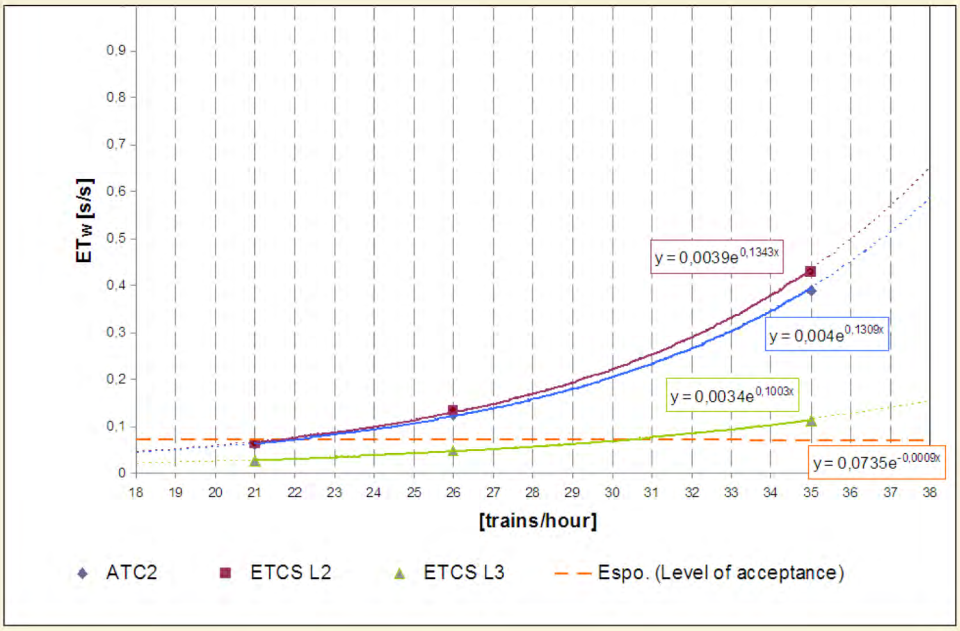
Evaluation of ETCS on railway capacity in congested areas

A case study within the network of Stockholm

MONICA MAGNARINI



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1. Introduction

1.1. Aims of the thesis

The thesis is aimed at investigating the railway operation with the most advanced European control and signalling system, by analysing a specific case study.

Starting from the description of the state of the art, the second and third level of ETCS/ERTMS and the Galileo satellite system are taken into exam as a basis for realising the semi-continuous tracking. The study is firstly aimed at evaluating which could be, at a theoretical level, the increase of capacity on the lines given to a continuous tracking of trains, applied to the kernel function of train spacing.

The thesis is intended to focus on a case study, the southern part of central station of Stockholm. In that location ten tracks are dedicated to the through traffic and trains leaving from Stockholm Central Station to the South have to pass on a bridge, over that the railway line is composed by a double track, connecting Stockholm Central Station to the South Station, where the four-track begins. This is a case of bottleneck and given of the high daily traffic passing there, it is a critical point (*Figure 1.1*).

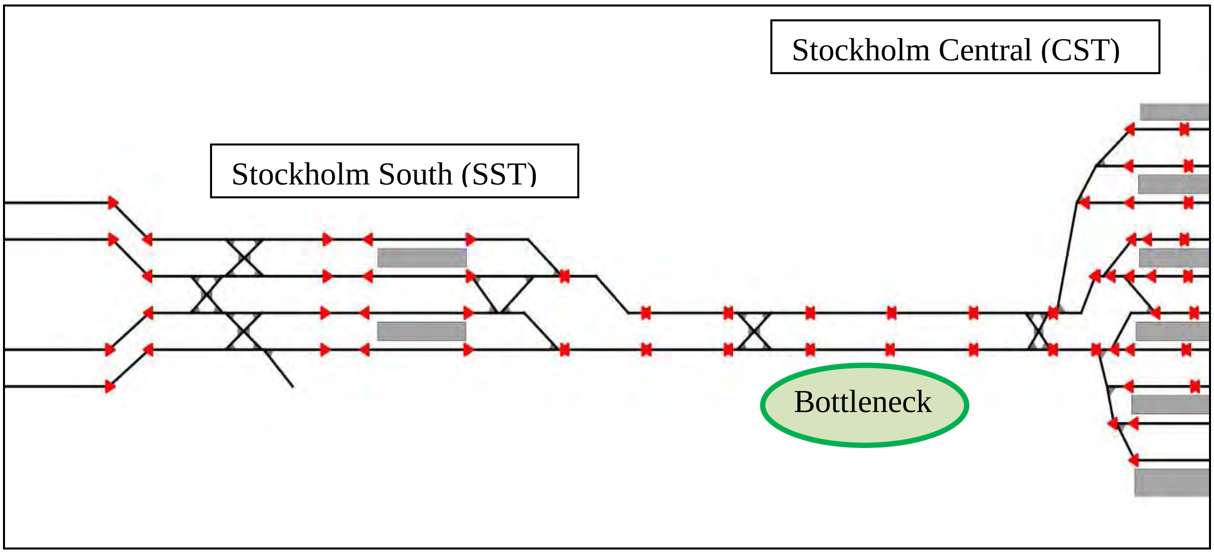


Figure 1.1 *Scheme of the line section involving the bottleneck*

Specifically, the area from Stockholm central station to Fleminsberg is going to be the area of interest for this thesis (*Figure 1.2*). The line length is about 16 km, including the intermediate stations: Stockholm Södra, Årstaberg, Älvsjö, Stuvsta and Huddinge.

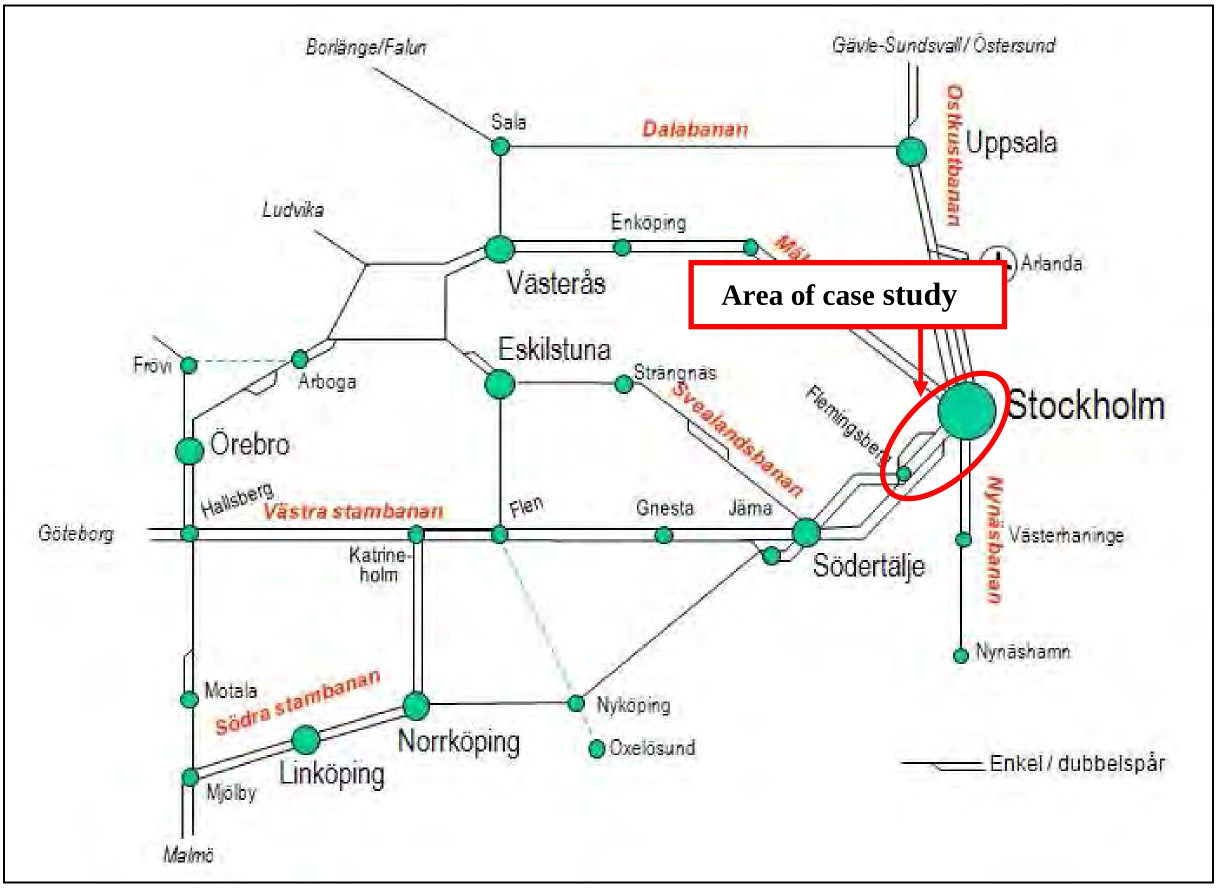


Figure 1.2 *Area of the case study [15]*

The aim of this work is therefore to evaluate the carrying capacity and the quality of railway operation within the above mentioned area in case of different signalling systems.

1.2. Background

Recent years have seen a considerable growth in the whole transport sector, mainly due to the increasing integration of the international economies. On this scenario, revitalizing the railways is one of the principal measures proposed in European transport policy. Considering that, the progressive growth of the rail transport demand leads to an increasing use of rail infrastructure, which often has a limited availability related to the topological configuration. Therefore, in order to increase the railway capacity, two general different ways could be followed: building new infrastructures or managing the existing capacity more effectively by, for example, using computer-based decision support systems. The second one has to be preferred, being a more cost-effective solution to absorb the extra traffic. Only if this is not enough investments will be required for new infrastructures.

The railway capacity is affected by several factors, due to the complex structure of rail systems and this is the reason why capacity is not static. It also means that giving its definition is not so easy, although it seems to be a self-explanatory term in common language. The physical and dynamic variability of train characteristics makes capacity dependent on the particular mix of trains and order in which they run on the line; furthermore, it varies with changes in infrastructure and operating conditions.

As regard the case study, it has to be underlined that in Stockholm over a fifth of Sweden's population lives. The capital is the centre of government and finance and it is also by far the country's busiest rail centre. A metropolitan area with a population of around 1.75 million, Stockholm is the most demanding for local and regional public transport. Located in the south east of Sweden, it is where the country's main long-distance passenger rail routes converge. Although tracks were doubled or quadrupled at various points around Stockholm in the last decades of the 20th century, Central Station's southern approaches (where is the bottleneck) remain the great limiting factor for service improvements.

The aforementioned scenario it has been the reason why Banverket, the Swedish Rail Administration (today it is called Trafikverket), has approved the construction of a rail tunnel through Stockholm city centre, with a planned opening date in 2017. Construction of Citybanan began in 2008. This new tunnel, known as Citybanan (‘the city line’, *Figure 1.3*), is intended for the exclusive use of the Pendeltåg system (commuter trains), and would separate commuter traffic onto separate tracks from long-distance trains while traveling through the city. This would ease the rail systems' congestion problems, and permit the Swedish Transport Administration to schedule more frequent service. It would also allow more frequent service for other trains, increasing the capacity for large parts of the Swedish rail network since many trains go to and from Stockholm.

Figure 1.3 *Future scenario with the urban tunnel Citybanan*

Train coupling

Looking at the features of the line of the case study presented later, the train coupling could be considered a good operational solution in order to save capacity. As an example the train coupling is a method used in Munich where the urban trains leave as a triple traction unit and at further stations it is split in separated unit that travel in three different directions; then on the way back to Munich the train is assembled the opposite way. The goal is capturing most of the people travelling within the city centre with a unique train and then separating the train where in the suburbs the demand is lower. In such a way where the line is suffering higher demand the infrastructure occupation is reduced, compared with the case if three different trains were leaving in separate scheduled times. In the German city this specific mode of operation is enabled by the automatic central buffer coupling that allows for a rapid coupling and separation of trains.

But in Stockholm the train coupling is prevented from being realised because of two main reasons:

1. At present during the peak hour the commuter trains are composed by two cars with a total length of 214 meters. If a third wagon is added, the train will be longer than most of the platforms dedicated to the commuter trains. Extending platforms is expensive mainly because of the change in position of switches and so on.
2. Nowadays commuter trains used in the network of Stockholm are not been built looking at the coupling mode. It means that such coupling operation could take quite long time and therefore it could be not a real advantage in term of saving capacity.

The train coupling can be realised in case of both suitable infrastructure and train characteristics. The adaptation of the latter can be expensive and therefore a right cost benefits analysis must be carried out in the case of Stockholm in order to evaluate if the relative save in capacity is enough to justify such expenses, mainly in the future scenario involving Citybanan.

1.3. Safety

Even if the safety aspect on railway system has not been the aim of the thesis, it is important to give preliminary remarks about this subject because it is obviously tightly related to the railway operation.

Safety is one of three main requirements, together with efficiency and availability, which are expected to be fulfilled by a railway system, in order to be competitive with the other means of transport. The term of safety refers to the functional safety threatened by technical failures and unintentional human mistakes which can cause dangerous consequences. If errors or failures occur within a railway network, two kinds of effect could be expected: in the best case trains will be delayed while, in the worst case, derailments or collisions can happen. As regards the second possibility, when collisions occur in railway system the related damage is always high, mainly because of the considerable amount of inertial masses (trains) which are crashing one against the other. Considering that and taking into account the definition of risk (safety indicator parameter) mentioned in [21]:

$$Risk = "Damage" \times "Hazard\_risk"$$

it is clear that in order to decrease the quantity of risk, lowering the hazard rate appears the only one possible thing to do.

The signalling system, especially its reliability, plays a significant role in this issue, being responsible of traffic regulation. Beside aspects directly related to the behaviour of the entire system in case an hazardous situation happens, and therefore looking at the reaction of the system when some event out of normal already occurs, it can be interesting to point out possible benefits reducing the perception-reaction time of the driver providing him with advanced information. The input about the advanced information in order to improve the perception-reaction time of the driver come from the knowledge of *Moretto system* [14], so-called by the name of its inventor the Italian engineer Gianantonio Moretto, and that looks to be applied within secondary railway lines with low traffic density. This system is suggested as a tool for a conscious driving, based on radar detection of events occurring within the area of interest of the train and their communication to the driver through a simple screen fitted up in the driver cabin. In this way the driver readiness in reacting is improved. Therefore Moretto wants to be an auxiliary tool and do not be a replacement of command and control system of train movements.

It looks clear that advanced information issue makes sense on railway lines with low traffic density, where a signalling system like both ETCS Level 2 and Level 2 are not implemented.

In fact, coming from interoperability and safety requirements, the ETCS signalling system is aimed at improving the railway lines capacity and, all the same, to achieve acceptable safety standard. Taking into consideration the Level 2 and Level 3 of ETCS, they use the radio-based block for a more efficient spreading of informations in order to set out two parallel goals:

- Optimization of line consumption, running trains as close as possible (get minimum the headway between two following trains).
- A more efficient readiness of system reaction in case of no extension of movement authority for a train (for example because one other train is still occupying the next block section).

Where a signalling system as ETCS is not implemented, anyway the safety aspect needs to be carefully considered, because lowering the hazard rate is always important, in both main and secondary railway lines. It looks really hard making use of a simulator tool to quantify benefits safety related, coming from signalling systems like ETCS or systems aimed at affecting and improving the perception-reaction time of the driver.

Finally all previous comments would be a starting point of discussion for further qualitative analysis about safety aspects, parallel to capacity aspects, related to the signalling system.

1.4. Methodology

In order to reach the aims mentioned in section 1.1, the project will be carried out following next chronological steps:

1. *Preliminary study*

In this phase an overview on current knowledge will be provided about railway transport, specifically on line capacity, signalling systems and their relationships.

Moreover the technical and operational analysis of the line involved in the case study is presented. Four kinds of trains, with their different characteristics and performances, will realize train patterns: long distance trains, regional trains, commuter trains and freight trains.

Actually, within the southern area of Stockholm central station, the two directions are independent, therefore only the south direction will be discussed. Moreover, the two directions have got different daily traffic distribution. In fact the inbound traffic (towards Stockholm) presents a peak hour in the morning, while the outbound traffic (from Stockholm) has got a peak hour in the afternoon instead. A period of 2 hours will be considered for providing evaluations.

2. *Theoretical application*

After the analysis of infrastructure of the Stockholm case study, under the point of view of technical and operational aspects, a theoretical application will be accomplished in order to calculate the optimal capacity of the line of the case study in case of different signalling systems (ATC2, ETCS/ERTMS Level 2 and the future ETCS/ERTMS Level 3), following the model presented in [26]. Findings coming out from the theoretical application, will represent expected results for the next simulation phase.

3. *Simulation with Railsys*

In this phase, with a simulation approach by making use of RailSys software, evaluations about capacity and quality of railway operation will be provided, in above mentioned area, in case of different signalling systems and different timetables.

As regard of signalling systems, these will be firstly the actual ATC2 and moreover the ETCS/ERTMS level 2 and the future level 3.

On the other hand, as regards the timetable, at first that of 2008 is going to be evaluated, which, together with the ATC2 signalling system and initial perturbation level (from real delay data), will define the input for the first scenario. Then, two more timetables will be built, increasing the number of trains per hour but all the same keeping the traffic proportion in order to make significant evaluation and to calculate the upper limit of capacity in case of different signalling systems fitted up on the line.

Choosing different kinds of combination between signalling system, timetable and perturbation level, different scenarios are going to be defined. For each created scenario, simulations will provide delay values that will be the measure of capacity and quality of railway operation over the line. Therefore, it will be possible to provide with performance evaluations and comparisons between different scenarios.

4. *Results and conclusions*

At the end, comparisons between analytical calculation and simulation will be done. Moreover some general results on the use of the semi-continuous signalling system referred to the aforementioned case study will be presented.

The methodology followed is shown in *Figure 1.4.*

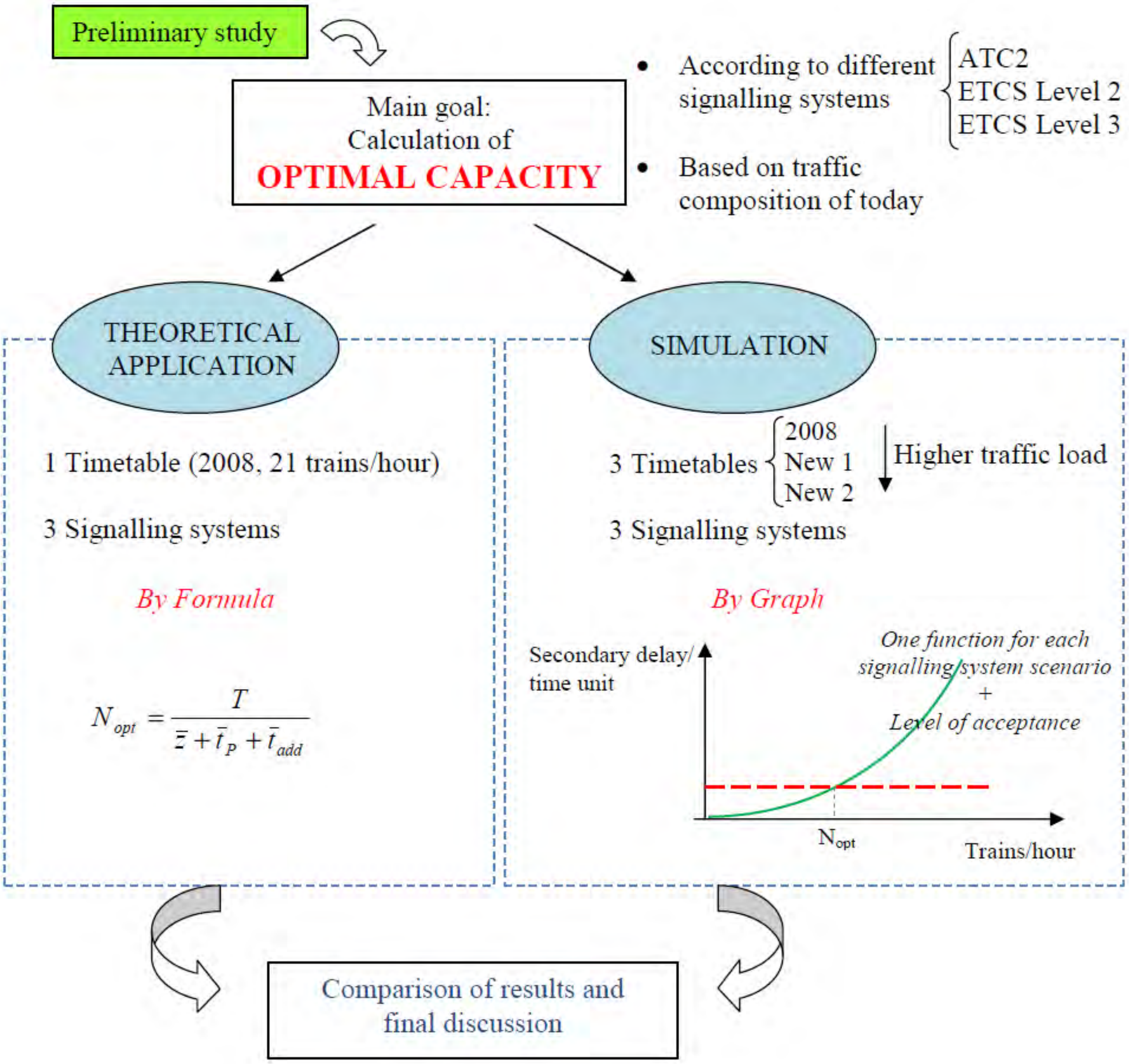


Figure 1.4 *General methodology*

2. Literature review

The capacity issue is a wide and complex theme. Several authors faced this topic, mainly aimed at describing how and how much capacity is affected by inherent parameters and trying to find out its definition.

