each train is SBI2. The distance between the indication point and the main signal is the maximum, thus 6637 m.

4.1.6.2 Conventional main line

For the conventional main line the constant correction factors

- kv · kr = 0,89
- kt = 1,11

identical to the ones in chapter 4.1.4.2 are used.

If the service brake is available the following values for the different train types arise:

Service brake available					
Train	Speed [km/h]	SBI1 (with overlap)		SBI2 (without overlap)	
		l [m]	a_b [m/s²]	l [m]	a_b [m/s²]
HST	160	1632,83	0,605	2010,60	0,491
EC	160	1553,90	0,636	1852,73	0,533
REX	140	1091,48	0,693	1571,02	0,481
R	100	571,30	0,675	849,97	0,454
IRC	100	1149,88	0,336	1890,43	0,204
RC	90	983,53	0,318	1643,68	0,190

Tab. 13: Braking distance for the conventional main line (service brake available)

Relevant for each train is SBI2. The distance between the indication point and the main signal is the maximum, thus 2011 m.

If the service brake is not available (emergency brake) the following values for the different train types arise:

Service brake not available (emergency brake)					
Train	**Speed** [km/h]	**SBI1** (with overlap)		**EBI** (no overlap)	
		l [m]	**a_b** [m/s²]	**l** [m]	**a_b** [m/s²]
HST	160	1632,83	0,605	1539,49	0,642
EC	160	1553,90	0,636	1460,55	0,676
REX	140	1091,48	0,693	1336,76	0,566
R	100	571,30	0,675	744,22	0,518
IRC	100	1149,88	0,336	1422,38	0,271
RC	90	983,53	0,318	1222,43	0,256

Tab. 14: Braking distance for the conventional main line (service brake not available)

For the passengers train (high speed, high braking percentage) the braking percentage is limited to 135. So the SBI1 (SBD braking curve) is relevant. For the other trains the EBI is deciding. Hence the distance from the distant to the main signal is 1633 m.

4.1.6.3 Regional line

For the regional line the constant correction factors

- kv · kr = 0,89
- kt = 1,11

identical to the ones in chapter 4.1.4.2 are used.

If the service brake is available the following values for the different train types arise:

Service brake available					
Train	Speed [km/h]	SBI1 (with overlap)		SBI2 (without overlap)	
		l [m]	a_b [m/s²]	l [m]	a_b [m/s²]
REX	80	449,59	0,549	718,89	0,343
R	80	400,33	0,617	620,36	0,398
RC	80	828,59	0,298	1035,30	0,238

Tab. 15: Braking distance for the regional line (service brake available)

Relevant for each train is SBI2. The distance between the indication point and the main signal is the maximum, thus 1035 m.

4.1.7 Acceleration after a stop

The acceleration of the trains after a scheduled stop is calculated with an exact method using the parameters of the driving dynamics (delta-v-step-method). After a train was slowed down by another train, the following values of acceleration for the calculation of the equivalent buffer time are used:

Passenger train		Freight train	
v [km/h]	a_a [m/s²]	v [km/h]	a_a [m/s²]
0 – 45	0,5	0 – 45	0,2
45 – 85	0,4	45 – 70	0,1
85 – 300	0,3	70 – 300	0,1

Tab. 16: Acceleration after slowing down due to a slower leading train

For the scenario ETCS level 1 with infill loop an average acceleration of 0,4 m/s² for passenger trains and 0,15 m/s² for freight trains is used as an approximation for the calculation of the equivalent buffer time.

4.1.8 Reaction time

ETCS-controlled trains do not need the reaction time of 0,2 Minutes for the reaction of the loco driver. If a train accelerate from a stop, the time components:

$$t_{\text{signal recognition}} + t_{\text{shuting the door}} + t_{\text{order to start}} = 4 + 4 + 4 = 12\text{ s}$$

must be regarded.

4.1.9 Investigated configurations of ETCS

For the three infrastructure applications the following configurations of ETCS are analysed:

- ETCS level 1
- ETCS level 1 with infill-balises
- ETCS level 1 with infill loop
- ETCS level 1 with radio infill
- ETCS level 1 limited supervision
- ETCS level 1 with optimized block sections
- ETCS level 2
- ETCS level 2 with optimised block sections
- ETCS level 3

The different variants with their characteristics and the modelling in SPURPLAN/ ANKE are shown in the following table.

Automatic train control system	Infrastructure			Comment	SPURPLAN/ANKE
	high-speed line	conven-tional main line	regional line		
ETCS level 1	x	x	x		Indication point in distance of the longest braking distance from the main signal
ETCS level 1 with optimized block sections		x [1]		instead of 3000 m block sections reduction to minimum 1000 m in relevant sections	cf. ETCS level 1
ETCS level 1		x		Emergency brake (service brake not available)	cf. ETCS level 1
ETCS level 1 with a second infill-balise	x	x		a second Infill-Balise 400 m ahead of the main signal	cf. ETCS level 1
ETCS level 1 with infill loop or radio infill*		x		optimal infill between distant and main signal (1000 m)	cf. ETCS level 1
ETCS level 1 limited supervision		x		Emergency brake (service brake not available)	distant signal 1000 m ahead of the main signal
ETCS level 2	x	x	x	Service brake	
ETCS level 2		x		Emergency brake (service brake not available)	
ETCS level 2 with 400 m block sections	x	x		CIR-ELKE	400 m long ETCS block sections
ETCS level 2 with optimized block sections		x [2, 3]		Service brake	
ETCS level 3	x	x	x	moving block	50 m long ETCS block sections

Tab. 17: Different variants of the ETCS with their characteristics

* *ETCS level 1 with infill loop and with radio infill is considered as equal in this study. A marginal difference occurs because of radio transmission times.*

1 ETCS level 1 with optimized block sections, instead of 3000 m block sections reduction to minimum 1000 m in relevant sections.