2.1 Capacity

In [1] the authors classify three separated methodologies, but in some way complementary, for carrying out capacity assessment, distinguishing them in analytical, optimization and simulation methods.

The article [10] goes into depth giving a wide overview of different techniques developed along years for capacity evaluation, making comparisons among them, underlying advantages and drawback of their applications.

Furthermore, both sources [1] and [10] introduced to the complexity of a railway system. They explain how capacity is close dependent by several factors that are often interconnected defining such complexity. Specifically those elements are classified into infrastructure, traffic and operational factors. Moreover in [1], authors studied in several Spanish railway line how capacity is affected by train speed, commercial stops, train heterogeneity, block length and timetable robustness.

Definition

Since the railway capacity is a dynamic concept influenced by several factors, in UIC Code 406 [9] is written:

"Capacity as such does not exist. Railway infrastructure capacity depends on the way it is utilised."

Furthermore, in that leaflet the interconnected influence on capacity consumption between four main elements (number of trains, average speed, stability and heterogeneity) is shown in the chart called "*the balance of the capacity*".

Starting from this chart, Landex A. [11] suggests to consider a three dimensional diagram, called "*the capacity pyramid*" in order to involve processes (procedures at departures, staff schedules, many passengers at the stations, etc.) and external factors (weather conditions, breakdowns and accidents) at the definition of the capacity consumption.

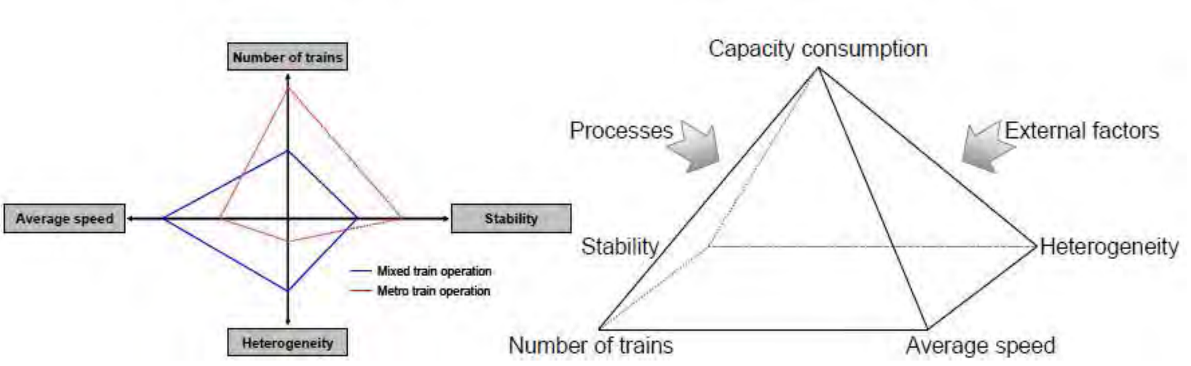


Figure 2.1 *The balance of capacity and capacity pyramid [11]*

In both [1] and [10] the authors marked and defined different kinds of capacity used in the railway environment: theoretical capacity, practical capacity, used capacity and available capacity.

Moreover the UIC Code 406 [9] defines a method for the calculation of capacity consumption, called the *Compression Method*. This method is based on the blocking time model. In order to apply this method the main input data are the pre-constructed timetable (a real operational one or a case study) and the infrastructure layout. The infrastructure consumption is calculated by the infrastructure occupation provided compressing the train paths of the timetable within a pre-defined time window, to which is added buffer times for timetable stabilisation and maintenance requirements.

Lindner T. and Pachl J. [13] went into depth how to apply the compression method suggested in UIC Code 406, giving recommendations about details left opened or not mentioned in that leaflet in exam. Mainly they give suggestions how to enrich the original timetable in case of train path availability and also how to apply the same compression method in case of not pre-constructed timetable, it means using a virtual traffic diagram.

Signalling system and capacity

One of the parameters affecting the railway capacity is the signalling system.

In the paper "Influence of ETCS on line capacity. Generic study" [26], the authors investigated the effect on line capacity of different configurations of ETCS for three kinds of track layouts: high speed line, conventional main line and regional line. The capacity analysis are made following two approaches: UIC Code 406 and STRELE-formula. The results coming from the first approach are in general higher than that of the second one, because of the different calculation of capacity consumption: UIC Code 406 uses the recommended values of infrastructure occupation while the STRELE-formula is focused on the limitation of the acceptable sum of unscheduled waiting times. The same authors underline that only few parameters have affected capacity in this case study (signalling system, speed profiles, operational patterns). Therefore it is not possible to generalise the mentioned capacity figures for all railway lines, but anyway they can give a first idea of the impact of ETCS on capacity.

The general goal of signalling systems is optimizing the train spacing in order to enable running as much as number of trains, fulfilling service quality and safety requirements. Main distinction among train spacing is concerning fixed or moving block.

Based on formulas defining train separation in both kinds of system, in [6] authors discuss capacity performances; the capacity for a system working with moving block is higher or at least equal to that of fixed block. Moreover coming from the evaluation of speed-flow function, they recognized 50-80 km/h as the optimal speed to maximize the capacity in case of moving block regulation. Afterwards, as regards the fixed block they provided functions for underlying how both length of block section and number of approach aspect of signals could affect capacity.

In [11] authors analysed the headway definition in case of discrete ATC (typical for Danish railways and similar to Swedish ATC), the continuous ATC (traceable back to ETCS Level 2) and moving block, also deriving capacity calculation in such cases which are respectively providing from the lowest to the highest capacity.

2.2 Simulation

The common classification of “delays” distinguishes between primary and secondary, in some sources also called exogenous and reactionary delays. In [16], where Norwegian studies are presented in order to analyse influencing factors on train punctuality, the authors use primary delays to refer delays caused by direct influence on the train, while secondary delays are referring to delays caused by other trains. On the other hand, in [28] delays are classified in basis of the locations and sources of generation as initial, original and knock-on delays. Both initial and original are included in the other definition as primary delays, while knock-on delays correspond to secondary delays.

In [24] the operation on the Western main in Sweden connecting Stockholm and Göteborg is studied with the simulation tool Railsys. Especially results about the influence of the scheduled time supplements and buffer times on punctuality are discussed by means of delay analysis. In that paper primary delays are used as input and furthermore performance evaluations are based on knock-on delays created by simulation.

In [8] the study commissioned by Trafikverket (the Swedish Transport Administration) and carried out by Vectura (a Swedish Consulting Company) about the impact of ERTMS on line capacity is presented. This research has been also focused on defining likely values of constant deceleration for different trains to use in Railsys software in order to model both ATC2 (the actual signalling system in Stockholm area) and ETCS.

3. Description of the case study

The thesis is focused on analysing how the new ERTMS/ETCS signalling system can affect the railway capacity in a specific environment of a congested area. The area of interest is represented by the Western main line leaving from the Stockholm until Flemingsberg station (about 16 kilometres to the South). Stockholm is actually the hub of Swedish rail transport, where most long distance passenger rail routes converge. But the Southern approach is a critical issue: there in fact the line is passing over a bridge on the West side of the Centralbron (the Central Bridge for car transit) and between Stockholm Central Station, where ten tracks are dedicated to the through traffic, and Stockholm South Station only a double track is available. As mentioned in paragraph 1.2 in seven years a new railway tunnel (Citybanan) will partially modify the configuration of the network, when the number of tracks available in the bottleneck will be doubled and therefore it will be relieved by the commuter trains traffic. Nevertheless the thesis is aimed at evaluating the influence of ETCS in a congested area and the specific future scenario involving the new urban tunnel will not be considered.

Actually, along the line from Stockholm Central Station to Flemingsberg, the two directions are almost independent, therefore only one direction will be the subject of the case study. There is an open discussion with different opinions on whether one direction more than the other must be preserved by problems due to the bottleneck. Some people think it is more important to reduce the amount of delays affect trains leaving from Stockholm because such lateness will have repercussions over most lines around Stockholm and beyond. On the other hand, some other people think it is more important that mainly for long distance trains approaching the Swedish capital they must not be affected by high delay, waiting before entering the last part of the line close to their destination. With this in mind, only the southbound traffic will be investigated.

In order to carry out more meaningful evaluations, the study will refer to a time window of 2 hours involving the rush period; since the two directions record the peak in demand in different time during the day (in the morning for the inbound traffic and in the afternoon for the outbound traffic) the reference time will be between 16 and 18.

3.1 Technical description

The area of the case study (*Figure 3.1*) involves the line around 16 km long, from Stockholm Central Station (CST) and as far as Flemingsberg (FLB).

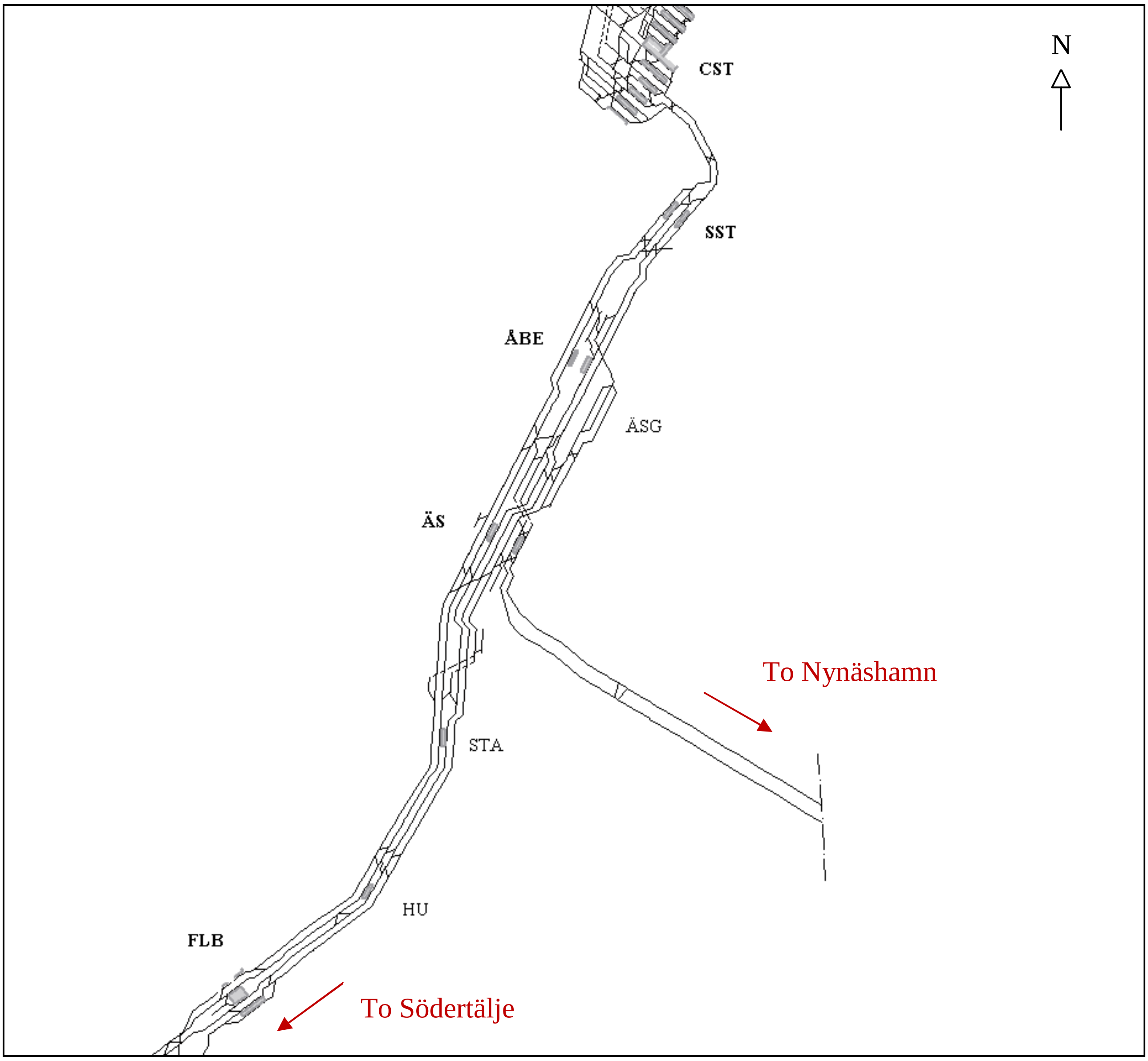


Figure 3.1 *Network of the case study*

The case study will focus on five stations as summarized in *Table 3.1* showing intermediate and progressive distances, the latter referred to the first station (Stockholm Central).

Name	ID	Distance to next station [km]	Progressive distance [km]
Stockholm Central	CST	2,339	0
Stockholm South	SST	2,514	2,339
Årstaberg	ÅBE	2,642	4,853
Älvsjö	ÄS	7,925	7,495
Flemingsberg	FLB	-	15,420

Table 3.1 *Stations involved in the case study*

Between Älvsjö and Flemingsberg two intermediate stations are located: Stuvsta (STA) and Huddinge (HU), but they will not be involved in specific evaluations.

Along the line of the case study both the maximum speed and the number of tracks vary, as summarized in *Table 3.2*.

Line section	Layout infrastructure	V_{max}
CST → SST	Double track	80 km/h
SST → ÄS	Four tracks	120 km/h
ÄS → FLB	Four tracks	130 km/h (on the inner track) 160 km/h (on the outer track)

Table 3.2 *Characteristics of line sections*

From *Table 3.2* it can be observed that the line section between Stockholm Central and Stockholm South is the weak point because there only a double track is available. Being aware of that, north of Stockholm Central Station three platforms are allocated for train maintenance and some other tracks are used for example by long distance trains in order to stand while the food for the restaurant service is loaded. It means that North of the bottleneck some tracks can be used to store trains in case of disruption of service, when for example the bottleneck must operate as a single track line. But this kind of solution can be applied in case of partial breakdown of the operation. If the problem cannot be solved in short time the traffic must be reduced for example canceling commuter trains across the bottleneck and people must be directed to the metro system or buses.

3.2 Operational description

3.2.1 Rolling stocks

Actually five kinds of rolling stock are scheduled in the timetable during the rush period in the afternoon, looking at the southbound traffic, involving:

- ✓ Long distance trains: X2000, Rc6.
- ✓ Regional trains: X40.
- ✓ Commuter trains: X60.
- ✓ Freight trains: Rc4.

Train characteristics are presented in Appendix A.

According to the actual timetable provided by Trafikverket, details about track allocation, train stops and priority are given in next subsections.

Track allocation

In Stockholm Central Station five tracks are dedicated to the southbound traffic, from number 10 to 14. The three outer tracks (number 10,11 and 12) are allocated to long distance, regional and freight trains, while the two inner tracks (number 13 and 14) are used by commuter trains. From Stockholm Central Station to Stockholm South Station all trains share the left side track, since a double track only is available for the entire traffic. Where there are four tracks instead, the inner track is dedicated to the commuter trains, while on the outer track long distance, regional and freight trains are allocated. Such configuration is observed within both stations Stockholm South and Årstaberg.

In Älvsjö seven tracks are located; two of the additional three tracks compared with Årstaberg are due to the split of commuter trains going to Nynäshamn, while the third one is added in order to enable freight trains to enter the line after the stop in Älvsjö Godsbangård (Äsg).

Train stops

All trains stop in Stockholm Central Station.

Commuter trains are the only one stopping at all stations along the line of the case study, with a scheduled dwell time equal to 40 seconds. During the investigated two hours, one third of the commuter trains are going to Nynäshamn and therefore they exit the line of the case study just after the stop in Älvsjö; while the remaining two thirds are going to Södertälje, thus running over the entire line.

Both Rc6 and X40 trains only stop in Flemingsberg with 60 seconds of scheduled dwell time. The X2000 trains do not stop at any station along the line involved in the case study.

Finally, regarding the freight train, the one scheduled in the peak period is leaving from Stockholm Central Station direct to the freight yard located in Älvsjö Godsbangård (Äsg) between Årstaberg and Älvsjö as shown in Figure 3.1. That train is leaving the line just before Årstaberg, it reaches Äsg where it is standing for the goods loading and later on it is leaving after more than one hour (therefore out of the reference time) entering the line just before Älvsjö.

Priority

The aforementioned train categories have different priority during the operation time. The X2000 has the highest priority, while the freight train has the lowest one; finally the Rc6, X40 and X60 have all the same level of priority between the one of X2000 and that of the Rc4.

3.2.2 The current timetable

As reference timetable, the one from 2008 will be considered, since no big differences have been applied later on. Going on in the thesis Timetable 2008 will be referred as the operation of today.

The timetable has got the following main features:

1. *Traffic proportion.*

   The five categories of trains involved in the operation have specific relative proportions over the total number of trains running along the investigated two hours (from 16 to 18) and they are summarized in *Table 3.3*.

	Timetable 2008	
	Number (over 2 hours)	**Proportion [%]**
X60	24	57,1
X2000	8	19,0
Rc6	5	11,9
X40	4	9,5
Rc4	1	2,4
TOTAL	42	100

Table 3.3 *Traffic composition in actual timetable*

2. *Train pattern*.

   Actually the timetable of today is featured by a constant interval between commuter trains (5 minutes) and between them one train of different category is running; not always two commuter trains are spaced out by one other train, providing extra buffer times in order to favour the timetable stability. During the time window from 16 up to 18, the succession of commuter trains is always the same: two trains going to Södertälje (therefore running the entire line of the case study until Flemingsberg) and one train going to Nynäshamn (exiting the line of the case study in Älvsjö). The long distance trains Rc6 are leaving from Stockholm Central Station each 20 minutes; the X2000 and X40 trains do not have a constant interval over time.

3. *Scheduled running time allowances*.

   In the actual timetable running time allowances are scheduled only for commuter train travels between Årstaberg and Flemingsberg as shown in *Figure 3.2*.

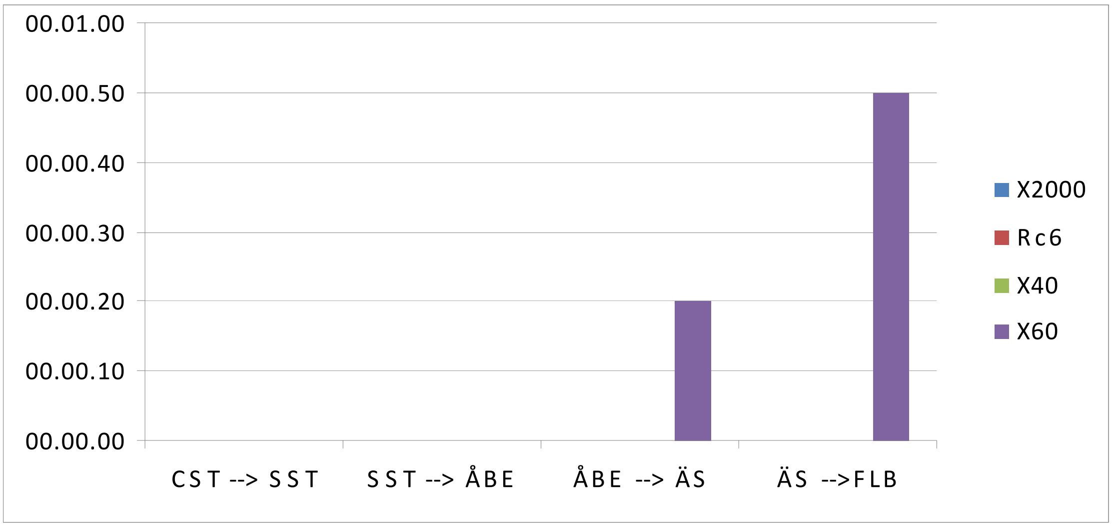


Figure 3.2 *Scheduled running time allowances*

Those margins are implemented in the timetable in order to aid trains to be on time; they are usually applied just before the train destination or also before important stations where for example different lines are converging and therefore the delay of a train there could cause significant problems affecting other trains entering and leaving the network.

The case study is involving a restricted area just out Stockholm Central Station: therefore the scheduled running time of long distance and regional trains are not raised by that kind of margins.

3.2.3 The current signaling system ATC2

On Swedish railway network two kinds of automatic train control are used: the ATC2 (on most main lines) and the ATC1 (on secondary lines).

The line of the case study is entirely equipped with the ATC2. The main feature of the latter is that signals are able to give information on how many meters behind the following signal the train must stop; while, in case of ATC1, signals are only giving information on the aspect of the next signal. That means ATC1 provides with speed staircase supervision, while with ATC2 the speed supervision curve based on the characteristics of individual train is possible.

Moreover, in ATC signaling system, within each block section one or more balise groups are fitted up in order to accomplish the unilateral spot transmission, from trackside to the train passing on there.

Specific arrangements along the bottleneck

Once again being a critical line section, along the bottleneck some special arrangement to the ATC2 signaling system has been applied since June 2009 in order to improve capacity performance. Between CST and SST the block sections’ length is equal to 250 meters, while in the rest of the line they are about 1000 meters. On the bottleneck during the last year some extra balises have been installed; actually double balise groups are located within each block section, at 50/75 meters and 125 meters ahead of the signals.