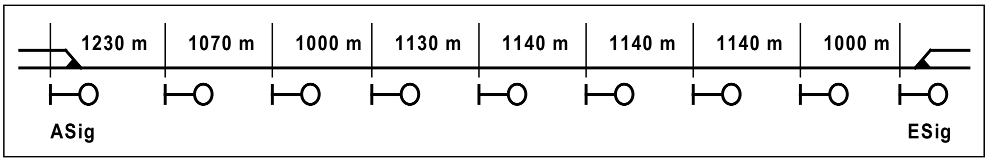


Fig. 15: Block sections for the ETCS level 1 scenario with minimum 1000 m block sections

Additionally the following scenarios are calculated for the main line:

ETCS level 2 with a minimal block length of 400 m.

2

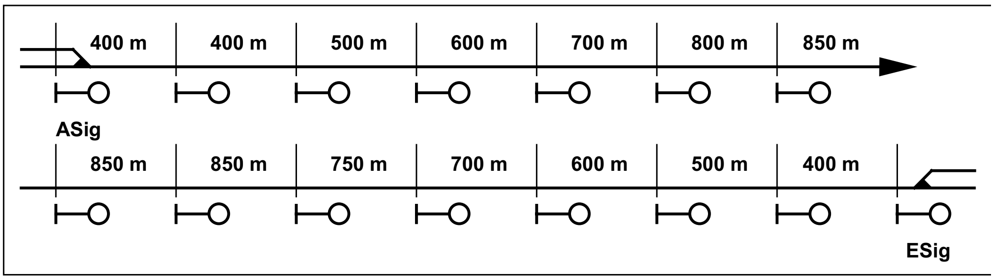


Fig. 16: Block sections for the ETCS level 2 scenario with minimum 400 m block sections

3 ETCS level 2 with a minimal block length of 50 m.

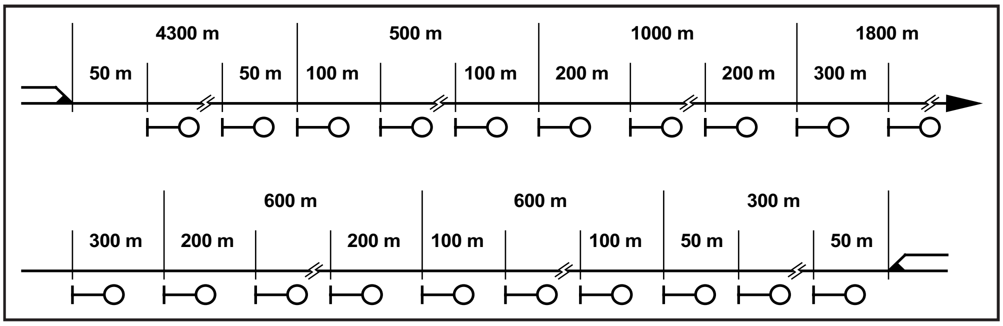


Fig. 17: Block sections for the ETCS level 2 scenario with minimum 50 m block sections

4.2 Calculation

4.2.1 Minimum headway time

The average headway time will be calculated as follows if only the occurrence and not the order of the trains are known:

$$\bar{z} = \sum z_{ij} \cdot p_{ij}$$

$\bar{z}$ average headway time,
z_{ij} Minimum headway time for the trains i and j
p_{ij} probability of occurrence of train order ij

The minimum headway time for the different infrastructures and different automatic train control systems are shown in the appendix.

4.2.2 Buffer time

The average determinative buffer time $\bar{t}_{P,erf}$ results from the limitation of the acceptable sum of unscheduled waiting times according to the equation of the STRELE-formula. Parameters of the delay (average delay at entry $\bar{t}_{VE}$ and probability of delay at entry p_{VE}) are necessary for the calculation. In this study the German infrastructure network average values for high frequented lines are used.

Abbr.	Train	p_{VE}	$\bar{t}_{VE}$ [min]
HST	ICE, TGV, Thalys, …	0,30	4
EC	IC, EC, …	0,30	4
REX	RE, TER, REX, …	0,60	3
R	RB, R, …	0,60	3
IRC	IRC, …	0,50	30
RC	RC, …	0,60	30

Tab. 18: Average values of delay

The UIC Code 406 does not use delay. For the calculation of the average determinative buffer time $\bar{t}_{P,erf}$ the recommended values of infrastructure occupation

- ρ_{zul} = 0,6 for the high speed line
- ρ_{zul} = 0,6 for the main line and
- ρ_{zul} = 0,7 for the regional line

are used for a time window of t_U = 1440 minutes (24 hours = one day).

4.2.3 Ranking

For using the STRELE-formula, the ranking of the train must be considered. The long-distance passenger trains are equal-ranking and have the highest rang. The short-distance passenger trains and the freight trains are equal-ranking.

4.2.4 Equivalent buffer time

During operation a train can be delayed. If the following train is as fast as or faster than the delayed one ($v_1 \leq v_2$) and the next block section is occupied, the second train will be slowed down or stopped by the automatic train control system. If the next block section is cleared, the following train can release itself with a release speed of $v_{release}$ = 20 km/h for no infill. The equivalent buffer time $t_{p,add}$ compares full infill with the respective scenario. According to this, the equivalent buffer time for ETCS level 2 and ETCS level 3 is zero. [8]

4.3 Capacity consumption

The optimal number of trains for the total infill is

$$N_{opt,total\,inf\,ill} = \frac{t_U}{\bar{z} + \bar{t}_{P,erf}}$$

For the variants “particular infill” and “no infill” the equivalent buffer time is added to the buffer time in the denominator and the optimal number of trains decrease

$$N_{opt} = \frac{t_U}{\bar{z} + \bar{t}_{P,erf} - \bar{t}_{P,add}}$$

5 Results

In this study capacity analysis are made for different track layouts with different configurations of ETCS. The calculations are made with UIC Code 406 and with the STRELE-formula. The results are illustrated in the following chapters. The first diagram shows the total number of trains per day for the different ETCS application configuration calculated with the two methods. The second diagram illustrates the results of the ETCS configurations for the calculation with UIC Code 406. The reference value is ETCS level 1 with 100 % capacity. The values according to the STRELE-formula are similar to the ones of UIC Code 406 and therefore not shown.