One block section is always used as overlap for the block section in rear. In normal conditions at least one block section must be free between two following trains. In case of large amount of delay trains packing is allowed. Beyond the standard release speed equal to 40 km/h, the signaling system provides a lower one 10 km/h. With a speed equal to 10 km/h trains are permitted to have a sight running and therefore they can bring themselves nearer to the train ahead. Such arrangement also allows a faster solving of situations involving train queues. As explained in the section *3.1* in case of significant breakdown of the operation trains are stopped before enter the bottleneck. Therefore the lower release speed is a help to solve queues involving few trains standing but it is not the solution in case of accidents.

3.3 Signaling system scenarios

Beyond the current ATC2, other two kinds of signaling system will be investigated (ERTMS/ETCS Level 2 and ERTMS/ETCS Level 3) in order to evaluate if such new European standardized systems could improve the capacity over the line of the case study.

3.3.1 The ERTMS system

The ERTMS (European Rail Traffic Management System) is a new standard involving safety, signaling and communication, aimed at reaching interoperability requirements. At present European countries have their own safety and signaling system and such scenario cause inefficiency in international rail traffic; the ERTMS system is focused on simplifying, improving and developing international railway transport services in order to pull down such barriers and increase the competitiveness of railway compared with other means of transport. ERTMS is firstly looking at the implementation on high speed lines of European corridors, however the installation on all railways will be possible.

The ERTMS project is defined by two subsections: ETCS (European Train Control System) and GSM-R (the radio communication system for railways).

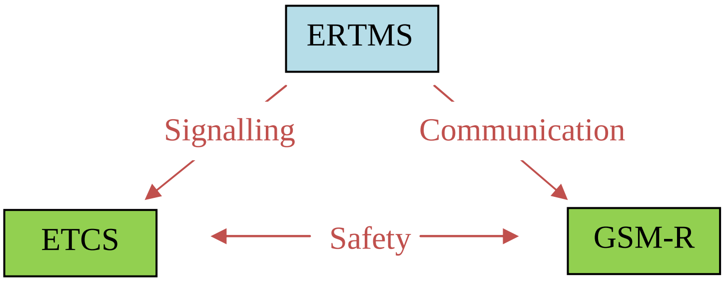


***Figure 3.3** The ERTMS components*

As regards the signaling part, the ETCS includes three implementation levels:

- → Level 1: semi continuous track – train communications.
- → Level 2: continuous train – radio block centre communications.
- → Level 3 (still at a research phase): moving block theory.

Even if only the last two levels will be investigated over the line of the case study, all three levels are now briefly described.

ERTMS/ETCS Level 1

The ETCS Level 1 is based on a fixed block system.

The Level 1 accomplishes a spot data transmission between the trackside and the driver cab, making use of beacons (Eurobalises) located on the sleepers adjacent to the lineside signals at required intervals. Data transmitted concern signal aspect and route data, while detection devices are still needed in order to locate the train.

The trainborne equipment receives the Movement Authority by balises and such subsystem automatically calculates the maximum speed and the next braking point, taking into account the train braking characteristics and the track description data. The speed of train is continuously supervised by the ETCS on-board equipment.

In order to optimize the train running, the data transmission can be made as semi-continuous fitting up extra balises or a special cable laid along the track or making use of additional radio communications, providing respectively so-called balises, loop and radio In-fill.

ERTMS/ETCS Level 2

Also the ETCS Level 2 is based on fixed block system for the train separation issue, but here lineside signals are not necessary. The Level 2 is a radio-based block where block sections are virtual.

Both Movement Authority and information equivalent to the signal aspects are transmitted by the Radio Block Centre (RBC) to the train via GSM-R. Also in this case, the speed of train is continuously supervised by the ETCS on-board equipment. Each RBC is providing the supervision over a certain area, therefore along the line several RBC can be as reference; antennas installed along the line and linked to the Radio Block Centre are used for the data transmission between RBC and trains. The train integrity supervision still remains in place at the trackside, in fact the tail of the train must be detected with track circuits or axle counters.

In Level 2 beacons are only used to transmit static messages, such as location, mainly in order to correct distance measurement errors made by the trainborne subsystem; in this case a bi-directional communication among trackside and the train occurs.

Nowadays, also for ETCS Level 2 the possibility to support the train location with a satellite positioning system is discussed. The train integrity is still provided by the track side, but mainly looking at possible system malfunctioning, a satellite system like EGNOS (European geostationary navigation overlay system) or the future Galileo can help the train localization.

ERTMS/ETCS Level 3

At present the ETCS Level 3 is partially defined, being still at a research phase, and it is not yet been implemented on any lines.

In this case the train position is detected on-board, making use of a satellite positioning system, and balises are only used for calibrating the odometer.

The real innovation for such implementation level is the adoption of the moving block; this means that train headways come close to the principle operation with absolute braking distance spacing, where the tail of the train ahead is the protected point.

In Level 3 the train integrity must be guaranteed; accurate and continuous position data are supplied to the control centre directly by the trainborne subsystem, rather than by trackside detection devices. As regards the integrity issue, using satellite positioning systems is also suggested in ETCS Level 3, in particular it refers to the European Galileo project; in such a way higher accuracy in train location and therefore train separation could be provided. However, this kind of support by satellite positioning system cannot be the only one operating, but it could be an efficient complementary tool to the train-borne equipment part dedicated to that issue. In fact, in some particular environments the signal by satellites could not be guaranteed, for instance inside tunnels or canyon zones. Moreover, the chance to combine together the use of both Galileo and GPS systems is also discussed, because with the co-operation of such systems an even higher level of accuracy could be reached.

4. Theoretical application

Methods to assess railway capacity could be classified in three groups, as classified in both [1] and [10]:

- Analytical methods.
- Simulation methods.
- Optimization methods.

Analytical methods make use of mathematical expressions and formulas for modeling the infrastructure in a simple way and in order to provide results of first approximation. Simulation methods build up models representing real-world systems including perturbation in order to validate the timetable data. Finally, optimization methods are based on obtaining optimal saturated timetables using mathematical programming techniques instead; the main method involved in that category is saturation, where line capacity is obtained by scheduling a maximum number of additional train services in a timetable.

In this section, a theoretical application is proposed in order to calculate the optimal capacity of the case study line according to different signaling systems. The optimal capacity, even called practical capacity in [1], represents the practical limit of representative traffic volume (featured by the actual train mix, priorities and so on) that can be moved on a line at a reasonable level of reliability. On the other hand it is defined as theoretical capacity the number of trains that, during a specific time interval, could be run over a route permanently and ideally at minimum headway [1].

4.1. Calculation methodology

The next application will follow the approach presented in [26], involving a model developed for all three levels of ETCS based on the blocking time method and in adaptation of UIC Code 406 [9] which describes only the assessment for lines with conventional signaling system.

In order to define the optimal capacity two main elements will need to be calculated: the average minimum headway and the average buffer time. The former is provided with the application of the blocking time method. The second is suggested to be calculated with following two different approaches: one is based on the so-called STRELE-formula which is taking into account a quality measure of operation defined by unscheduled waiting times and considering as input real data coming from the specific case study. On the other hand the UIC Code considers a general recommended value of infrastructure occupation without taking into account of specific delay data.

As regard of timetable, from where the relative frequencies of trains combinations will be read, the reference time will be 2 hours long between 16 and 18. It has been investigated the timetable of 18th September 2008 because it is a weekday, out of summer period, in order to prevent traffic restrictions due to holidays. The choice of a time in the afternoon is due to the fact the outbound traffic (from Stockholm Central toward the South) is supposed to record the peak hour in that time interval of the day.

According to [17] that in order to assess capacity for a line, the capacity of every single line section shall be calculated and the highest value of capacity consumption on a line section shall determine the capacity consumption along the whole line, looking at the line of case study, the line section involving the bottleneck is considered as the critical point. Therefore the calculation will be restricted along the line section between the stations of Stockholm Central and Stockholm South.

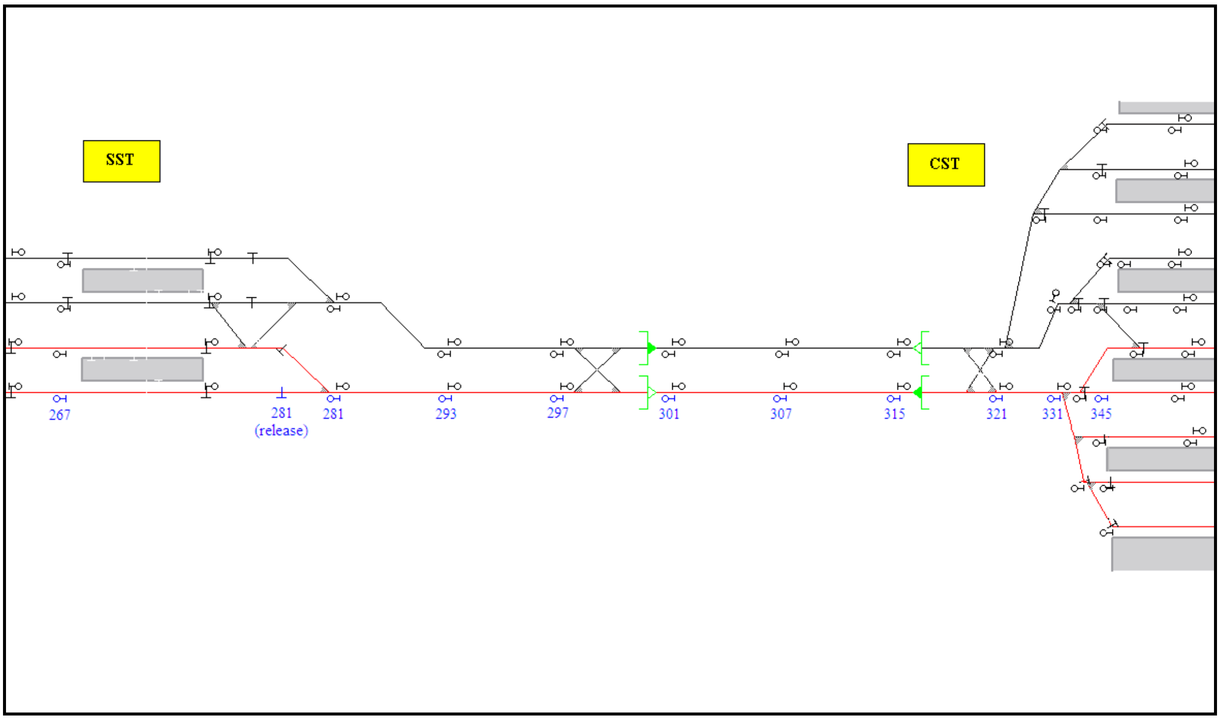


Figure 4.1 *Infrastructure layout along the bottleneck*

4.2 Limitations

The model that will be followed has been developed for a generic study investigating the capacity issue on railway line. Already in that model some hypotheses have been applied and those which are used as well in the next theoretical application on the case study are listed below:

- A level line profile is supposed, it means, concerning the calculation of running time, the component of resistance force due to the gradient is neglected.
- To calculate the running time a basic time, coming directly from the characteristics of train movement without time supplements, has been considered. Usually, as suggested in [9], the basis time is raised by a time supplement which is assigned depending on type of route (route for passenger or freight trains) and which is used to compensate for smaller-scale irregularities in the course of train travel.
- As regards the ETCS/ERTMS Level 3, it has been modelled as a fixed block system with block section length equal to 50 m, as a good approximation of the blocking time band.

Because of specific characteristics of the area of case study, in order to apply the theoretical model presented in [26], it is deemed necessary to define some further hypotheses which are evidently going to affect the goodness of results and that have to be rightly considered in last assessment. Those hypotheses are summarized in following points:

- The issue about the capacity of the station Stockholm Central has been neglected. It means all trains waiting for their leaving toward the station Stockholm South are standing in one of supposed infinite tracks, without get any disturbance each other.
- For each train type a constant value of deceleration is considered, as explained in next section; in the reference model [26] they calculate that parameter according to the brake percentage conversion method instead.
- In [26] the approaching time is calculated referring to the maximum speed of trains (because it is involving a case on railway lines); but in this case study of Stockholm, where on the bottleneck all trains have equal maximum speed of 80 km/h, the most discriminating aspect could be the difference among acceleration performances of different train types recorded in one of the first block sections after leaving Stockholm Central. Therefore the location of the indication point has been calculated block

section by block section in order to also take into account where train speed is not constant.

- In the station Stockholm South, where two tracks are dedicated to each direction, all commuter trains travel through the inner track, while all long distance, regional and freight trains travel through the outer track. This condition has been considered because how the two tracks in Stockholm South are dedicated to different trains that are stopping or not there, it could also be an important factor to define the minimum headway time.

4.2. Calculation

In [26] the formula for calculating the optimal number of trains is provided:

$$N_{opt} = \frac{T}{\bar{z} + \bar{t}_P + \bar{t}_{add}}$$

with: T the total elapsed time of the considered period.

$\bar{z}$ the average minimum headway (it is the minimum space in time allowed between two following trains)

$\bar{t}_P$ the average buffer time (it is a supplement time scheduled between two trains in order to reduce the delay propagation)

$\bar{t}_{add}$ the equivalent buffer time (it is an extra buffer time scheduled in case of spot transmission, in order to take into account the lack of continuous information between track and train within the block sections).

Regarding the average minimum headway, its calculation will be based on the blocking time model.

On the other hand two different ways on which to base the calculation of the average buffer time are suggested [26]: STRELE-formula and UIC Code 406. The former will be based on the pursuing an acceptable level of operation reliability taking into account delay data recordings along the specific line of the case study, while the second will not take into account any specific measure of service quality being based on the recommended value of infrastructure occupation.

The methodology of the optimal capacity calculation carried out with the theoretical application is summarized in *Figure 4.2*.

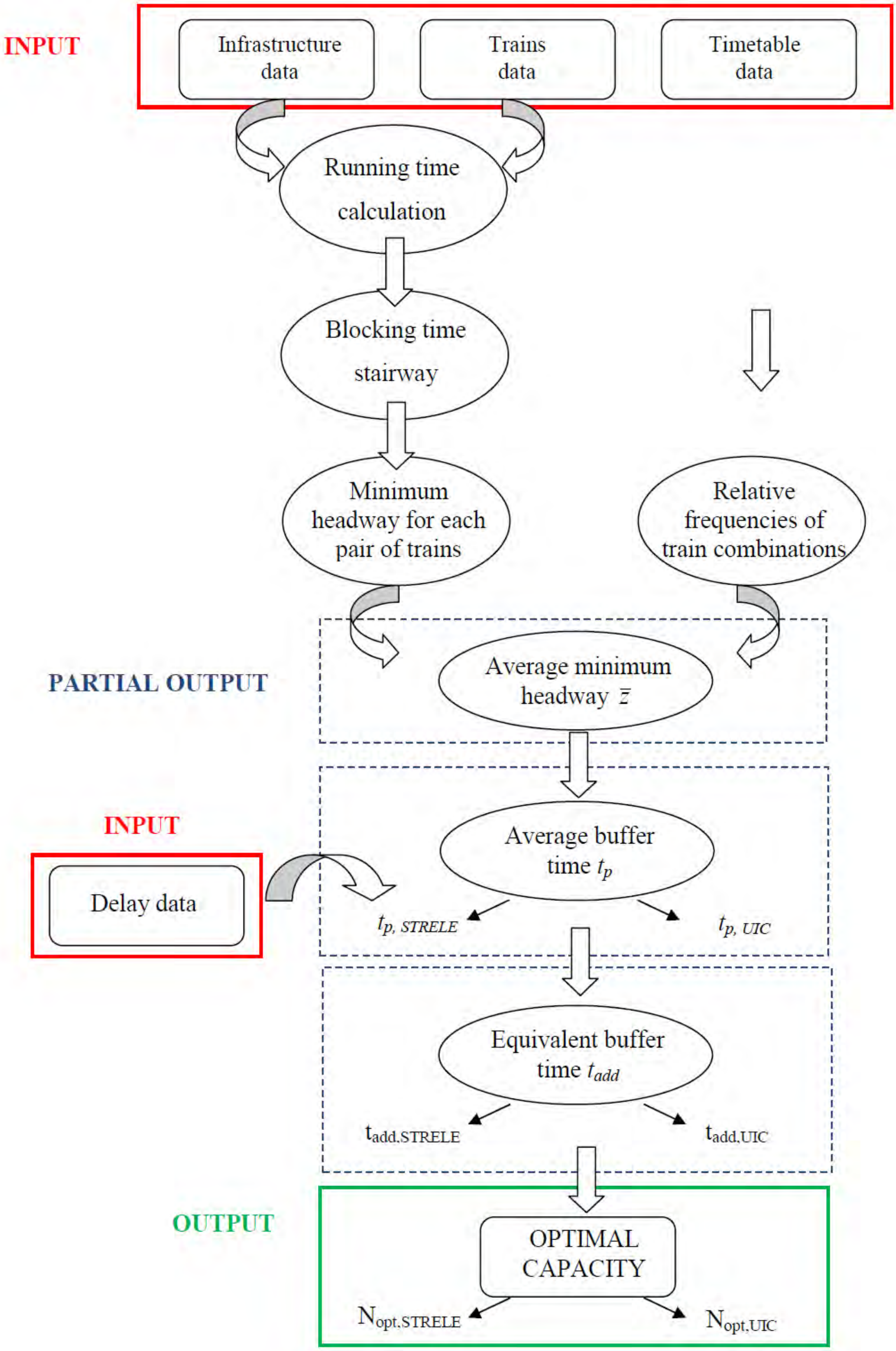


Figure 4.2 *Methodology of optimal capacity calculation*

4.3.1 Calculation of the running time

In order to define the running time, for each kind of train the acceleration curve, the braking curve and the phase at constant speed need to be calculated. It's important to remember that on the line section between the station of Stockholm Central and Stockholm South the maximum speed is 80 km/h. The procedure of the calculation of the running phases is explained below.

Acceleration curve

To calculate the acceleration curve a delta-V method has been used:

- Definition of ΔV equal to 1 km/h.
- Creation of V-steps: division of the speed from 0 to the top speed each kilometre per hour (ΔV).
- Calculation of traction force F_T at each V-step by Railsys data, according to the diagrams of traction force in function of speed available for each kind of rolling stocks within the Railsys Timetable and Simulation Manager module and presented in Appendix A.
- Calculation of resistance force F_R, trough the trinomial formula:

  $$F_R[kN] = F_{R,b} + F_{R,\omega} + F_{R,a}$$

  The three components represent, in order:

  1. Rolling resistance resulting from friction between axle journal and bearing.
  2. Wheel-to-rail rolling resistance.
  3. Air resistance.

  It's possible to write the same formula underlying the relation between resistance force and speed:

  $$F_R[kN] = R_0 + R_1 \cdot V + R_2 \cdot V^2$$

  Still making use of Railsys Timetable and Simulation Manager module, it is possible to obtain values of constant terms R_0, R_1, R_2 for each kind of rolling stock; therefore with this formula it is easy to calculate the resistance force for each V-step.
- Calculation of acceleration

  $$a\left[\frac{m}{s^2}\right] = \frac{F_T - F_R}{m_d}$$

where m_d is the dynamic mass of the train. Once again, the coefficient used to transform the nominal mass to dynamic mass is known by Railsys module.

- Calculation of time interval Δt to increase of one speed unit:

$$\Delta t[s] = \frac{\Delta v}{\frac{a_1 + a_2}{2}}$$

- Calculation of total time

$$t[s] = \sum \Delta t$$

- Calculation of space covered during Δt

$$\Delta s[m] = \frac{v_1 + v_2}{2} \cdot \Delta t$$

- Calculation of total space covered

$$s[m] = \sum \Delta s$$

Braking curve

Before to present the procedure of the braking curve calculation, an important remark is necessary about deceleration values used. In order to reach results more easily comparable with next findings coming from the simulation approach, in the same way how Railsys works, in this theoretical application a constant value of deceleration has been considered (one value for each kind of rolling stock). These values are provided in [8], a research about the impact of ERTMS system, commissioned last year by Trafikverket (the Swedish Transport Administration) to Vectura (Consulting Company): the goal of that study was to point out the interrelation between braking curves considered in ATC2 and those used in ETCS Level 2. Furthermore they calculated the constant value of deceleration which was likely to be used in Railsys in order to reflect a real behavior of that two signaling systems. This issue will be important when the position of the indication point for each block section must be defined, in order to calculate the approaching time.

The procedure of the braking phase calculation is quite similar of that for the acceleration:

- Definition of ΔV equal to 1 km/h.
- Creation of V-steps: division of the speed from the top speed to 0 each kilometre per hour (ΔV).
- Calculation of braking force F_B at each V-step:

$$F_B = m_d \cdot a$$

Where:

- ✓ m_d is the dynamic mass of train
- ✓ a is the constant deceleration; it is a characteristic value for each kind of train, coming from [8]:

Train type		Deceleration *[m/s²]*	
		ATC2	**ETCS**
X2000	Long distance	0,81	0,60
Rc6	Long distance	0,81	0,60
X40	Regional	0,81	0,60
X60	Commuter	0,81	0,60
Rc4	Freight	0,46	0,25

Table 4.1 *Deceleration values*

- Calculation of resistance force F_R, through the trinomial formula in the same way as the acceleration curve.
- In this case the resistance force is helping the braking, therefore it needs to calculate a new value of deceleration, which it will be called real deceleration a_{real}:

$$a_{real}\left[\frac{m}{s^2}\right]=\frac{F_B+F_R}{m_d}$$

Now the calculation of time and space covered is exactly the same as in the case of acceleration curve.

Even if commuter trains are the only ones stopping at station Stockholm South, braking curves are calculated for all five kind of rolling stock because it is going to be useful for the calculation presented next.

Phase at constant speed

In this phase speed, traction force and resistance force are constant; therefore Δt equal to 1 second has been chosen and the calculation of time and space covered has been made in the same way as the case of acceleration and braking curve.

Commuter trains stop at the station Stockholm South; for this reason the calculation of the phase at constant speed is made from the final distance of acceleration phase to the starting point of braking. But all other trains do not stop in Stockholm South, therefore the phase at constant speed is calculated until the progressive distance corresponding to that station (2339 m). In the specific case of freight train, it takes the entire length from Stockholm Central to Stockholm South to reach the speed of 80 km/h.

The running time curves of all kind of rolling stocks are shown in *Figure 4.3*.

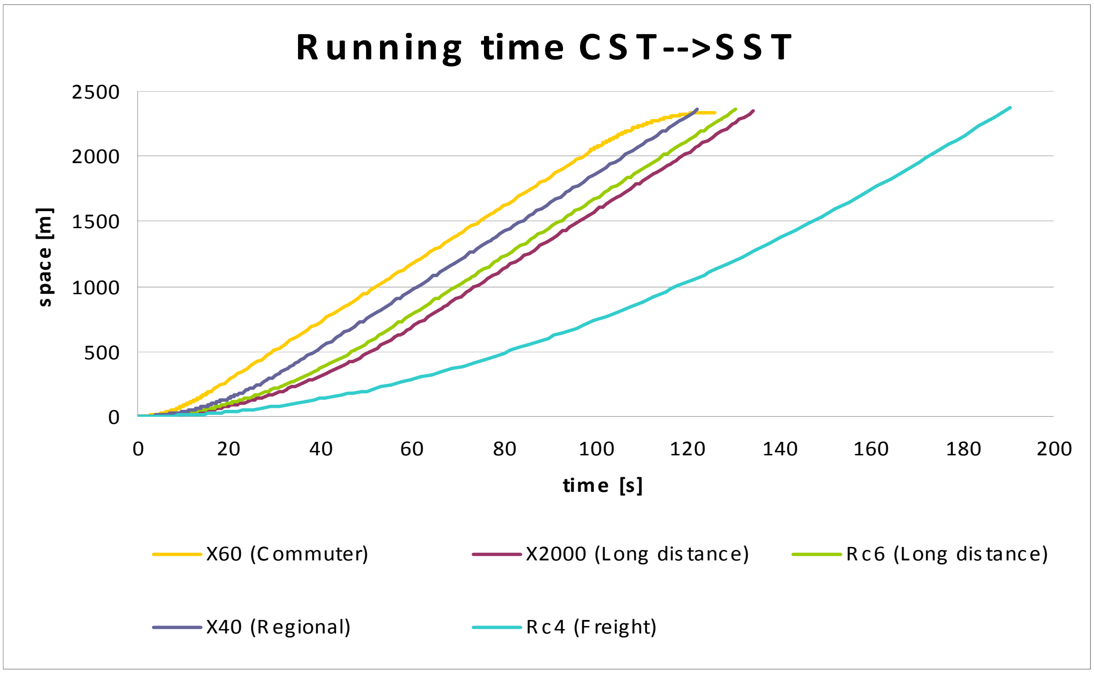


Figure 4.3 *Running time diagrams according to different train categories*

4.3.2. Calculation of the blocking time

The blocking time is the total elapsed time a section of a track (a block section or an interlocking route) is allocated exclusively to a train movement and therefore blocked for other trains [18]. That time is generally longer than the physical occupation, as shown in *Figure 4.4*.

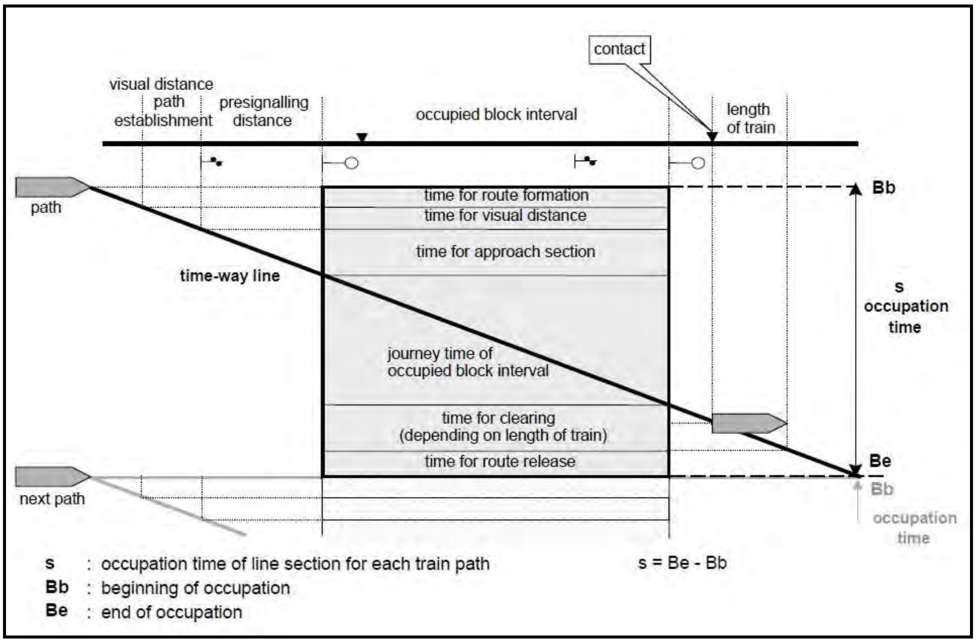


Figure 4.4 *Scheme of blocking time occupation [9]*

The blocking time for each block section results by the sum of the following components (for a train without a scheduled stop at the entrance of that section):

1. The switching time: it is the time for clearing the signal.
2. The driver reaction time: it is a certain time the driver needs to view the clear aspect of the signal that gives the approach indication to the signal at the entrance of the block section (this can be a block signal or a separate distant signal).
3. The approaching time between the signal that provides the approach indication and the signal at the entrance of the block section.
4. The running time between block signals.
5. The clearing time: it is the time necessary to clear the block section and, if required, the overlap with the full length of the train.
6. The release time to “unlock” the block system.

As regard of driver reaction time, as mentioned in [26], along the line it is equal to 4 seconds, while if a train accelerate from a stop it must be regarded the following components:

$$t_{signal\_ricognition} + t_{shutting\_door} + t_{order\_to\_start} = 4 + 4 + 4 = 12[s]$$

The running time between block signals is easily calculated interpolating data from the dynamics of train movements, supposing they are linear between the v-steps.

As regards the clearing time, for both ATC2 and ETCS Level 2 overlaps are considered, it means trains must clear the overlap beyond the block section with the entire train length; given to the small length of block sections (250 meters) over the bottleneck, next block section is used as overlap. With the ETCS Level 3 overlaps are not considered.

Concerning the release time, it has been considered equal to 5 seconds for ATC2 and ETCS/ERTMS Level 2. Actually for ETCS/ERTMS Level 3 release time is not a component of blocking time.

As regard of the switching and approach time, they are directly dependent to the signalling system and therefore they are separately presented in following sub-sections.

ATC2

Concerning the switching time, 5 seconds has been considered as likely switching time, as suggested by experienced people working in the railway field.

A general ATC system receive information about the aspect of next signals by balises fitted up along the line; in particular ATC2, updating data from balises, gives information to the train at what distance it has to be able to stop, depending to the current aspect of signals.

Therefore according to the current speed, ATC2 system informs the driver about the optimal speed profile to reach the target point.

From previous calculations combined with infrastructure data, at each information point (both signals and balises) the speed and the corresponding braking distance at that specific speed are known. Therefore for each block section, according to the dynamic of train movement, it is possible to detect the right balise representing the critical information point; the running time between that information point (balise) and the signal at entry of the block section represents the approach time.

ETCS/ERTMS Level 2

As regards the switching time, in case of ETCS/ERTMS Level 2 it is define by the system reaction time. It depends on the transmission and processing times of the components:

- Driver–Machine–Interface (DMI)
- European Vital Computer (EVC)
- Radio Block Centre (RBC)

As recommended in [26], the following values are considered in the calculation of the switching time:

	Mean value for ETCS level 2 [s]
Interlocking to RBC	0,05
RBC	1,5
RBC to train	1,1
EVC + DMI	1
System reaction time	**3,65**

Table 4.2 *Switching time components for ETCS Level 2*

Having a continuous data transmission between train and infrastructure (allowed by the radio block system), for each block section the system detect the indication point according to the current speed of the train. 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. If the train is moving with constant speed (for example in the specific case of this calculation, it is moving with the top speed of 80 km/h), it is easy to calculate the approaching time dividing the total braking distance necessary to brake from 80 km/h to 0 by the top speed 80 km/h. Instead if the train is moving along the acceleration phase, it is necessary to find out the intersection point between the acceleration curve and the braking curve translate up to the final point where the train have to stop in case of red signal, as the example shown in *Figure 4.5* (the indication point is represented by the abbreviation IP):

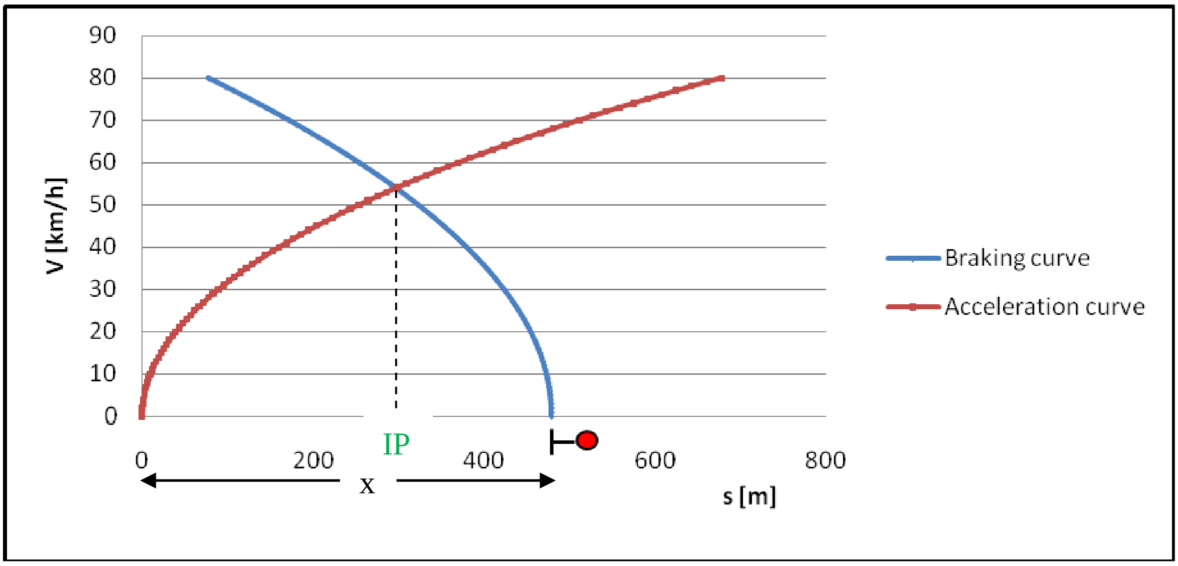


***Figure 4.5** Positioning of Indication point for ETCS Level 2*

As before the running time between that indication point and the signal at entry of the block section represents the approaching time.

ETCS/ERTMS Level 3

The switching time, as for the ETCS/ERTMS Level 2, is defined by the system reaction time and it depends on transmission and processing of aforementioned components.

In the case of ETCS/ERTMS Level 3, once again as recommended in [26], following values are considered in the calculation of the switching time:

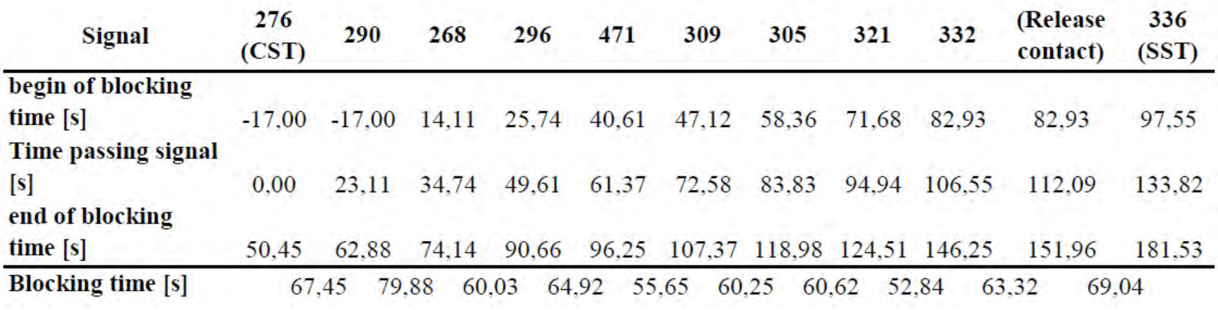
	Mean value for ETCS level 3 [s]
Train integrity	4
Train 1 to RBC	1,1
RBC	1,5
RBC to train 2	1,1
EVC + DMI	1
System reaction time	**8,7**

***Table 4.3** Switching time components for ETCS Level 3*

As regard the approaching time, the procedure to calculate that component of blocking time is exactly the same explained for ETCS/ERTMS Level 2, in this case made for each block section of 50 meters length.

The ETCS/ERTMS Level 3 does not need the release time; in fact, as explained in [26], 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. This safety margin has been considered equal to 7 seconds.

As an example the results of running time and blocking time calculation for the train X2000 in case of ATC2 signalling system are shown in *Table 4.4*.



Signal	276 (CST)	290	268	296	471	309	305	321	332	(Release contact)	336 (SST)
begin of blocking time [s]	-17,00	-17,00	14,11	25,74	40,61	47,12	58,36	71,68	82,93	82,93	97,55
Time passing signal [s]	0,00	23,11	34,74	49,61	61,37	72,58	83,83	94,94	106,55	112,09	133,82
end of blocking time [s]	50,45	62,88	74,14	90,66	96,25	107,37	118,98	124,51	146,25	151,96	181,53
Blocking time [s]	67,45	79,88	60,03	64,92	55,65	60,25	60,62	52,84	63,32	69,04	

Table 4.4 *Example of blocking time definition for X2000 train according to ATC2 signalling system*

Tables concerning the blocking time of all train category in case of different signalling system are reported in Appendix B.

In *Table 4.5* blocking time components according to the three investigated signalling systems are summarized.

	ATC2	**ETCS Level 2**	**ETCS Level 3**
Switching time	5 sec	3,65 sec	8,7 sec
Driver reaction time	12 seconds after a stop, 4 seconds along the line		
Approaching time	Time elapsed from the critical information point to the enter of the block section	Time elapsed from the indication point and the enter of the block section	
Running time	Coming from the dynamic of train movement		
Clearing time	Block section + Overlap, with the entire train length		Block section, with the entire train length
Release time	5 sec	5 sec	0 sec (Safety margin: 7 sec)

Table 4.5 *Blocking time components according to the signalling system*

4.3.3. Calculation of the average minimum headway $\bar{z}$

By taking into consideration the blocking time stairways, in order to calculate the minimum line headway for every possible pair of reference trains it needs to calculate the blocking time overlap in every block section. The blocking time overlap of a block section equals the amount of time the train path of the second train has to be postponed to eliminate the blocking time conflict in this block section [17]; it is possible to calculate that time in this way:

$$blocking\ time\ overlap = end\ blocking\ time\ 1^{st} train - begin\ blocking\ time\ 2^{nd} train$$

When the blocking time overlaps for all block sections have been calculated, the maximum value represents the minimum headway between the two trains.

The average minimum line headway is calculated by the following equation:

$$t_h = \sum (t_{h,ij} \cdot f_{ij})$$

Where:

- $t_{h,ij}$ is the minimum line headway for the train j following the train i.
- f_{ij} is the relative frequency of combination: train j following train i. This data is calculated from the absolute frequency F_{ij} known by the timetable:

$$f_{ij} = \frac{F_{ij}}{(n-1)}$$

The results of the average minimum line headway calculation in case of the three investigated signalling systems are summarized in *Table 4.6.*

	Average minimum line headway [s]
ATC2	86,26
ETCS L2	81,27
ETCS L3	64,12

Table 4.6 *Average minimum headway for different signalling systems*

4.3.4. Average buffer time t_p

The buffer times are scheduled between two trains in order to absorb secondary delays, it means that a train delayed could affect and obstruct the following one. If these times are underestimated the timetable stability could be weak but, on the other hand, if they are overestimated the number of available paths will be reduced and therefore the capacity as well. Thus buffer times must be rightly quantified in order to reach a good agreement among timetable stability and capacity exploitation.

In next two sub-sections the calculation of the average buffer time is presented, following two different approaches: one based on the STRELE-formula and the other depending on the infrastructure occupation defined by the UIC Code 406.

STRELE-formula

Coming from its definition, the optimal capacity is the maximum number of trains that could be scheduled over a railway line keeping an acceptable level of reliability and quality of train operation. The main performance indicator of the quality operation is the average of unscheduled waiting times, as recalled by *Figure 4.6*.

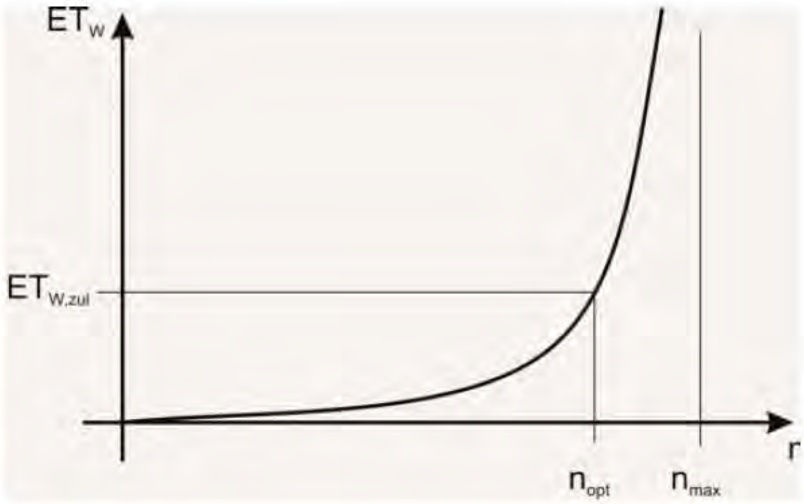


Figure 4.6 *General scheme about the relation between train number and waiting times [26]*

In general secondary delays arise from threading trains into the line section; in [26] the Schwanhäußer formula is mentioned for the calculation of average unscheduled waiting times:

$$ET_W = \left(p_{VE} - \frac{p_{VE}^2}{2}\right) \cdot \frac{\bar{t}_{VE}^{\,2}}{t_P + \bar{t}_{VE} \cdot \left(1 - e^{-\bar{z}/t_{VE}}\right)} \cdot$$

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

with

t_p: average buffer time

z: average determinative minimum headway time

z_g: average determinative minimum headway time of equal-ranking successions of trains

z_v: average determinative minimum headway time of different-ranking successions of trains

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.

According to given quality measures, acceptable unscheduled waiting times can be defined. For the theoretical application to the case study, the acceptable sum of unscheduled waiting times mentioned in [26], as effective in German, will be used:

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

with p_{RZ} proportion of the passenger trains.

The average buffer time t_p results from the limitation of the acceptable sum of unscheduled waiting times, according to the following equation of the STRELE-formula:

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

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

This equation has to be solved to the time t_p. The result corresponds to the buffer time necessary for reaching a satisfying operating quality.

Parameters of the delay (average delay at entry t_{VE} and probability of delay at entry p_{VE}) are necessary for the calculation. For the case study, the empirical distributions of entry delays for each train category are known; therefore, in order to be able to apply the STRELE-formula, a weight average according to the number of trains in each category, for both t_{VE} and p_{VE} has been calculated.

According to this approach, results about average buffer times in case of different signalling systems are shown in *Table 4.7*.

	z *[sec]*	**z_g** *[sec]*	**z_v** *[sec]*	**t_{VE}** *[min]*	**p_{VE}**	**p_g**	**t_p** *[sec]*
ATC2	86,26	92,75	77,97	2,83	3,54%	56,10%	52,22
ETCS L2	81,27	88,05	72,59				49,03
ETCS L3	64,12	74,60	50,74				36,39

Table 4.7 *Average buffer time for different signalling systems by STRELE-formula approach*

UIC Code 406

In [26] a formula for the calculation of the average buffer time derived from the infrastructure occupation A is suggested:

$$\bar{t}_P = \frac{\bar{z} \cdot (1 - \rho_{zul})}{\rho_{zul}} = \frac{A \cdot (1 - \rho_{zul})}{N \cdot \rho_{zul}}$$

with: $\bar{z}$ is the average minimum line headway

ρ_{zul} recommended value for the infrastructure occupation of UIC Code 406 (for the case study, it is equal to 0,75 being the peak hour and a mixed traffic line)

N existent number of trains (for the case study, the number of trains is equal to 42, within the time window investigated of the reference timetable).