5.1 High-speed line

The increase in capacity of ETCS level 1 with a second infill balise 400 m ahead of the main signal is marginal in comparison to ETCS level 1. ETCS level 2 shows an increase in capacity. ETCS level 2 with 400 m block sections and ETCS level 3 have a similar high capacity.

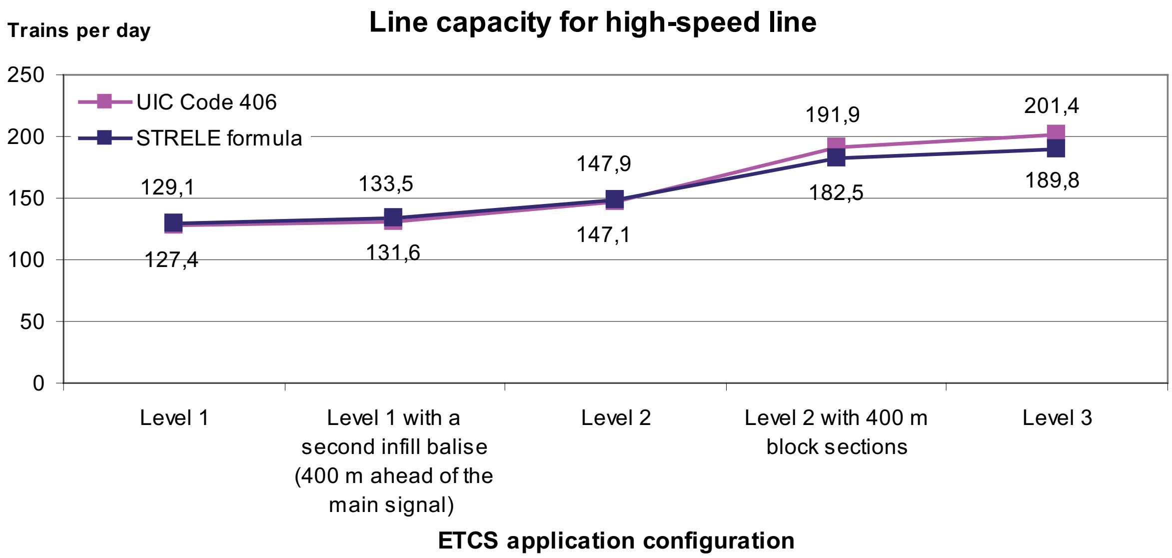


Fig. 18: Line capacity for the high-speed line

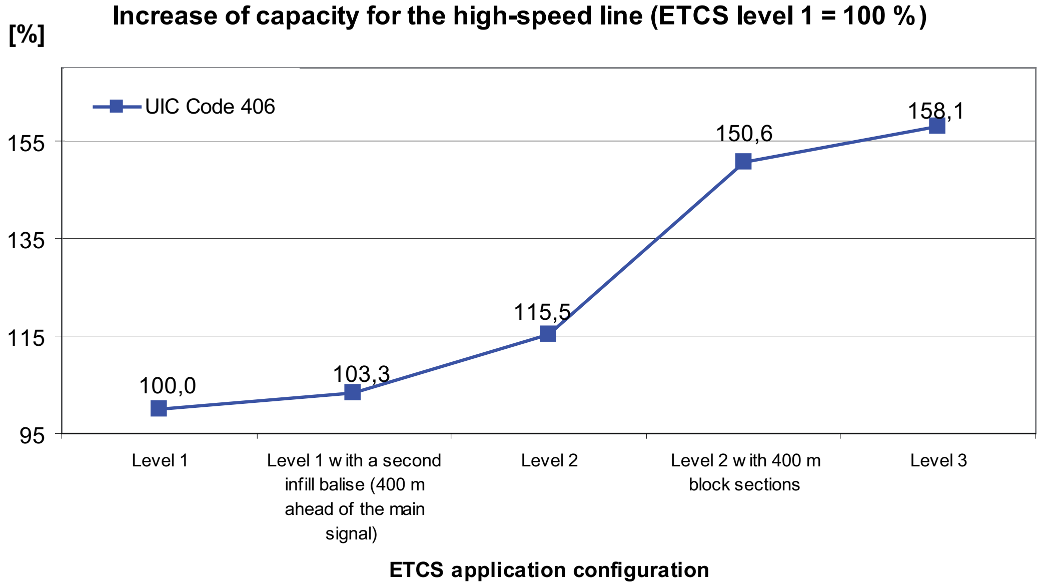


Fig. 19: Increase in capacity for the high-speed line

5.2 Conventional main line

The different configurations of ETCS level 1 infill (one balise, second infill balise, infill loop or radio infill) show only a light variation in capacity. The availability of the service brake (ETCS level 1 with limited supervision, ETCS level 1 or 2 with service brake not available) influences the capacity more distinctively. The highest capacity results with an optimal length of the block section (ETCS level 1 with optimized block sections, ETCS level 2 with 400 m block sections and ETCS level 3).