The value of infrastructure occupation easily results multiplying the number of trains with the average minimum headway.

$$A = N \cdot \bar{z}$$

Still dividing by the reference time window (2 hours, equivalent to 7200 seconds), also the line exploitation rate is defined:

$$\eta = \frac{N \cdot \bar{z}}{T}$$

Finally, according to the UIC approach value of average buffer times in case of different signalling systems are summarized in *Table 4.8*.

	A *[sec]*	**η**	**t_p** *[sec]*
ATC2	3623,02	50,32%	28,75
ETCS L2	3413,17	47,41%	27,09
ETCS L3	2693,22	37,41%	21,37

Table 4.8 *Average buffer time for different signalling systems by infrastructure occupation*

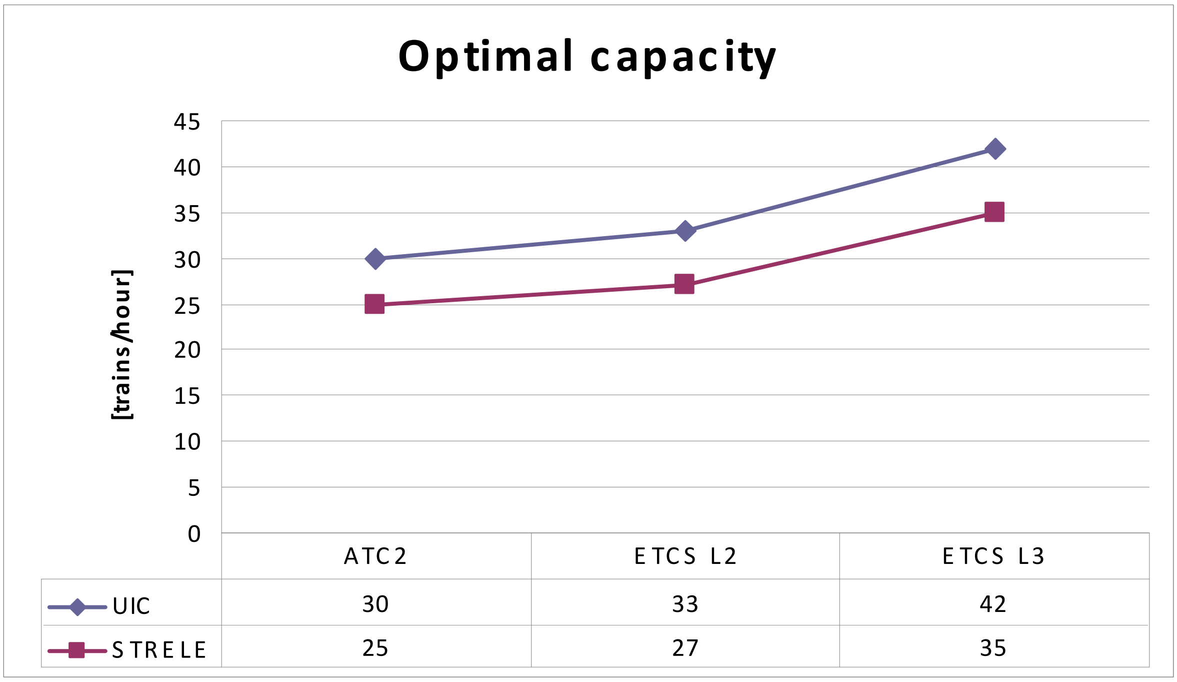
The average buffer times calculated with the STRELE-formula are higher than the others coming from the definition of infrastructure occupation. In fact, with that second approach specific delay data are not considered and therefore there is no explicit interrelation between capacity and quality.

4.3.5. Equivalent buffer time t_{add}

The equivalent buffer time is a supplement of buffer that expresses the influence of the infill. The automatic train control with infill functionality (balise and loop) allows a train slowed down at the pre-signal due to a slower train ahead and also to get information to accelerate if the next block section is cleared. According to this, the equivalent buffer time for ETCS Level 2 and Level 3 is equal to zero. Instead for ATC2 (comparable to the ETCS Level 1) the equivalent buffer time must be calculated. In [26] how to quantify this time component is not mentioned; for the calculation of the case study, the 10% of the average buffer time has been considered as equivalent buffer time.

4.4. Results and comments

Following the aforementioned calculation methodology, results about optimal capacity are shown in *Figure 4.7*.



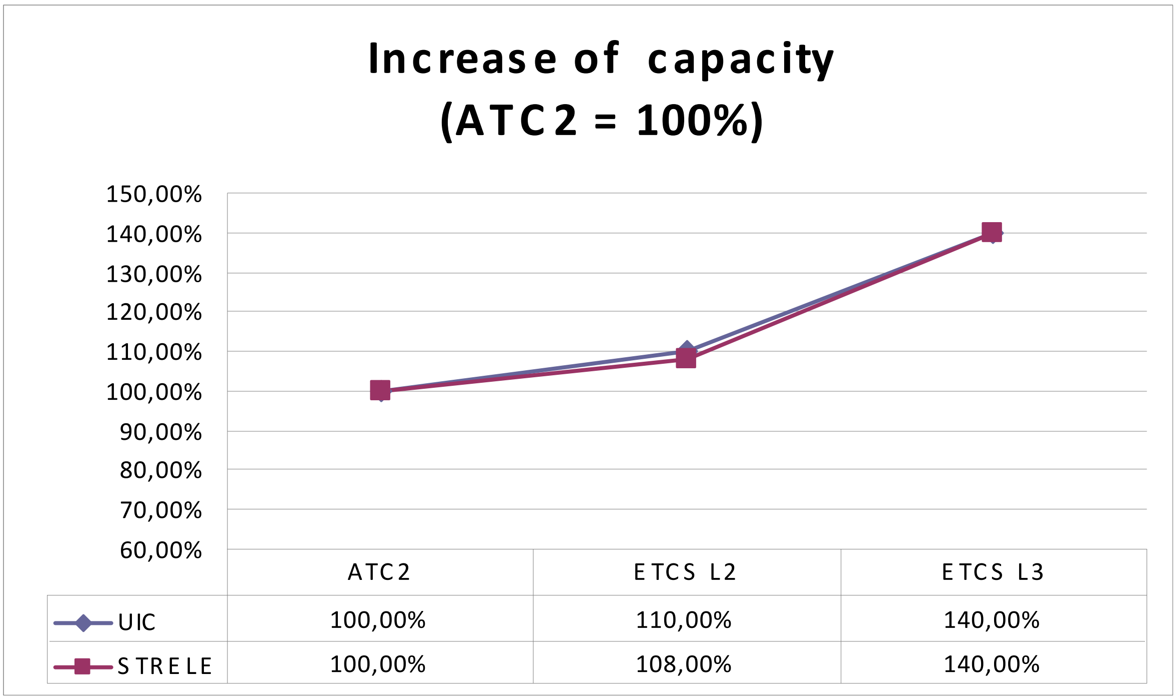
	ATC2	ETCS L2	ETCS L3
UIC	30	33	42
STRELE	25	27	35

Figure 4.7 *Optimal capacity results according to UIC and STRELE-formula approach*

It appears that results of the capacity analysis with UIC Code 406 are higher than ones with STRELE-formula; the reason is the different calculation of the average buffer time and therefore of the capacity consumption: UIC Code 406 uses the recommended values of infrastructure occupation without any correlations to a desirable level of operation quality, while with the STRELE-formula the limitation of the acceptable sum of unscheduled waiting times is decisive.

Moreover the ATC2, the one without full infill compared with both ETCS Level 2 and Level 3, leads the lowest capacity. The partial infill of ATC2 counts more than restrictive braking performances considered in ETCS signalling systems.

Compared with ATC2, the amount of increase in capacity with ETCS Level 2 and ETCS Level 3 actually is the same with both methods, STRELE-formula and UIC Code 406. This is clearly shown in *Figure 4.8*.



	ATC2	ETCS L2	ETCS L3
UIC	100,00%	110,00%	140,00%
STRELE	100,00%	108,00%	140,00%

Figure 4.8 *Increase of capacity leads by UIC and STRELE-formula approaches*

As a conclusion, from next simulation approach the following result will be expected: the capacity in case of ATC2 and ETCS/ERTMS Level 2 will be quite the same, or a bit higher for ETCS/ERTMS Level 2 (from the calculation the difference is around 10%), while the capacity will be higher with ETCS/ERTMS Level 3 (from calculation the increasing is equal to 40%).

5. Simulation

Simulation is a problem-solving methodology for the solution of many real-world problems. Through simulation, it is possible to build up a model, in order to imitate and evaluate the performance of a real system by asking “what if” questions.

Making use of the simulation approach, several advantages are provided concerning different aspects. The main benefit is that you can easily and quickly apply to the model all changes you want regardless real expenses of these changes, without making disruption to the real system. On the other hand this aspect must rightly be considered, because it is necessary to investigate if suggested renovations are feasible or not also under the economical point of view. One other benefit coming from simulation, is that you can observe states speeding up or slowing down phenomena in order to deeply investigate them. Furthermore, simulation allows taking a microscopic examination of the system to determine cause and effect connection between elements involved in the model. Finally the subject of the investigation is always a complex system; therefore simulation makes possible to better understand the interactions among the variables that make up such complex scheme and how those variables affect performance of the entire system.

Several simulation tools have been developed in railway environment and what draws them together is the aim of the optimization of infrastructure and operation, helping the rail industry make decisions. One of them is called Railsys® and it is provided by the German enterprise RMCon (Rail Management Consultants) in close co-operation with the Institute of Transport, Railway Construction and Operation at the University of Hannover. Instead at the Swiss Federal Institute of Technology the software OpenTrack® has been developed. Nowadays both of previous tools are used by railway supply industry, consultancies and universities in different countries. One other simulation tool is Railsim® and it is provided by the American company called Systra.

The evaluations carried out in this thesis has been supported by the first simulation tool aforementioned: Railsys®.

5.1. Railsys®

Railsys® is a railway simulation tool composed by three main modules:

- *Infrastructure Manager*. In this section the layout of the infrastructure is built up, involving tracks, signals, overlaps and all significant elements that are defining the hardware of the railway system.
- *Timetable and Simulation Manager*. This is the largest part of the program and it includes two different parts tightly linked one to each other. Timetable Manager allows the user to create a timetable, entering trains with their characteristics, paths, alternative tracks at stations and so on. Then, through Simulation Manager, operational days are simulated, running trains affected with delay distributions and according to their priority (both elements previously defined by the user).
- *Evaluation Manager*. Finally this module makes possible data evaluation of multiple simulations providing diagrams and tables and also exporting data in Excel format.

5.2. Simulation methodology

The simulation analysis will follow next chronological steps:

1. *Infrastructure settings*.
   The layout of the actual infrastructure has been provided by previous projects, but settings for applying the new signalling systems ETCS Level 2 and ETCS Level 3 must be done, in order to define different scenarios.
2. *Timetable definition*.
   This part will be the most dense section and it will involve:
   - → Rolling stock settings: priority and behaviour in case of delays and deceleration performance must be set for each category of trains.
   - → Two new timetables will be created, beyond the one of today, in order to evaluate how signalling systems affect the operation and to provide a capacity measure.
   - → Implementation of delay distributions.
   - → Validation of the model.

3. *Simulation.*

   First of all, framing the experimental design will be necessary and then multiple simulations will be provided, running a proper number of replications previously defined. The simulation includes two hours before the investigated period in order to warm up the system, and two hour after.

4. *Evaluation results.*

   Thanks to data coming from the multiple simulation and collected in the module Evaluation Manager of Railsys, performance and capacity evaluations will be based on:

   → Average arrival delays.

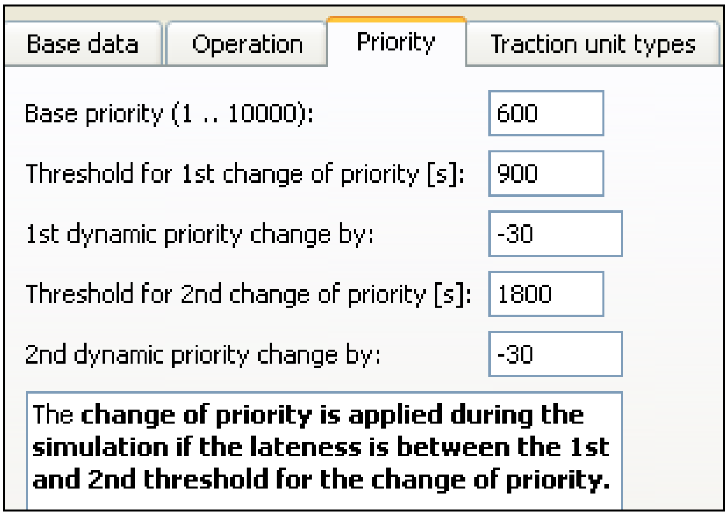
   → Punctuality.

   → Secondary delays.

5.3. Data preparation

5.3.1. Trains settings

One of the main operational feature of trains that must be defined is the dispatching priority. It is an important setting regarding the simulation because it defines the rules to dispatching a train before another one in current operation. In the case study, the X2000 train is the train with highest priority, while the freight train has the lowest. With Railsys a relative priority between trains could be set and also a dynamic change of priorities depending on the user-defined threshold of delay is provided.



Base priority (1 .. 10000): 600
Threshold for 1st change of priority [s]: 900
1st dynamic priority change by: -30
Threshold for 2nd change of priority [s]: 1800
2nd dynamic priority change by: -30

The change of priority is applied during the simulation if the lateness is between the 1st and 2nd threshold for the change of priority.

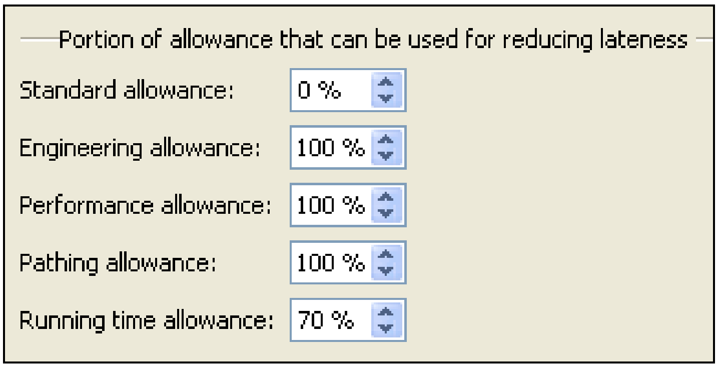
Figure 5.1 *Priority settings*

Data regarding all types of trains involved in the operation of the case study are summarized in *Table 5.1*.

	X2000	**Rc6**	**X40**	**X60**	**Rc4**
Base priority (1 ... 10000)	600	590	590	590	20
Threshold for 1st change of priority [s]	900	300	300	300	300
1st dynamic priority change by	-30	-30	-30	-30	-5
Threshold for 2nd change of priority [s]	1800	900	900	900	0
2nd dynamic priority change by	-30	-30	-30	-30	0

Table 5.1 *Train priority*

Within operational train characteristics a standard allowance is defined; the standard allowance is equal to 3% for all train categories and it is representing a reserve of the running time in order to take into account the driver behaviour. That allowance is never reduced for catching up delays, while in order to catch up delays, 70% of the running time allowance could be used instead.



Portion of allowance that can be used for reducing lateness

Standard allowance: 0 %

Engineering allowance: 100 %

Performance allowance: 100 %

Pathing allowance: 100 %

Running time allowance: 70 %

Figure 5.2 *Reducible allowance*

The running time allowance will be explained in next sections.

In ETCS Level 3 scenarios, in the section about characteristics of trains operation the box “Moving block” must be ticked in order to enable trains running in moving block mode.

Finally, different values of deceleration for each train categories must be set in case of ATC2 or ETCS signalling systems; the same values presented in the theoretical application in sub-section 4.3.1 are applied in the simulation.

5.3.2. Signalling systems settings

Within the module Infrastructure Manager, some arrangements are necessary for the three investigated signalling systems.

Block sections

In order to use the ATC2 signalling systems, the block sections must be set as “ATC-S”, that means the Swedish ATC2 presented in the chapter 3.

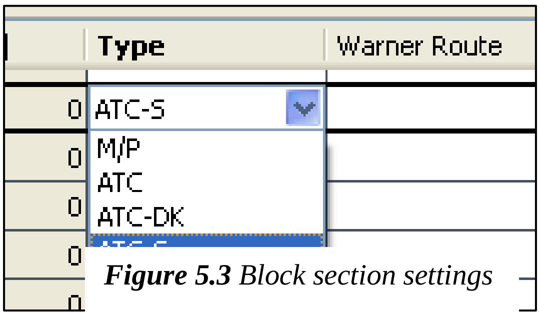


Figure 5.3 *Block section settings*

In order to model the ETCS Level 2 and Level 3 in Railsys® block sections have to be defined as “ATC”; in this way, the entire length of the block sections is equipped with loops, which give a unidirectional communication from the infrastructure to the train and therefore allows continuous information updating about the signal aspects.

Finally, block sections must be set as “Moving” in order to apply ETCS Level 3, since that signalling system is working with the logic of moving block.

Interlocking types

Within the section of definition of interlocking types, it is possible to define the setting time and the releasing time; the same values used in previous theoretical application are applied in the simulation tool and they are summarized in *Table 5.2* (the accuracy of these input data is one second).

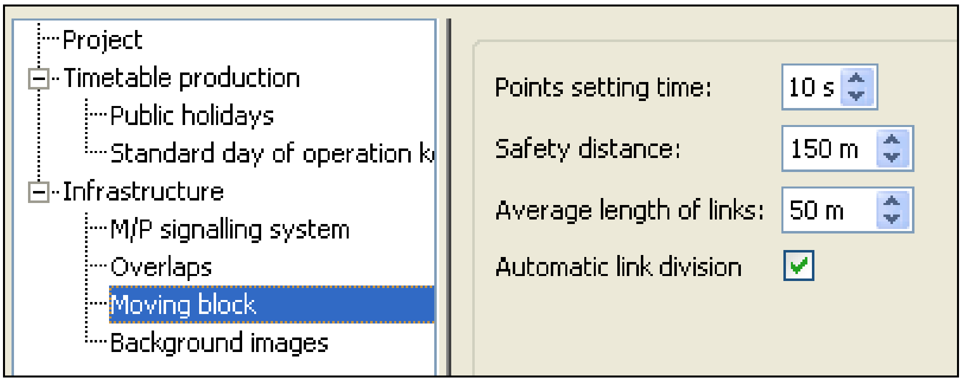
	Setting time [s]	**Releasing time [s]**
ATC2	5	5
ETCS Level 2	4	8
ETCS Level 3	9	0

Table 5.2 *Setting and release times*

Further moving block settings

In order to model the ETCS Level 3 on the line, few more settings listed below are necessary for the moving block [20]:

- Point setting time: it defines the time required for setting all sets of points and 10 seconds have been used for that option.
- Safety distance: it represents the distance between the end of the train ahead and the end point of the braking distance of the following train. It has been considered equal to 150 meters (it corresponds to the 7 seconds considered in previous theoretical application).
- Average length of links: it defines the length of the internally generated link sections used to map train runs in moving block mode. Such length has been set as 50 meters.
- Finally the box “Automatic link division” must be enabled to use the moving block function.



Points setting time: 10 s

Safety distance: 150 m

Average length of links: 50 m

Automatic link division ☑

***Figure 5.3** Moving block settings*

5.3.3. Definition of new timetables

The purpose of the thesis is to investigate advantages and drawbacks, equipping the line of the case study with the new systems ETCS Level 2 and Level 3. In order to finally give capacity measures coming from delay level, two new timetables are built, beyond the one of today, increasing the number of trains running over the line. In such a way, deep evaluations will be made for different signalling systems at different traffic loads. The new timetables are quite tight (mainly the second one), but their construction is not aimed at obtaining a realistic and reliable timetable, but only at forcing the number of trains per hour in order to observe the delay trend from that it will be possible to define the optimal capacity.

Scenarios that will be simulated need to be comparable. For this reason, the new timetables, which will handle a higher number of trains, must keep similar features to the actual timetable, especially they must preserve the same or at least as close as possible the following characteristics:

- traffic composition
- train patterns
- scheduled running time allowances.

Thus, considering characteristics of current timetable already presented in section 3.2.2, the new timetables are built following the criteria described below.

First step has been to reduce the constant time interval between commuter trains: 4 minutes (for timetable NEW 1) and 3 minutes (for timetable NEW 2). Knowing the number of commuter trains over the two hour period (from the time interval just defined) and their percentage on traffic proportion which must be preserved, the total number of trains between 4 p.m. and 6 p.m. is easily calculated: 52 trains for timetable NEW 1 (it means 26 trains/hour) and 70 trains for timetable NEW 2 (it means 35 trains/hour). Now, by the total number of trains and the traffic composition, the number of trains for each category is calculated and a summary is reported in *Table 5.3*.

	Timetable 2008		**Timetable NEW 1**		**Timetable NEW 2**	
	Number	*Proportion [%]*	*Number*	*Proportion [%]*	*Number*	*Proportion [%]*
X60	24	57,1	30	57,7	40	57,1
X2000	8	19,0	10	19,2	14	20,0
Rc6	5	11,9	6	11,5	8	11,4
X40	4	9,5	5	9,6	7	10,0
Rc4	1	2,4	1	1,9	1	1,4
TOTAL (2 hours)	**42**		**52**		**70**	

Table 5.3 *Traffic composition in all three timetables for 2 hours*

In new timetables, one long distance or regional train is always scheduled between two commuter trains (to keep as close as possible the type of train pattern to the timetable of today) and the same scheduled running time allowances are preserved for train categories in new timetables as in the current one.

The three graphical timetables are shown in the Appendix C.

Regarding the freight train, it is the only category for which the nominal number over the two hours is not changing over all timetables. This is because the investigated time period is involving the peak hour, therefore it seems likely that no more than one freight train is scheduled there: in that specific time window priority is given to the passenger trains is always given.

5.3.4. Delay distributions

In order to make the simulation closer to the real operation (and therefore get meaningful evaluation results), the scheduled timetables must be perturbed. The same perturbations will be applied in all scenarios that will be created, once again in order to make them comparable.

For the case study only entry delays will be considered and they will obviously be applied at Stockholm Central, the station where trains are entering the line (looking at the investigated southbound traffic).

For different train categories empirical data from departure delays in Stockholm Central are available. Those data have been recorded under four months (from September to December 2006) for the whole day during week days (from Monday to Thursday). The difference between the timetable of 2006 and the one of 2008 is not significant, thus using distributions coming from a different time period is assumed not affecting the model too much. The decision is to use these distributions as entry delays. This assumption must be considered on future evaluations. In fact, empirical data, coming from departure recordings, are already including some dwell time extensions in Stockholm Central. It means that using that data for entry delays, the latter are a bit overestimated.

The delay distributions applied in the simulation at each category of trains are shown in Appendix D.

Even line delays and dwell time extensions usually could be implemented in simulation approach but in this case study they are not. Because the investigated line is short, line delays should be small and rare. as regards to dwell time extensions, they should be applied only to commuter trains that stop at stations involved in the area of the case study, while this kind of delays should be applied to all trains in Stockholm Central Station. But because of the entry delays used, being departure recordings how previously explained, they already involve dwell time extensions.

5.3.5. Validation

Validation is the determination that the model built up in the simulation tool is an accurate representation of the real system.

The layout of the actual infrastructure has been provided by previous project [24], therefore the validation will concern only testing the goodness of entry delay distributions. If there is an existing system, then an ideal way to validate the model is to compare its output to that of the real system. Empirical data concerning arrival delay in Älvsjö are available, thus their distribution is compared with the same distribution coming from the simulation in the actual scenario (ATC2 signalling system, timetable 2008).

Graphical results of this comparison are shown in the Appendix E.

The two distributions are quite close for all train categories; but, more evidently as regards X40 and X2000 trains, the arrival delay distribution related to the simulation output appears a bit worse than that of real data. That difference could be traced back to the fact that the entry delay distributions used in the simulation are actually coming from departure data recordings and therefore the entry delay are a bit overestimated (as explained in previous section). Anyway the same kind of error will affect all scenarios, being the only entry delay distribution applied, therefore comparisons between scenarios and signalling systems are possible and the model is validated.

5.3.6. Definition of number of replications

Making use of a simulation tool and using random numbers from delay distributions as input, it is really important to run enough replications to ensure the results are statistically stable.

As the average arrival delay will be the indicator parameter for main evaluations about operation performances, its convergence and the convergence of its standard deviation will be tested over different number of cycles. This inquiry is made in the actual scenario (featured by ATC2 signalling system and timetable 2008). Moreover the stability of aforementioned parameters is checked in both Flemingsberg (because it is the last station of the case study area) and Stockholm South (because some significant evaluations will be carried out here).

Plotting the values of average arrival delay and its standard deviation, reported in Appendix F, 800 cycles is deemed as a reasonable number of replications. It must be observed that results concerning the freight train seems not to be stable with 800 cycles, at least it appears in the diagram of the standard deviation of arrival delay in Stockholm South. But that data is caused by a spread entry delay distribution for that train category and for this reason in that 800 cycles only one value of average arrival delay is really moved away from the others, make arising the standard deviation value. Anyway, taking into account that during the peak hour the freight train has the lowest priority the definition of number of replication is based in all train categories except the freight one. During the peak period the management of freight train movements are extremely flexible. In fact, if the freight train is late it will not depart from Stockholm Central until the next free time window and therefore it will not affect other passenger trains. This is also the reason because, even if the freight train is scheduled and it is running in the simulation, it will not be involved in any evaluation results.

5.4. Experimental design

Concerning the three signalling systems and the three timetables, nine scenarios are created and all of them will define the experimental design. Only one level of perturbation (as entry delay) is considered and the same will be applied to all nine scenarios.

The number of replication running for each scenario is fixed equal to 800.

5.5 Evaluation results

In order to see and to underline the main findings induced by simulations, it is important to identify the right indicator parameters to look at. Even if a scheduled process is provided by the timetable, it often happens that many factors (either within the railway system or from external sources) can affect running time or dwell time at stations. It is common to focus on delays and punctuality to make performance evaluation of train operation and capacity. In fact, the capacity utilization determined by a timetable has a relevant impact on punctuality, delays and therefore the overall operation, even if it do not reveal specific reasons for the variability of operation quality during a specific time period.

The train delay is the deviation from a scheduled event or process time of that train, while the punctuality is defined by the percentage of trains arriving at a location with a delay less than a certain time in minutes [28].

A train can be affected by different kind of delays classified according to location and sources [28]: initial, original and knock-on (or secondary) delays. Initial delays are those recorded when a train is passing through the boundary entering the investigated network; original delays are caused by speed limitations, dwell time extensions for alighting and boarding of passengers, technical failure and bad weather conditions; finally knock-on delays are those induced by other trains, it means when a train is delayed its lateness can hinder other trains by still occupying the route. The latter kind of delay can occur both at stations (when trains are ready but departure is denied) and along the line.

5.5.1 Average arrival delay

Looking at this first performance parameter, it is possible to make comments about the delay development along the line of the case study. Three diagrams representing the average arrival delay at all stations according to all nine scenarios are reported in *Figure 5.4*.

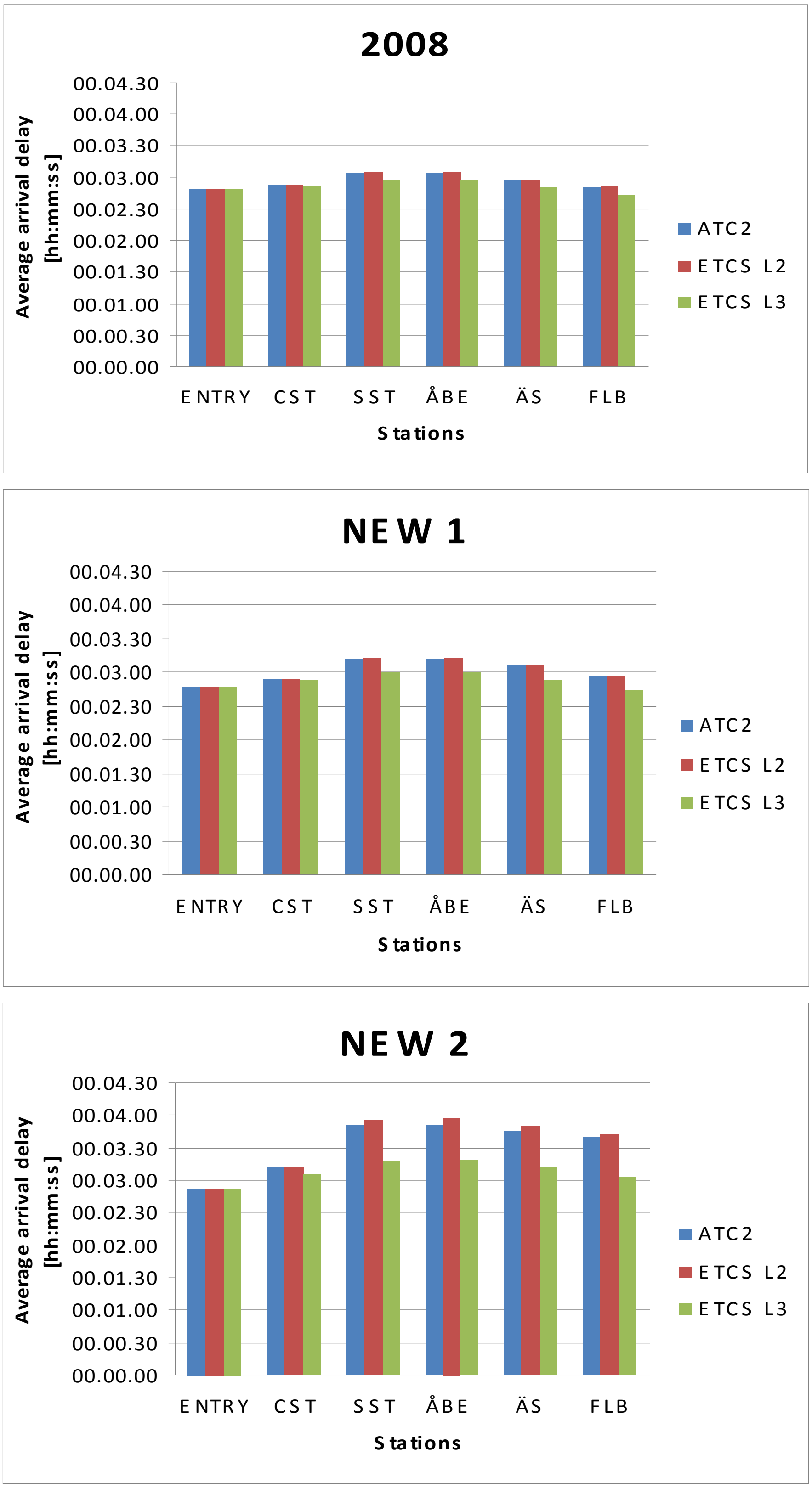


Figure 5.4 *Average arrival delay development*

First of all, it can be observed that the initial perturbation level is the same for all signalling systems in the three timetable scenarios, because the same entry delay distributions have been applied. Among the three timetable scenarios the value of entry delay lightly varies but the difference is not so relevant (2’49” in timetable 2008 scenarios, 2’47’’ in timetable NEW 1 scenarios and 2’54’’ in timetable NEW 2). These values could appear a bit large, but the explanation concerns the issue about the source of the empirical data, already discussed in previous section 5.3.

Some overall comments about common trend coming out from previous diagrams are possible:

1. The average arrival delay is firstly increasing comparing values at entry and at Stockholm Central Station (CST). This issue can be explained by the limited junction capacity, but it is not the focus of the thesis.
2. A further increase of average arrival delay is recorded over the first line section between Stockholm Central Station (CST) and Stockholm South Station (SST): in that part of the network the bottleneck is located and this is the obvious reason for that.
3. After Stockholm South Station, the average arrival delay is almost constant until Årstaberg (ÅBE) and then decreasing up to Flemingsberg (FLB). This kind of trend is justified by the running time allowances preserved for X60 commuter trains over that part of the line. As an example, the diagram concerning the average arrival delay in the first scenario (ATC2 signalling system, timetable 2008) for different train categories is shown in *Figure 5.5*.

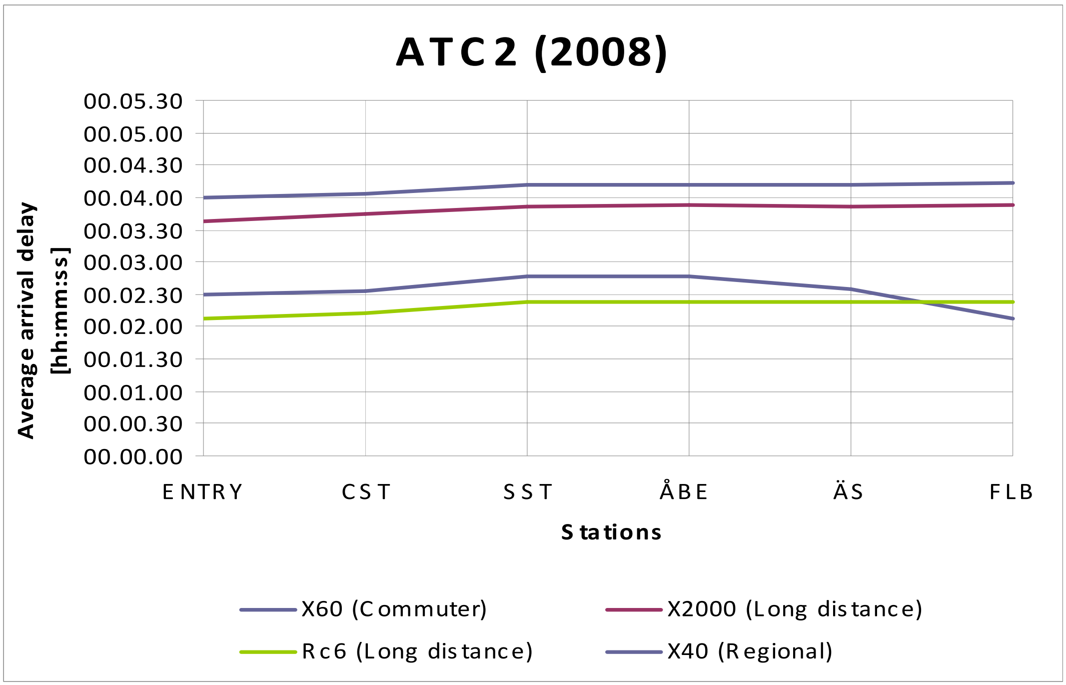


***Figure 5.5** Average arrival delay development according to the train categories*

At Flemingsberg only commuter trains have partially recovered the delay thanks to the running time allowances, while all other trains are keeping the same delay as in Stockholm South Station.

Stability discussion

From the analysis of average arrival delay it is possible to discuss the timetable stability. The latter is a fundamental feature to guarantee, or at least to favour, the reliability of train operations. Actually the timetable stability is pursued by scheduling proper buffer times in order to avoid and reduce delay propagation.

According to the type of railway system where the discussion is focused, two kind of stability can be defined: local stability in case of a sub-network (or so-called open system) and global stability in case of an entire network. Looking at the case study, it is concerning an open system, where trains are entering and exiting the investigated sub-network, therefore the first type of stability will be discussed.

An area is locally stable if the sum of output delays is smaller than the sum of input delays. In *Figure 5.6* the difference between the average arrival delay in Flemingsberg and the average entry delay in Stockholm Central Station is plotted.

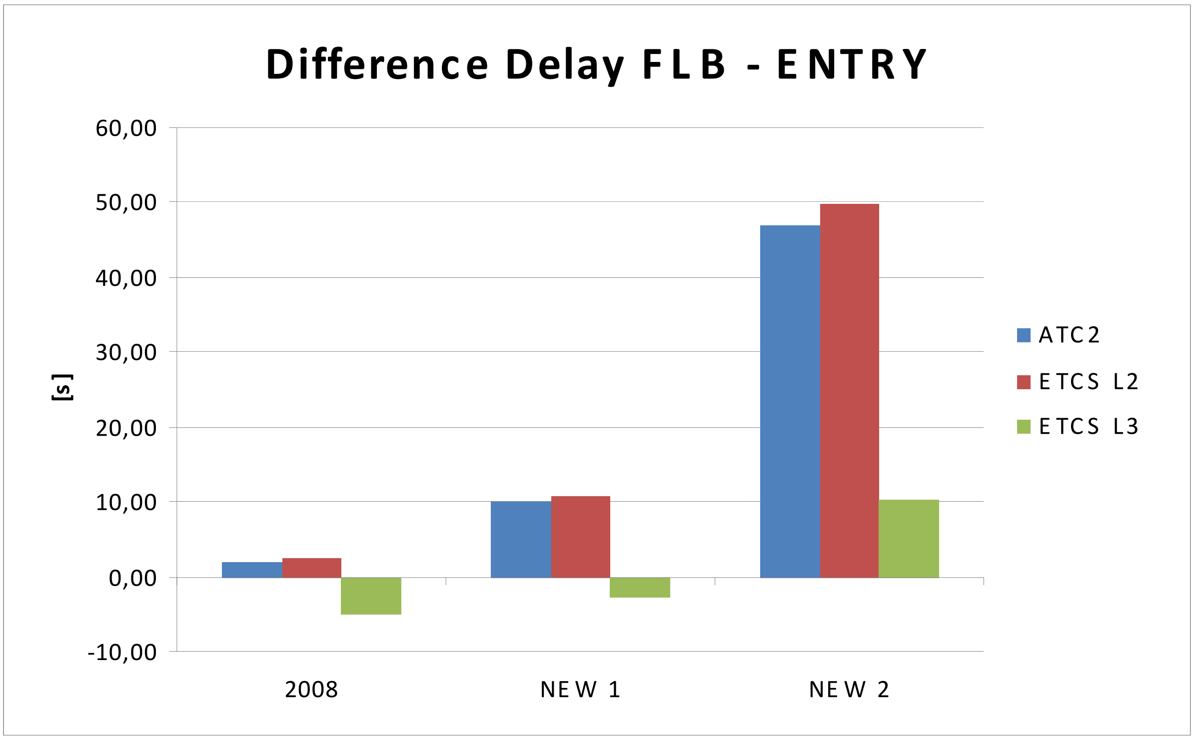


Figure 5.6 *Local stability investigation*

Looking at the timetable of today, it appears that only equipping the line with moving block the timetable stability is guaranteed. With the actual signalling system ATC2 and also with the ETCS Level 2 the aforementioned difference is lightly positive, therefore the area cannot be defined locally stable. The other two timetables have been designed with the aim to increase traffic flow in order to provide further evaluations about capacity definition for all signalling systems. It is evidently clear that local stability is getting worse, when the number of trains per hour is arising. However, it is interesting to notice that still with timetable NEW 1 (26 trains/hour) the ETCS Level 3 allows the local stability of the timetable; in the last scenario with timetable NEW 2 none of the investigated signalling systems provide timetable stability.

5.5.2 Punctuality

Comments made about the average arrival delay development along the line of the case study could be reflected all the same looking at the punctuality. In Sweden, a train arriving at a location 5 minutes later than the schedule is considered on time, as defined by SJ AB, the main Swedish railway operator. Therefore the following remarks will handle the punctuality as the percentage of trains arriving with lateness no higher than 5 minutes.

In *Figure 5.7* the punctuality development along the investigated network according to the nine scenarios is shown, now directly focusing the attention to Stockholm Central Station, Stockholm South Station and Flemingsberg (because previously recognized as main meaningful points for evaluations over the line).

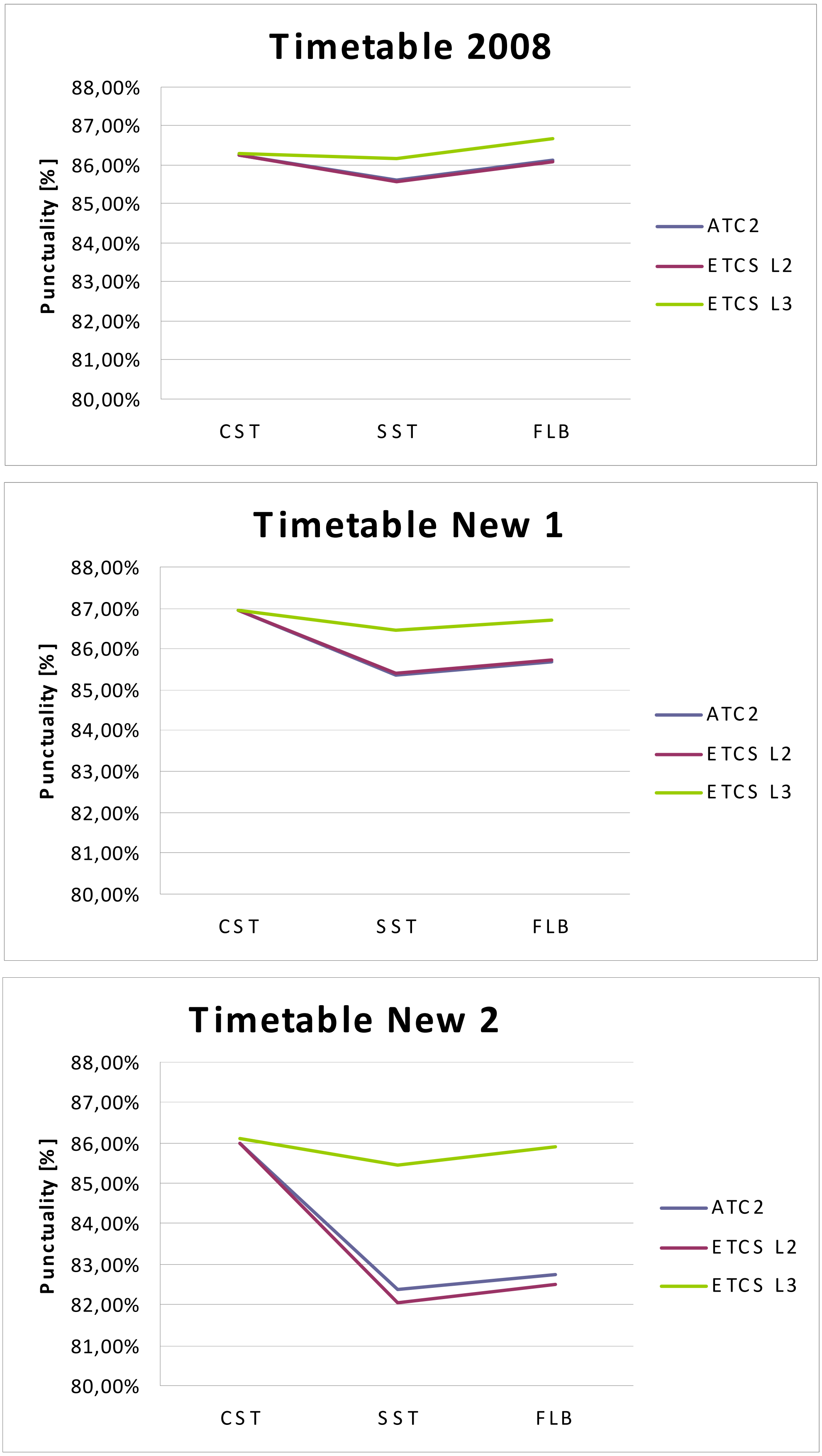


Figure 5.7 *Punctuality development*

The line section involving the bottleneck, it means between Stockholm Central Station (CST) and Stockholm South Station (SST), is once again recognized as the critical part of the network; in fact, it is here where the punctuality is dropping in all nine investigated scenarios. In general, the higher number of trains per hour, the higher the loss in punctuality at Stockholm South Station is recorded. However the size of this decrease in punctuality is not the same looking at different signalling systems, as is shown in *Figure 5.8*.