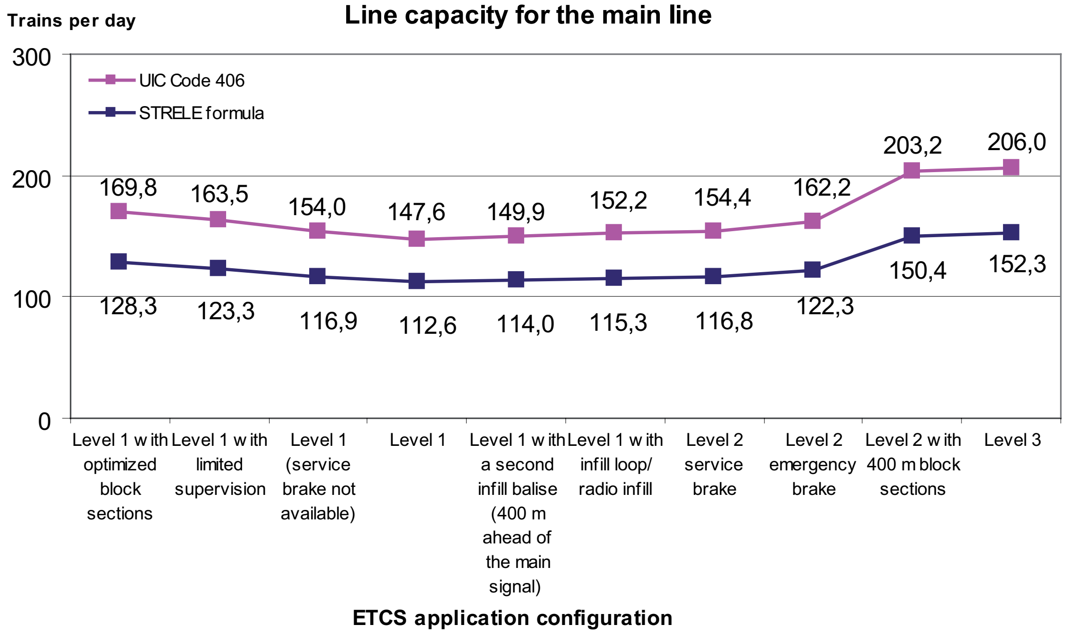


Fig. 20: Line capacity for the conventional main line
(Special subcases of ETCS Level 2 with optimized block sections are presented in Fig. 24)

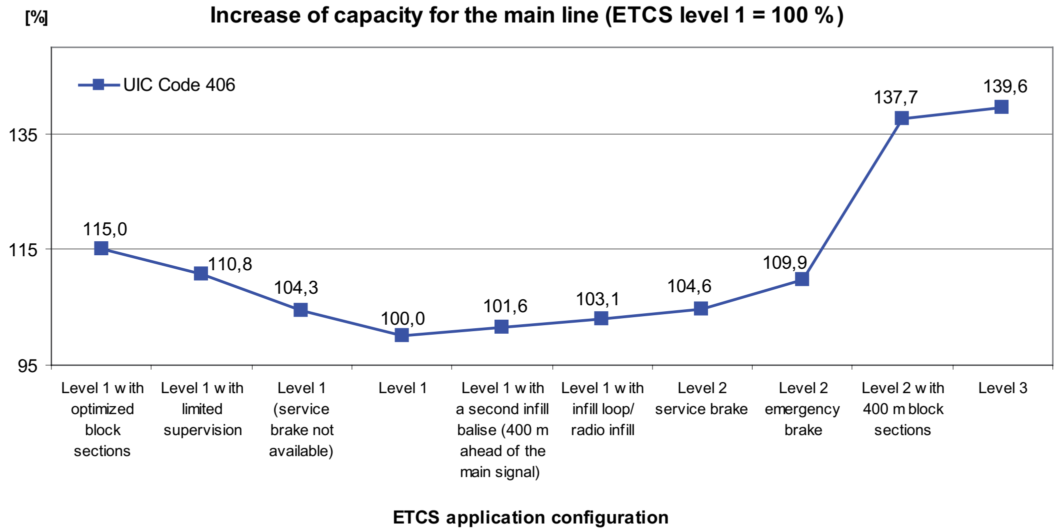


Fig. 21: Increase in capacity for the conventional main line
(Special subcases of ETCS Level 2 with optimized block sections are presented in Fig. 24)

5.3 Regional line

On the regional line there is nearly no difference between ETCS level 1 and ETCS level 2 because all trains have the same speed and the same blocking time in the block section between two stations. Only ETCS level 3 leads to a higher capacity because of the moving block.

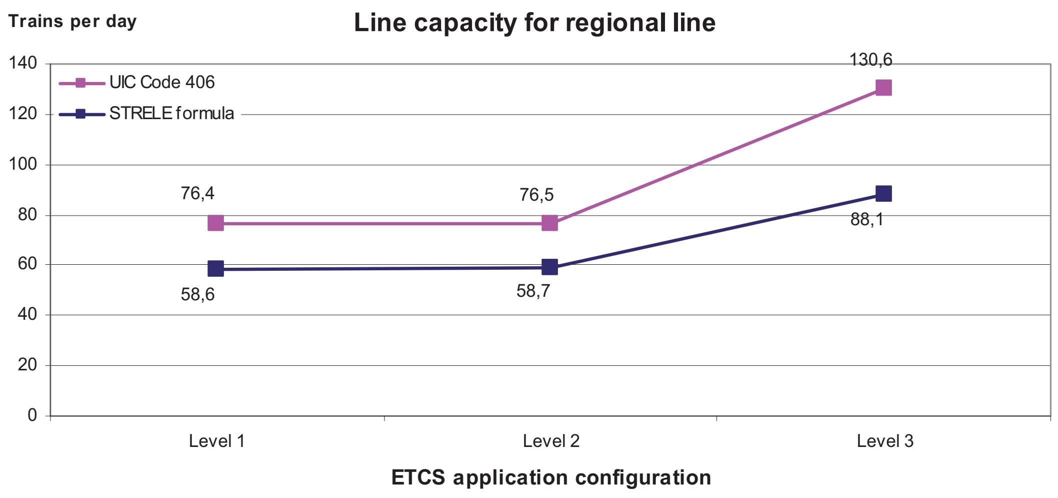


Fig. 22: Increase in capacity for the regional line

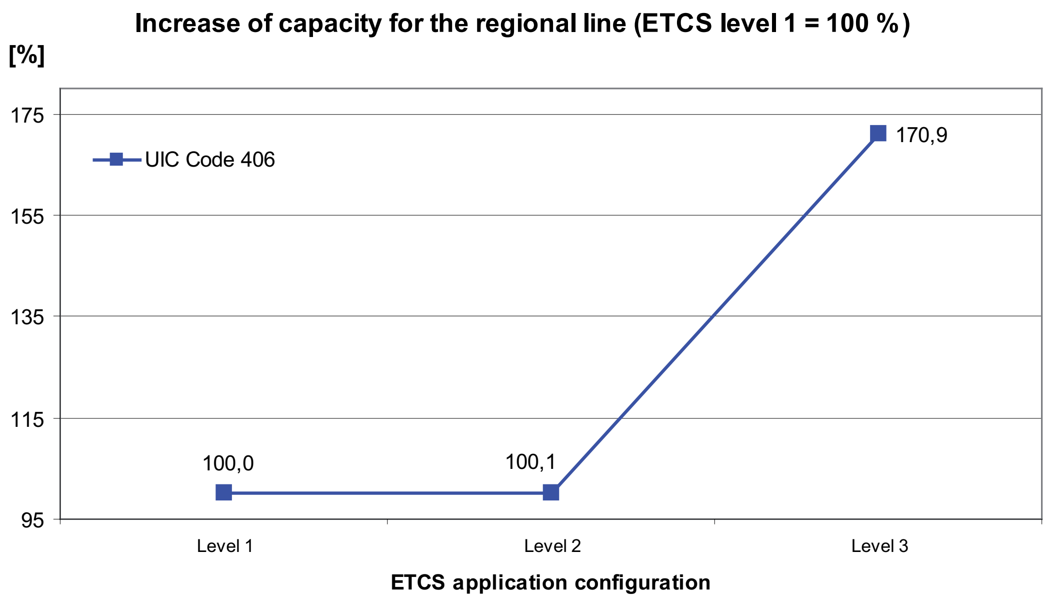


Fig. 23: Increase in capacity for the regional line

5.4 Comments on the results

The results of the capacity analysis with UIC Code 406 are higher than the ones with the STRELE-formula. The reason is the different calculation of capacity consumption. UIC Code 406 uses the recommended values of infrastructure occupation and for the STRELE-formula the limitation of the acceptable sum of unscheduled waiting times is decisive. If the trains have less delay, the capacity of a line increases. In this study high values of delay are assumed. An exception is the high-speed line without freight trains and low values of delay for the high-speed trains. There the results of the capacity analysis with UIC Code 406 and the STRELE-formula are approximately equal.

The different configurations of ETCS level 1 in full supervision with service brake intervention lead to the lowest capacity in all three cases. The influence of the infill on the line capacity is marginal as it is only used if a fast train is running densely behind a slower one ("stop-start motion"). In ETCS level 1 with limited supervision and ETCS level 1 without service brake, the higher emergency brake deceleration leads to a shorter approaching time at the main signal. Due to this, the minimum headway decreases and the capacity increases. ETCS level 1 with optimized block sections features a high capacity increase in comparison to ETCS level 1 in full supervision with service brake.

For all the case lines, ETCS level 2 shows only a light increase in the capacity compared to Level 1. On practical railway lines, the increase of Level 2 can be higher, due to a larger variation of the braking distances of the different train types. ETCS level 2 with 400 m block sections leads to a significant higher capacity.

ETCS level 3 has the highest potential for capacity increase because of the moving block. However the increase in capacity of Level 3 compared to Level 2 with optimised block sections is relatively moderate. On the regional line with no block sections between two stations, a random train mix is assumed. In this case, Level 3 has a relatively high capacity potential even on the single track line. If a strict pattern “one-direction/opposite direction” is assumed on the single track line, there would be no increase in capacity.

The block length has a big influence on the capacity. With analysing of the minimum headway time, an optimal number of block sections and capacity consumption can be found. The difference between a minimal block length in the relevant areas and a constant block length for the whole line is marginal. In Fig. 24 the following modifications of ETCS level 2 are illustrated:

- ETCS level 2 with a minimum block length of 400 m in comparison with ETCS level 2 with a global block length of 400 m
- ETCS level 2 with a minimum block length of 50 m in comparison with ETCS level 3 with a global block length of 50 m

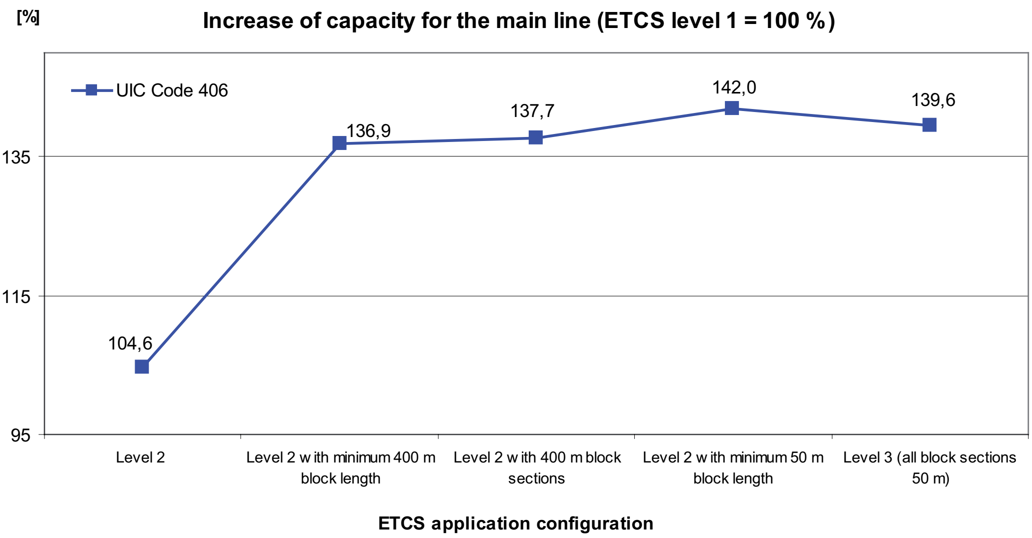


Fig. 24: Increase in capacity for the main line (modification of the block length)

The reason for the decrease of capacity of ETCS level 2 with the minimum block length of 50 m in comparison to ETCS level 3 is the system reaction time. The difference between the two system reaction times is 5 seconds. With a capacity of about 200 trains and a minimum headway time of ca. 4,2 minutes, a difference of:

$$\frac{5\text{ sec} \cdot 200\text{ trains}}{4{,}2\text{ min}} \cdot \frac{1\text{ min}}{60\text{ sec}} \approx 4\text{ train paths}$$

results.