Figure 5.8 *Loss in percentage points of punctuality in line section between CST and SST*

With the ATC2 and ETCS Level 2, in all three timetables, the punctuality loss is significantly greater than in case of ETCS Level 3; the punctuality loss recorded in scenarios featured by ATC2 or ETCS Level 2 with the actual timetable, is the same reached by ETCS Level 3 in scenario with timetable NEW 2.

Furthermore, looking at the line section between Stockholm South Station and Flemingsberg, the punctuality is lightly increasing over aggregate results, based on all trains. But analysing the same punctuality development for different train categories, once again it appears X60 commuter trains are gaining in punctuality thanks to running time allowances, while other trains are keeping the same punctuality level from Stockholm South Station. As an example, the diagram concerning the actual scenario is reported in *Figure 5.9* (the same trend is recorded in all nine scenarios).

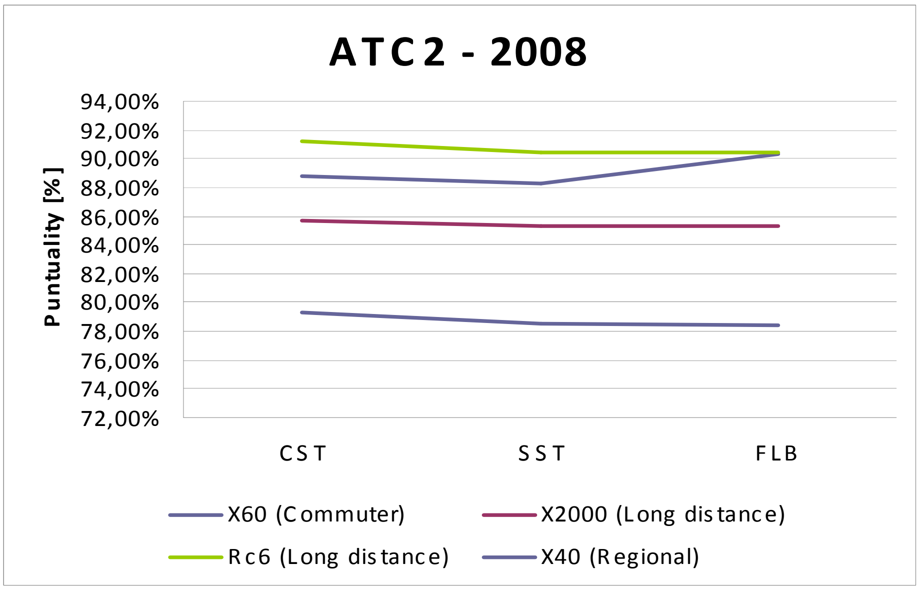
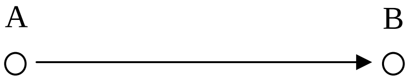


Figure 5.9 *Punctuality development according to train categories*

5.5.3 Secondary delay

Important performance evaluations and comments could be given looking at the secondary delays, it means delays suffered by a train due to the hindrance of another train. Of course, this kind of delay is destined to increase when the number of trains moved along the line is arising.

For the case study, it is possible to define secondary delays as shown in the next general scheme.



Secondary delay suffered over the line section A-B = Arrival delay at station B − Arrival delay at station A

The definition of the secondary delay by the difference between arrival delays of two consecutive stations is possible because original delays (both line delays and dwell time extensions) have not been implemented into the model. Therefore, it means any increase of delay is due to the interrelation with other trains and thus it represents the secondary delay. Moreover, because original delays have not been considered in the simulation model of the case study, secondary delays will be equivalent to the unscheduled waiting times.

In previous section 5.5.1 it has already been observed that the only increase of average arrival delay (except that related to the capacity of Stockholm Central Station) is recorded over the line section involving the bottleneck. This result is better shown by plotting the diagrams of secondary delay in case of the nine scenarios (*Figure 5.10*).

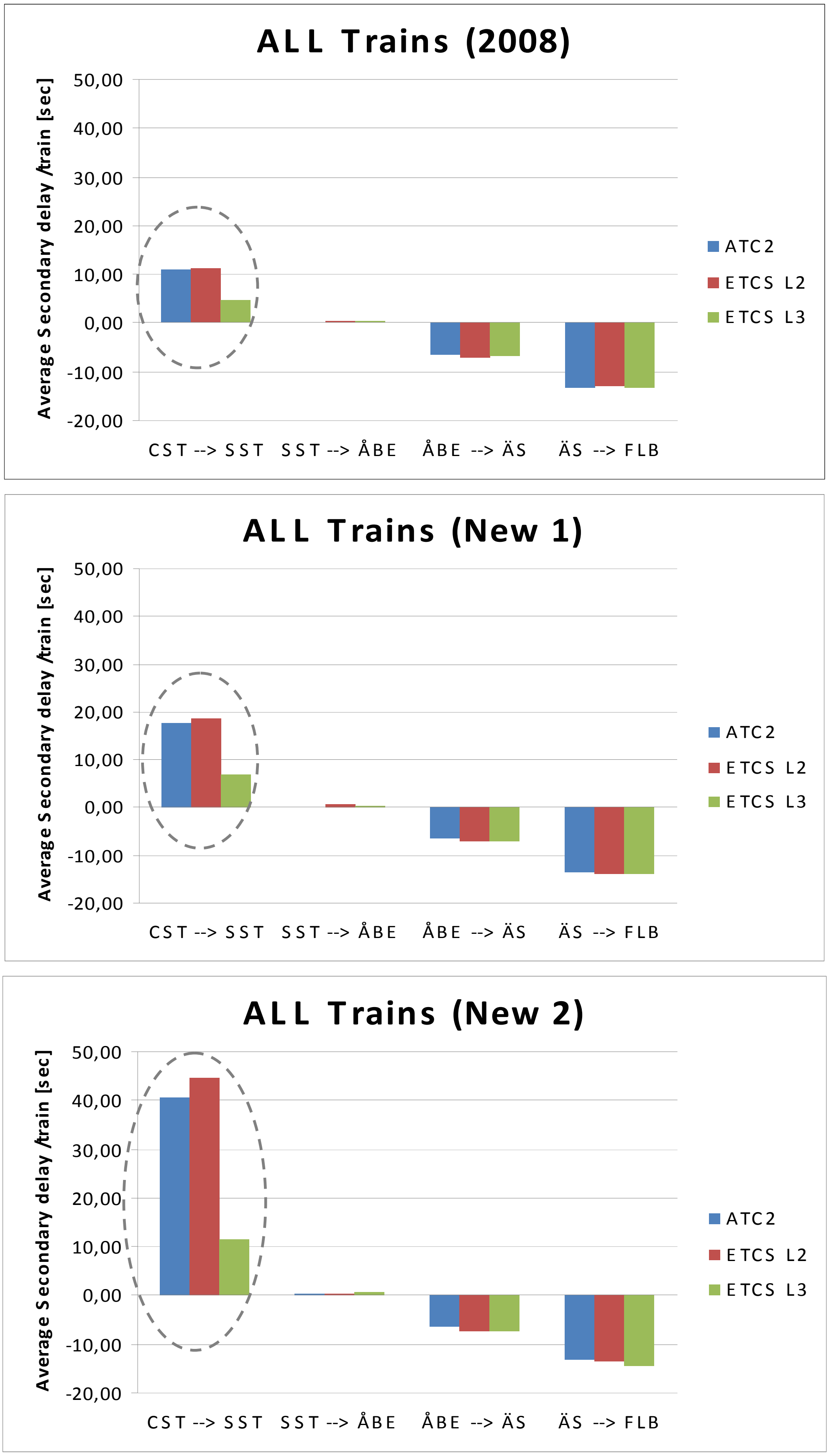


***Figure 5.10** Secondary delays development*

The dashed rings underline the positive value of average arrival delay difference between two following stations, it means where secondary delays occur (exactly where the bottleneck is).

The negative value in next line sections are due, once again, to running time allowances preserved for commuter trains; however it means, looking at aggregate results over all trains, in that part of the network secondary delays are not occurring. Moreover, it appears that the most relevant difference among the three previous diagrams is the increase of secondary delays where the number of trains per hour is arising. On the other hand the difference between average arrival delays, after Stockholm South Station, is remaining more or less the same, independently to both the addition in traffic load and the different signalling system applied. This remark leads to one further comment: the line section between Stockholm South and Flemingsberg, where tracks are doubled compared with the bottleneck, is not used close to its capacity limit and probably it will not happen as long as the bottleneck exists. This part of the line records a low line exploitation and it plays an important role on the delay recovering more than in the increase of capacity. Finally, benefits pointed out by ETCS Level 3 looking at the line section involving the bottleneck, are not so evident over the rest of the line of the case study. This could be explained because between Stockholm Central Station and Stockholm South Station trains are running at 80 km/h and according to [6], it is known that 80 km/h is actually the speed level where moving block can give best improvement in capacity performance. From Stockholm South Station and Flemingsberg the maximum speed increase up to 160 km/h and probably that part is too short to reveal good gain coming from ETCS Level 3.

Focusing into the line section involving the bottleneck it is useful the secondary delay results occurring in all nine scenarios in only one diagram (*Figure 5.11*), in order to easily make comparisons.

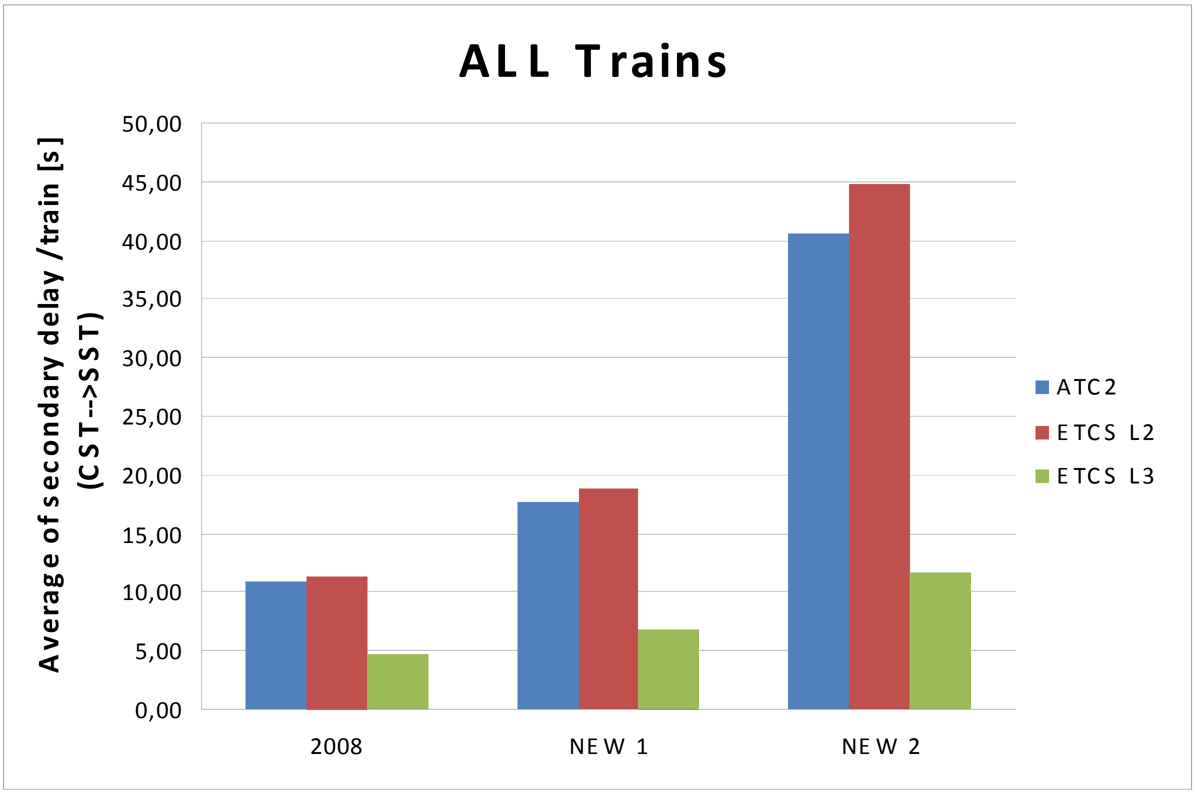


Figure 5.11 *Secondary delays suffered on the bottleneck according all nine scenarios*

The higher the number of trains per hour, the higher the secondary delay suffered by trains running over the line. However the increase provided by ETCS Level 3 is smaller than that provided by ATC2 or ETCS Level 2, especially comparing the timetable New 2 with the actual one: in scenarios featured by ATC2 or ETCS Level 2 the increased of secondary delay counts around 300%, while with ETCS Level 3 is 150%.

Now, in order to evaluate the sensitivity of the signalling system to increased traffic load, it is interesting to focus on the portion of trains suffering secondary delay, plotting that value over the median value of secondary delay (*Figure 5.12*).

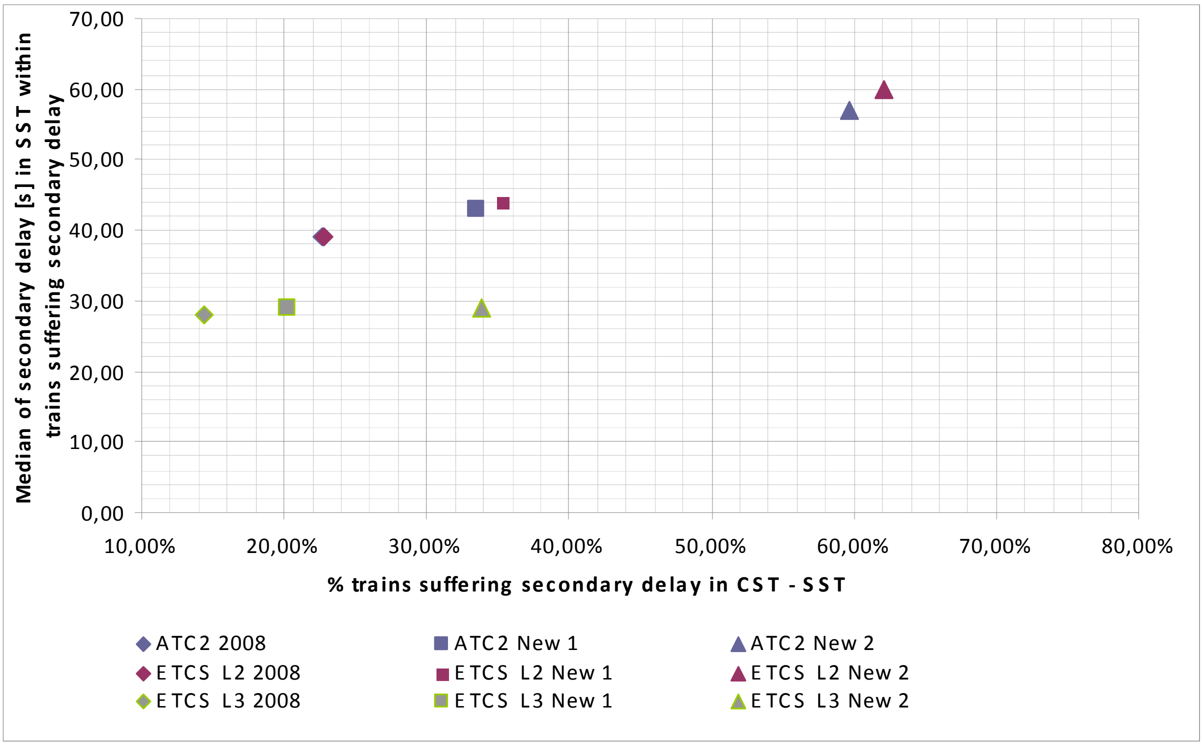


Figure 5.12 *Sensitivity of signalling systems to increased traffic load*

From *Figure 5.12* higher sensitivity to the increase of traffic flow for ATC2 and ETCS Level 2 compared with the sensitivity of ETCS Level 3 is revealed. In fact points related to the latter are more close to each other, while points concerning the other two signalling systems are more spread. With the same increase of traffic load, the ETCS Level 3 leads to a lower increase of both percentage of trains suffering secondary delay and median value of secondary delay. Moreover it can be observed the median of secondary delay in case of ETCS Level 3 is always lower than the median in case of ATC2 and ETCS Level 2, even in the scenario with the highest traffic load.

Finally, comparing ATC2 and ETCS Level 2, even if their points are very close referring to the same timetable, with ETCS Level 2 both the percentage of trains suffering secondary delay and the median value are lightly increasing more than values related to the ATC2. It might be because along the line section involving the bottleneck where block section length is optimized and the number of balises has been increased since last year, the lower value of deceleration performance of trains in ETCS scenario counts more than the not full infill with ATC2.

Capacity evaluation

With the simulation, the optimal capacity is defined by graphical approach. The target is defining one function of average unscheduled waiting times over number of trains per hour (*Figure 4.6*) according to each signalling system

Evaluations presented in previous section and focused on secondary delays were referring to an average secondary delay per train. The function shown in *Figure 4.6* is referred to the average unscheduled waiting time per time unit. Therefore it will be possible to transform the average secondary delay per train into unscheduled waiting time per time unit with the following formula:

$$ET_W\left[{}^{s}\!/_{s}\right] = \frac{AverageSecondaryDelay\left[{}^{s}\!/_{train}\right] \cdot N}{T[s]}$$

Where:

T is the time elapsed during the investigated period. For the case study this time is equal to two hours (7200 seconds)

N is the number of trains running during the investigated time window T and for which the average secondary delay [sec/train] has been calculated. Since the freight train is running in all timetable scenarios but has been excluded in previous evaluations for reasons explained in section 5.3.6, the parameter N used in the formula does not include the freight train.

In order to formulate capacity evaluations finally comparable with results coming from the theoretical application provided in Chapter 4, the same threshold of acceptable unscheduled waiting times $ET_{W,zul}$ already used there and depending on the proportion of passenger trains p_{RZ} will be considered.

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

Plotting the number of train per hour over the value of unscheduled waiting time ET_W for all nine scenarios, around these points, it is possible to define an analytical function linking the two parameters for each signalling system (*Figure 5.13*). In the same graph also the threshold value of unscheduled waiting time is plotted (this threshold is close to be constant, but it is not because the passenger trains proportion is lightly varying over the three investigated timetables).