6 Summary

The aim of the capacity study is to indicate the capacity consumption of the three typical cases of lines (high-speed line, conventional main line and regional line) with different ETCS application configurations. With the methods of UIC Code 406 “Capacity” and the STRELE-formula (method of Schwanhäußer) capacity of these variants are calculated.

Different train characteristics and the scheme for operation for these trains influence the minimum headway time for the variants of infrastructure and ETCS application configuration. With the minimum headway time, the buffer time, the equivalent buffer time and the optimal number of trains can be investigated.

The variation of capacity consumption depends primarily on the deviation of train characteristics, the scheme for operation and the track layout configuration. The different configurations of ETCS level 1 show a variation in their capacity. The infill will have an effect on the capacity if a fast train runs behind a slower one and if it is influenced by this. Also ETCS level 2 shows only a light increase in capacity compared to ETCS level 1 for all lines in all cases. ETCS level 2 with 400 m block sections and ETCS level 3 have a high potential for capacity increase.

The existing UIC Code 406 considers only conventional signalling systems but not other signalling systems like ETCS level 1, 2 and 3. For ETCS, the indication curve effects the capacity consumption. Therefore in a revised UIC Code 406 it is recommended to include the indication point in the blocking-time sequence.

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List of abbreviations

ANKE	Analytische Netzkapazitätsermittlung, analytic network capacity assessment
ATC	automatic train control
DMI	Driver-Machine-Interface, formerly known as MMI
EVC	European Vital Computer
LEU	Lineside Electronic Unit
RBC	Radio Block Centre
TOC	train operating company

Calculation of capacity consumption

n_{max}	(theoretical) capacity
n_{opt}	optimal capacity
ET_W	waiting time, average secondary delay
ET_{Wzul}	"level of service"
$\bar{t}_{p,add}$	average equivalent buffer time
z	minimum headway time
t_A	inter-arrival interval
t_B	average service time
a_b	deceleration
a_a	acceleration

STRELE–formula (Method of Schwanhäußer)

$\bar{t}_p$	average buffer time
$\bar{z}$	average determinative minimum headway time
$\bar{z}_g$	average determinative minimum headway time of equal-ranking successions of trains
$\bar{z}_v$	average determinative minimum headway time of different-ranking successions of trains
$\bar{t}_{VE}$	average delay at entry
p_{VE}	probability of delay at entry
p_g	probability of the occurrence of an equal-ranking succession of trains
p_{RZ}	proportion of the passenger trains

UIC Code 406

k	total consumption time [min]
A	infrastructure occupation [min]
B	buffer time [min]
C	supplement for single-track lines [min]
D	supplements for maintenance [min]
K	capacity consumption [%]
t_U	chosen time window, reference period [min]
ρ_{zul}	recommended value for the infrastructure occupation of UIC Code 406
N_{vorh}	existent number of trains

Braking Model

FLOI	first line of intervention
EBI	Emergency Brake Intervention
EBD	Emergency Brake Deceleration
SBI	Service Brake Intervention
SBD	Service Brake Deceleration
Tbe	emergency brake equivalent time
Tbs	service brake equivalent time
kv	shall be a speed dependent correction factor for deceleration
kr	train length dependent correction factor for deceleration
kt	correction factor for the build up time

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Appendix A Matrix of minimum headway time

These minimum headway times [min] are calculated with ANKE.

A.1 High Speed Line (HSL)

2nd train / 1st train	HST	EC
HST	3,79	3,73
EC	13,79	4,94

Tab. 19: Minimum headway time of HSL with ETCS level 1 (with and without a second infill balise)

2nd train / 1st train	HST	EC
HST	3,47	3,47
EC	13,82	4,38

Tab. 20: Minimum headway time of HSL with ETCS level 2

2nd train / 1st train	HST	EC
HST	2,51	1,29
EC	13,13	1,62

Tab. 21: Minimum headway time of HSL with ETCS level 2 with optimized block sections

2nd train / 1st train	HST	EC
HST	2,34	1,13
EC	12,82	1,38

Tab. 22: Minimum headway time of HSL with ETCS level 3

A.2 Conventional main Line (ML)

1st train \ 2nd train	HST	EC	REX	R	IRC	RC
HST	2,69	2,04	2,80	2,64	2,57	2,57
EC	3,83	2,86	3,13	2,97	2,86	2,86
REX	3,41	3,17	3,91	2,60	2,36	2,36
R	4,32	4,16	29,47	4,15	20,00	13,70
IRC	5,48	5,32	13,55	4,75	4,00	3,85
RC	6,29	6,13	20,66	5,53	11,11	4,40

Tab. 23: Minimum headway time of ML with ETCS level 1
(with and without a second infill balise, infill loop and radio infill)

1st train \ 2nd train	HST	EC	REX	R	IRC	RC
HST	2,54	2,40	2,47	2,42	2,42	2,42
EC	3,68	2,86	2,94	2,86	2,86	2,86
REX	3,29	3,17	3,74	2,36	2,36	2,36
R	4,20	4,16	29,31	3,92	19,99	13,69
IRC	5,13	5,08	13,14	4,26	3,76	3,59
RC	5,91	5,87	20,22	5,03	10,87	4,13

Tab. 24: Minimum headway time of ML with ETCS level 1
with service brake not available

1st train \ 2nd train	HST	EC	REX	R	IRC	RC
HST	2,40	2,40	2,40	2,40	2,40	2,40
EC	3,37	2,86	2,86	2,86	2,86	2,86
REX	3,25	3,13	3,25	2,37	2,37	2,37
R	4,21	4,16	28,2	3,34	18,25	11,94
IRC	4,73	4,68	13,38	3,56	3,41	3,32
RC	5,47	5,42	20,43	4,30	10,4	3,74

Tab. 25: Minimum headway time of ML with ETCS level 1
with limited supervision

1st train \ 2nd train	HST	EC	REX	R	IRC	RC
HST	1,93	1,93	1,93	1,93	1,71	1,71
EC	2,92	2,35	2,36	2,35	2,03	2,03
REX	2,57	2,44	3,71	1,85	1,58	1,58
R	3,49	3,43	28,46	3,95	18,9	12,6
IRC	4,45	4,39	12,33	3,29	2,68	2,53
RC	5,26	5,20	19,44	4,07	9,82	2,96

Tab. 26: Minimum headway time of ML with ETCS level 1
with optimized block sections

2nd train / 1st train	HST	EC	REX	R	IRC	RC
HST	2,52	2,43	2,43	2,43	2,43	2,43
EC	3,66	2,89	2,89	2,89	2,89	2,89
REX	3,32	3,20	3,53	2,39	2,39	2,39
R	4,23	4,19	29,15	3,26	20,03	13,73
IRC	5,12	5,07	12,95	3,70	3,75	3,42
RC	5,75	5,70	19,87	4,18	10,86	3,97

Tab. 27: Minimum headway time of ML with ETCS level 2 with service brake

2nd train / 1st train	HST	EC	REX	R	IRC	RC
HST	2,43	2,43	2,43	2,43	2,43	2,43
EC	3,47	2,89	2,89	2,89	2,89	2,89
REX	3,06	2,45	3,33	2,39	2,39	2,39
R	4,01	3,46	28,87	3,13	19,44	13,14
IRC	4,60	4,05	12,96	3,41	3,46	3,13
RC	5,23	4,68	19,89	3,82	10,57	3,68

Tab. 28: Minimum headway time of ML with ETCS level 2 with service brake not available

2nd train / 1st train	HST	EC	REX	R	IRC	RC
HST	1,44	0,94	1,28	1,28	1,28	1,28
EC	2,58	1,31	1,61	1,21	1,21	1,21
REX	2,30	2,16	3,20	0,75	0,75	0,75
R	3,20	3,13	27,86	2,80	17,95	11,59
IRC	4,35	4,02	11,97	2,31	2,02	1,77
RC	4,99	4,65	18,90	3,01	9,30	2,05

Tab. 29: Minimum headway time of ML with ETCS level 2 with optimized block sections

2nd train / 1st train	HST	EC	REX	R	IRC	RC
HST	1,49	1,05	1,29	1,29	1,29	1,29
EC	2,64	1,36	1,63	1,21	1,23	1,21
REX	2,22	1,98	3,15	0,83	0,85	0,83
R	3,03	2,97	27,76	2,66	17,88	11,50
IRC	4,18	4,01	11,87	2,11	1,92	1,63
RC	4,81	4,65	18,79	2,80	9,17	1,92

Tab. 30: Minimum headway time of ML with ETCS level 3

Additional scenarios:

1st train \ 2nd train	HST	EC	REX	R	IRC	RC
HST	1,46	0,94	1,28	1,28	1,28	1,28
EC	2,58	1,39	1,61	1,21	1,21	1,21
REX	2,30	2,16	3,20	0,75	0,75	0,75
R	3,20	3,13	27,86	2,80	17,95	11,59
IRC	4,35	4,02	11,97	2,31	2,25	1,77
RC	4,99	4,65	18,90	3,01	9,30	2,31

Tab. 31: Minimum headway time of ML with ETCS level 2 with minimum 400 m block sections

1st train \ 2nd train	HST	EC	REX	R	IRC	RC
HST	1,40	0,96	1,20	1,20	1,20	1,20
EC	2,55	1,27	1,54	1,12	1,14	1,12
REX	2,13	1,89	3,06	0,74	0,76	0,74
R	2,94	2,88	27,67	2,57	17,79	11,41
IRC	4,09	3,92	11,78	2,02	1,96	1,54
RC	4,72	4,56	18,70	2,71	9,08	1,98

Tab. 32: Minimum headway time of ML with ETCS level 2 with minimum 50 m block sections

A.3 Regional Line (RL)

2nd train / 1st train	REX	REX	R	R	RC	RC
REX	12,26	23,29	12,26	23,29	12,26	23,29
REX	23,29	12,26	23,29	12,26	23,29	12,26
R	11,62	11,70	11,62	11,70	11,62	11,70
R	11,70	11,62	11,70	11,62	11,70	11,62
RC	12,76	12,84	12,76	12,84	12,76	12,84
RC	12,84	12,76	12,84	12,76	12,84	12,76

Tab. 33: Minimum headway time of RL with ETCS level 1

2nd train / 1st train	REX	REX	R	R	RC	RC
REX	11,88	23,34	11,88	23,34	11,88	23,34
REX	23,50	11,83	23,50	11,83	23,50	11,83
R	11,77	11,90	11,77	11,90	11,77	11,90
R	11,78	11,70	11,78	11,70	11,78	11,70
RC	12,80	12,88	12,80	12,88	12,80	12,88
RC	12,88	12,80	12,88	12,80	12,88	12,80

Tab. 34: Minimum headway time of RL with ETCS level 2

2nd train / 1st train	REX	REX	R	R	RC	RC
REX	1,17	23,23	1,38	23,23	1,10	23,23
REX	23,19	1,13	23,19	1,31	23,19	1,09
R	1,11	11,52	0,99	11,52	0,71	11,52
R	11,59	1,07	11,59	0,95	11,59	0,86
RC	2,49	12,93	2,33	12,93	1,98	12,93
RC	12,97	2,41	12,97	2,33	12,97	1,94

Tab. 35: Minimum headway time of RL with ETCS level 3

Appendix B Equivalent buffer time

These equivalent buffer times [min] are considered for the different ETCS level 1 configurations. In the tables the input parameter and the equivalent buffer times are shown. The input parameters for the first train are the values of delay (t_{VE} and p_{VE}). The input parameters for the following train are the speed, the deceleration a_b and the acceleration a_a depending on the type of train (freight train (Gz) or passenger train (Pz)). Only if the first train is as fast as or slower than the second one, an equivalent buffer time exists. The results are shown in the framed part of the tables (with the slash meaning the first train is faster than the second one).

B.1 High speed line (HSL)

B.1.1 Level 1 (total infill – no infill)

$\bar{t}_{P,UIC}$ = 236 s

2nd train / 1st train		v [km/h]	300	200
		a_b	0,5	0,5
t_{VE}	p_{VE}	a_a	Pz	Pz
4	0,3		91,2	/
4	0,3		91,2	43,7

Tab. 36: Equivalent buffer time of HSL for no infill

B.1.2 Level 1 with a second infill balise 400 m ahead of the main signal (total infill – second balise)

$\bar{t}_{P,UIC}$ = 232 s

2nd train / 1st train		v	300	200
		a_b	0,5	0,5
t_{VE}	p_{VE}	a_a	Pz	Pz
4	0,3		62,0	/
4	0,3		62,0	21,5

Tab. 37: Equivalent buffer time of HL for second infill balise 400 m ahead of the main signal

B.2 Conventional main line (ML)

B.2.1 Level 1 (total infill – no infill)

$\bar{t}_{P,UIC}$ = 232 s

2nd train / 1st train		v	160	160	140	100	100	90
		a_b	0,5	0,5	0,5	0,5	0,2	0,2
t_{VE}	p_{VE}	a_a	Pz	Pz	Pz	Pz	Gz	Gz
4	0,3		19,4	19,4	/	/	/	/
4	0,3		19,4	19,4	/	/	/	/
3	0,6		28,8	28,8	21,6	/	/	/
3	0,6		28,8	28,8	21,6	10,1	55,0	/
30	0,5		22,5	22,5	16,3	7,1	47,8	/
30	0,6		22,5	22,5	16,3	7,1	47,8	36,1

Tab. 38: Equivalent buffer time of ML for no infill

B.2.2 Level 1 with a second infill balise 400 m ahead of the main signal (total infill – second balise)

$\bar{t}_{P,UIC}$ = 232 s

2nd train / 1st train		v	160	160	140	100	100	90
		a_b	0,5	0,5	0,5	0,5	0,2	0,2
t_{VE}	p_{VE}	a_a	Pz	Pz	Pz	Pz	Gz	Gz
4	0,3		11,9	11,9	/	/	/	/
4	0,3		11,9	11,9	/	/	/	/
3	0,6		12,7	12,7	9,2	/	/	/
3	0,6		12,7	12,7	9,2	5,4	27,5	/
30	0,5		9,7	9,7	7,0	4,4	22,3	/
30	0,6		9,7	9,7	7,0	4,4	22,3	16,3

Tab. 39: Equivalent buffer time of ML for second infill balise 400 m ahead of the main signal

B.2.3 Level 1 with infill loop/radio infill

$\bar{t}_{P,UIC}$ = 232 s

The influence of the infill is marginal and is not considered in this configuration.

B2.4 Level 1 with limited supervision (Emergency brake) (total infill – no infill)

$\bar{t}_{P,UIC}$ = 212 s

$$a_b = \frac{\left(v/3{,}6\right)^2}{2} \cdot \frac{1}{1000}$$

2nd train / 1st train		v	160	160	140	100	100	90
		a_b	1,0	1,0	0,8	0,4	0,4	0,3
t_{VE}	p_{VE}	a_a	Pz	Pz	Pz	Pz	Gz	Gz
4	0,3		9,2	9,2	/	/	/	/
4	0,3		9,2	9,2	/	/	/	/
3	0,6		10,0	10,0	11,1	/	/	/
3	0,6		10,0	10,0	11,1	15,5	18,8	/
30	0,5		7,3	7,3	8,1	11,1	14,7	/
30	0,6		7,3	7,3	8,1	11,1	14,7	17,1

Tab. 40: Equivalent buffer time of ML for limited supervision

B.2.5 Level 1 with service brake not available (total infill – no infill)

$\bar{t}_{P,UIC}$ = 224 s

2nd train / 1st train		v	160	160	140	100	100	90
		a_b	0,6	0,6	0,6	0,5	0,3	0,3
t_{VE}	p_{VE}	a_a	Pz	Pz	Pz	Pz	Gz	Gz
4	0,3		20,1	20,1	/	/	/	/
4	0,3		20,1	20,1	/	/	/	/
3	0,6		15,8	15,8	16,1	/	/	/
3	0,6		15,8	15,8	16,1	10,1	28,1	/
30	0,5		16,3	16,3	11,9	7,1	22,4	/
30	0,6		16,3	16,3	11,9	7,1	22,4	17,1

Tab. 41: Equivalent buffer time of ML for service brake not available

B.2.6 Level 1 with service optimized block sections (total infill – no infill)

$\bar{t}_{P,UIC}$ = 361 s

2nd train / 1st train		v	160	160	140	100	100	90
		a_b	0,6	0,6	0,6	0,5	0,3	0,3
t_{VE}	p_{VE}	a_a	Pz	Pz	Pz	Pz	Gz	Gz
4	0,3		27,1	27,1	/	/	/	/
4	0,3		27,1	27,1	/	/	/	/
3	0,6		28,8	28,8	21,6	/	/	/
3	0,6		28,8	28,8	21,6	10,1	55	/
30	0,5		22,5	22,5	16,3	7,1	47,8	/
30	0,6		22,5	22,5	16,3	7,1	47,8	36,1

Tab. 42: Equivalent buffer time of ML for optimized block sections

B.3 Regional line (RL)

$\bar{t}_{P,UIC}$= 680 s

2nd train / 1st train		v	80	80	80
		a_b	0,4	0,4	0,2
t_{VE}	p_{VE}	a_a	Pz	Pz	Pz
3	0,6		8,6	8,6	33,2
3	0,6		8,6	8,6	33,2
30	0,6		6,0	6,0	26,2

Tab. 43: Equivalent buffer time of RL

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