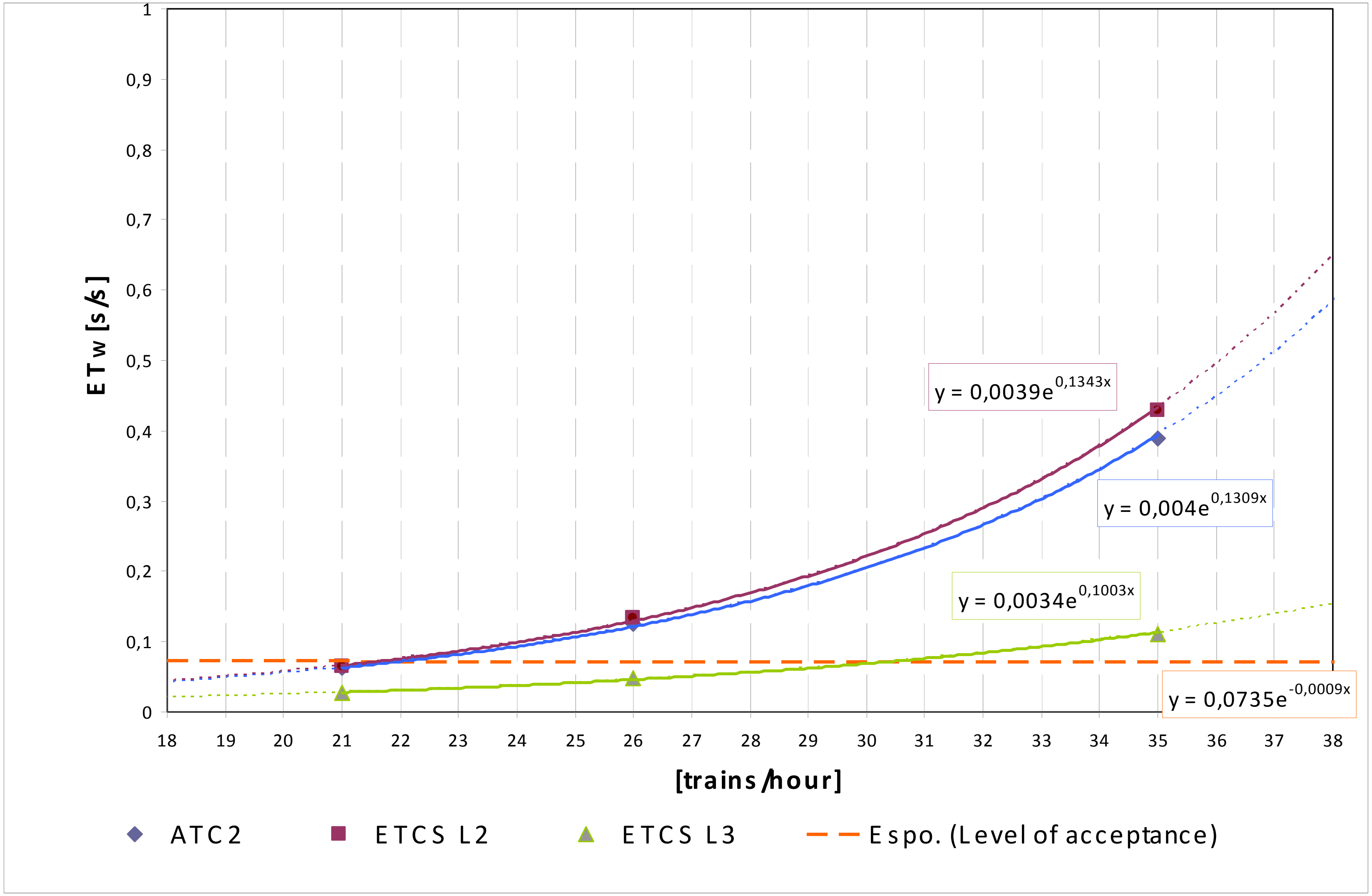


Figure 5.13 *Relation between train number and average unscheduled waiting, according to the signalling system*

By the intersection of each analytical function with the threshold line, the optimal capacity for each signalling system is defined (*Figure 5.14*).

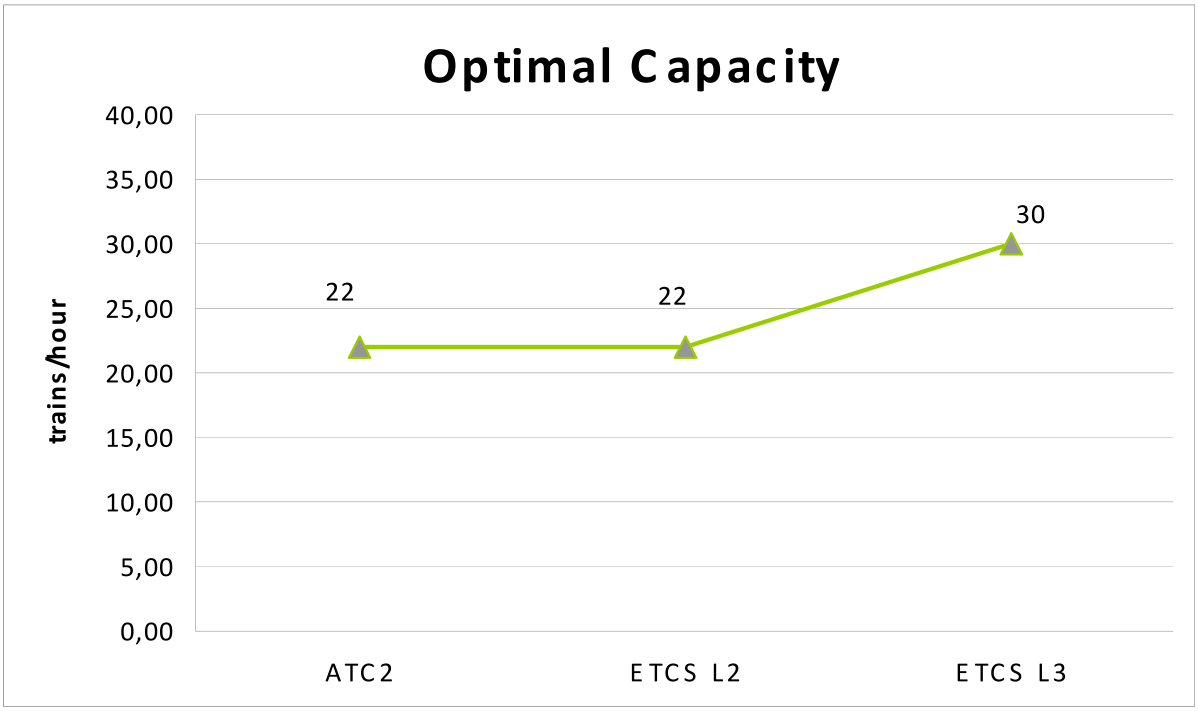


Figure 5.14 *Capacity evaluation according to signalling system by simulation results*

Findings coming from the simulation reveal that the optimal capacity that can be handled along the case study line is not increasing changing the signalling system from the actual ATC2 to the ETCS Level 2. But if the moving block (ETCS Level 3) will be applied the capacity of the line can improve of around 35%, increasing from 22 to 30 trains/hour.

Moreover these results suggest that actually over the line of the case study within the Stockholm southern network is running a number of trains (21) really close to the optimal capacity; it means the quality of operation is forced close to acceptable quality limit.

6. Conclusions

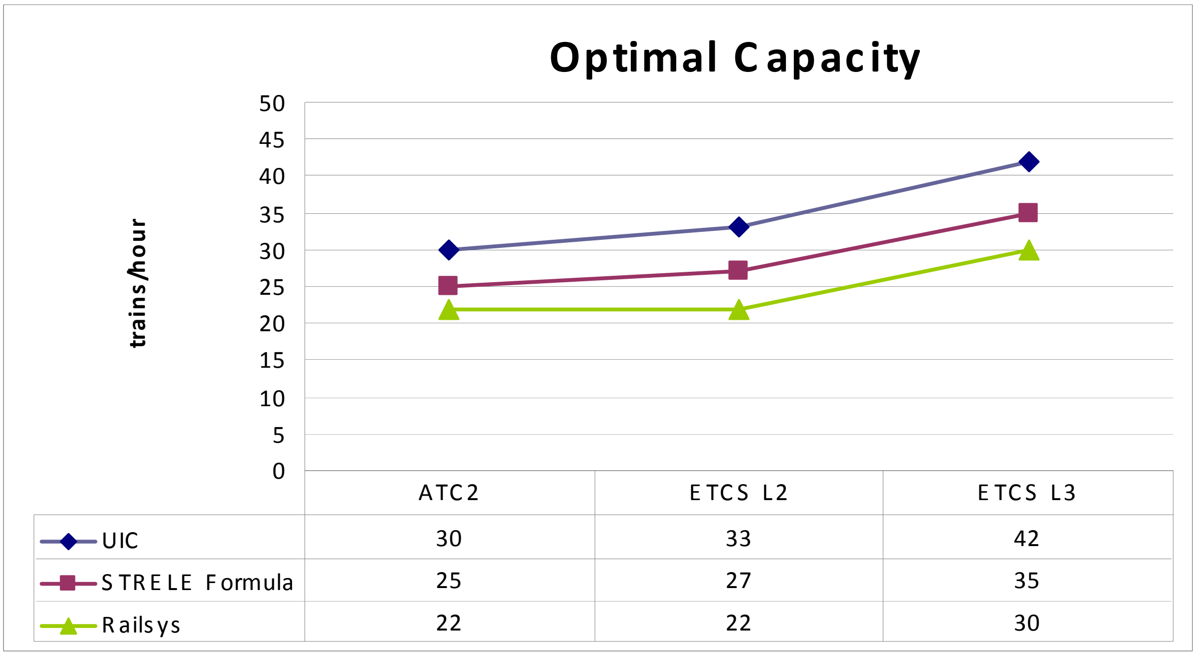
6.1 Comparison of results: theoretical application Vs simulation

Before making comparisons among results obtained from the theoretical application and from the simulation, it has to be pointed out what has been considered in different way in the two approaches. Such differences has been necessary mainly in order to simplify the application of the theoretical calculation:

- Within the theoretical application a level profile has been considered, while in simulation model gradients of line sections have been implemented in the infrastructure layout. Over all, along the bottleneck (where capacity evaluations have been carried out) the real profile is prevalently uphill, considering the investigated direction from Stockholm Central station towards Stockholm South station.
- Irregularities about driver behaviour have been taken into account in simulation approach (setting 3% standard allowance) but this factor has not been considered within the theoretical calculation.
- The utilization of tracks in Stockholm South station has been handled differently: within the theoretical calculation the inner track has been assigned at exclusively use to commuter trains, while the outer track is used only by long distance and regional trains. On the other hand, in the simulation model alternative tracks have been set at the stations, it means all trains can use both tracks according to actual needs of operation.

The first two points are favouring the theoretical approach to indicate higher performances, while the third point is helping the simulation approach. With this in mind, previous differences are considered not decisive and therefore comparisons between findings coming from the two approaches are possible.

From both theoretical application and simulation approaches findings about optimal capacity have been provided as presented respectively in previous chapters 4 and 5. The results can be presented in the same graph (*Figure 6.1*) to allow direct comparisons.



	ATC2	ETCS L2	ETCS L3
UIC	30	33	42
STRELE Formula	25	27	35
Railsys	22	22	30

Figure 6.1 *Optimal capacity results according to different methodology calculations*

Results coming from the simulation lead the lowest values of optimal capacity, while the calculation based on UIC Code show the highest values. The latter finding could be expected as already discussed in section 4.4, because with that methodology no explicit correlation to an acceptable level of quality operation based on delay data on the case study has been given, but it is just based on the recommended value of the infrastructure occupation.

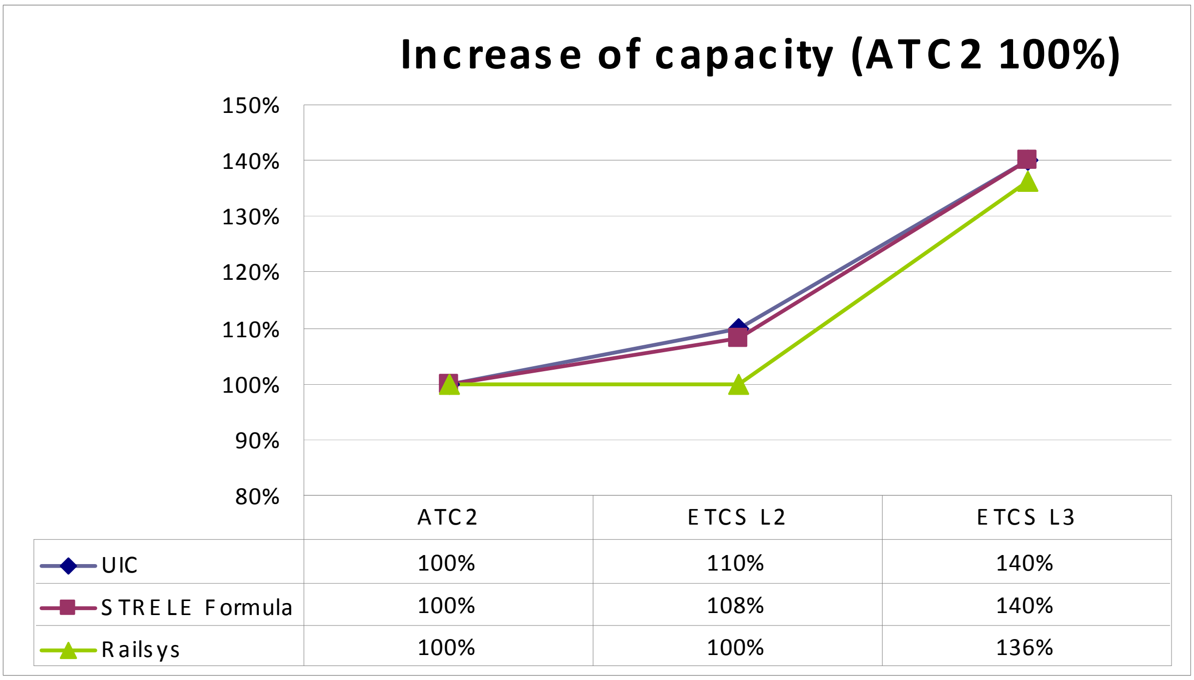
Therefore more meaningful comparisons could be done between results coming from the simulation and that from the STRELE-formula approach; in these two methods, in fact, the same reference level of service (valid for German standard railway lines) has been used in order to define the optimal capacity. Looking at the absolute results of optimal capacity, they can be affected by errors (but they are not considered significant) because the German standard might not reflect at best the level of acceptance in case of Swedish railway lines.

Nowadays common knowledge and thoughts about the railway line investigated in the case study reveal it is close to saturation. For this reason, it leads to consider simulation results more likely than that coming from the STRELE-formula approach. As a matter of fact, simulation suggested the optimal capacity in actual scenario is equal to 22 trains/hour, when actually trains running during the rush hour are 21. Even looking to the *Figure 5.15* the average of unscheduled waiting times for actual scenario are really close to the threshold represented by the limit of the acceptable level of service.

Moreover, by the theoretical approach, once again looking at the actual scenario, the result for the infrastructure occupation has been equal to 50% and that is too small considering nowadays the situation is close to be congested. In fact UIC recommended value in order to define if a line is congested or not, for the peak hour and for a line with mixed traffic, that value has to be equal to 75%. The reason of low exploitation rate could be double:

1. The optimization of block sections' length and the speed equal for all trains can lead to a lower exploitation rate even if the infrastructure is close to be congested in real.
2. One or more components of the blocking time have been underestimated as well as the average minimum headway and therefore the optimal capacity has been estimated as much as on the reality.

Plotting the percentage increase of capacity provided by the ETCS systems compared with ATC2 (*Figure 6.2*), further comparisons between theoretical and simulation results are possible.



	ATC2	ETCS L2	ETCS L3
UIC	100%	110%	140%
STRELE Formula	100%	108%	140%
Railsys	100%	100%	136%

Figure 6.2 *Increase of capacity compared with the ATC2 signalling system*

As already commented in section 4.4, by UIC and STRELE-formula the increase of capacity provided by ETCS system is approximately the same. But comparing that with Railsys results, the bigger difference is that simulation leads to the same optimal capacity for both ATC2 and ETCS Level 2, while through the theoretical approach ETCS Level 2 is giving a capacity improvement. Under a theoretical point of view, the continuous transmission made possible by ETCS Level 2 counts much more than the more restrictive braking curves, providing an increase in capacity. By simulation this improvement is not shown, it means that in real operation the two main aforementioned difference between ATC2 and ETCS Level 2 are compensating one each other, leading to the same capacity performances provided by the two discussed signalling systems.

Finally, looking at the increase in capacity due to ETCS Level 3 compared with ATC2, it is quantified more or less at the same level (around 40%) in both theoretical approach and simulation

6.2 Further study developments

Findings presented in the previous section, suggest further investigations about the impact of ETCS Level 2 and Level 3 looking at future scenario, when on 2017, the urban tunnel Citybanan will open and the bottleneck will be relieved of commuter train traffic and therefore traffic composition will change.

Moreover, results of this thesis should be implemented with the same kind of investigation extended over the entire Stockholm network, in order to be able to better evaluate if a signalling system change could be a good solution and which one must be chosen. Most of all as regards the ETCS Level 3, it revealed an important improvement over the case study line, mainly over the bottleneck, probably due to the optimal speed conditions (80 km/h); but along the line, out from the bottleneck train speed increases. Therefore it must be evaluated how much could be the improvement caused by moving block also where speed is higher than 80 km/h and where braking distance will count more in train spacing issue.

Finally, in that thesis a German standard value for the threshold of unscheduled waiting times has been used. In order to better reflect an acceptable level of service for a Swedish environment, the equation defining that limit must be correctly calibrated.

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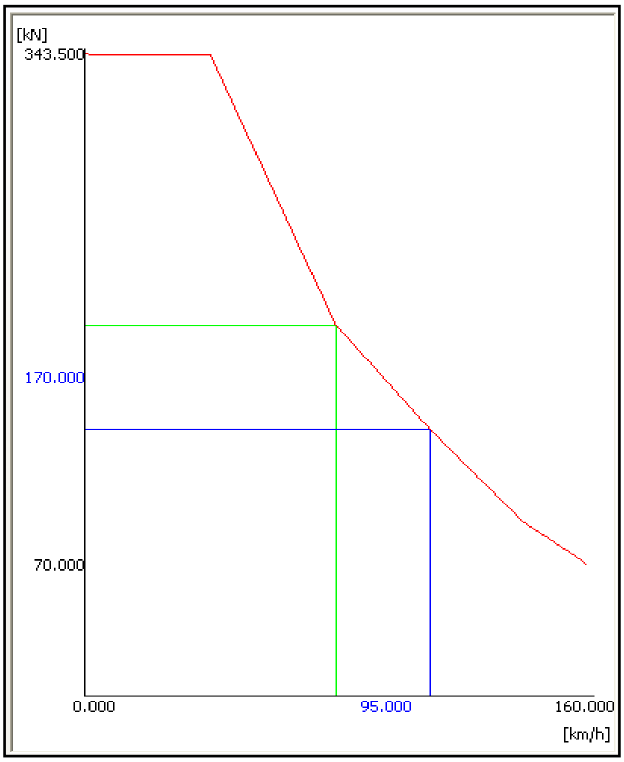
Appendix A. Characteristics of rolling socks



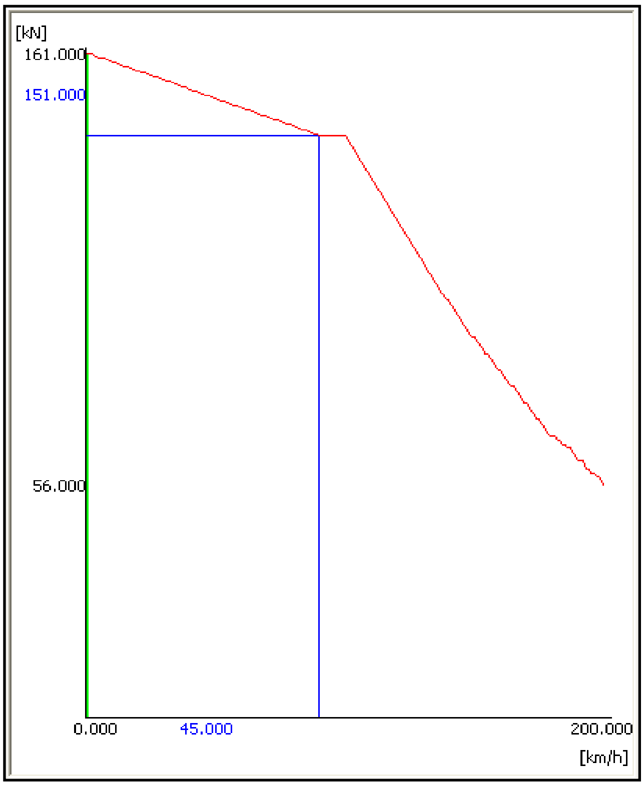
X60 Commuter train

Length: 214 m.

Mass: 206,1 ton.

V_{max}: 160 km/h.

Max traction force: 343,5 kN.



X2000 Long distance train

Length: 165 m.

Mass: 365 ton.

V_{max}: 200 km/h.

Max traction force: 161 kN.

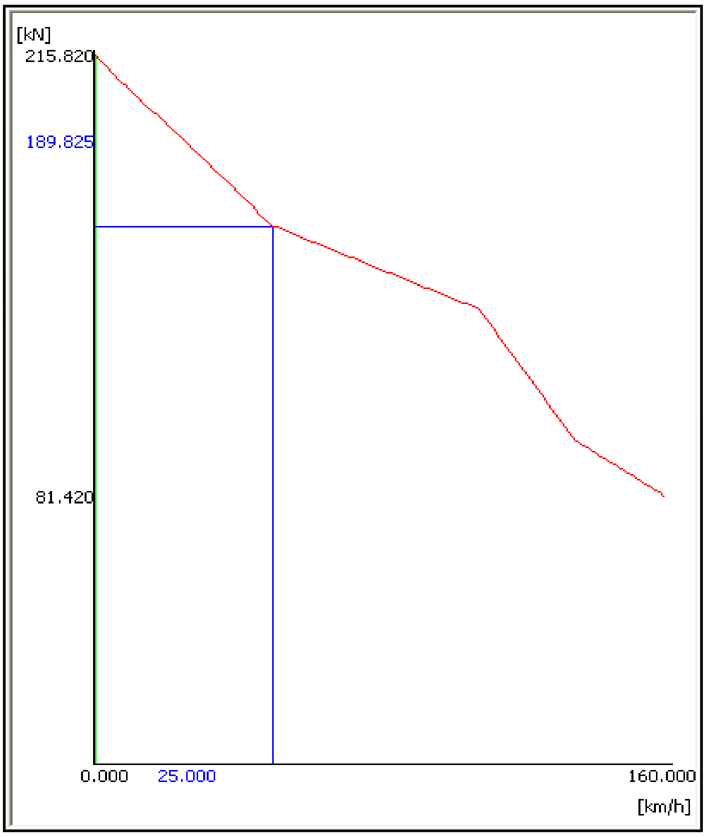
Rc6 Long distance train

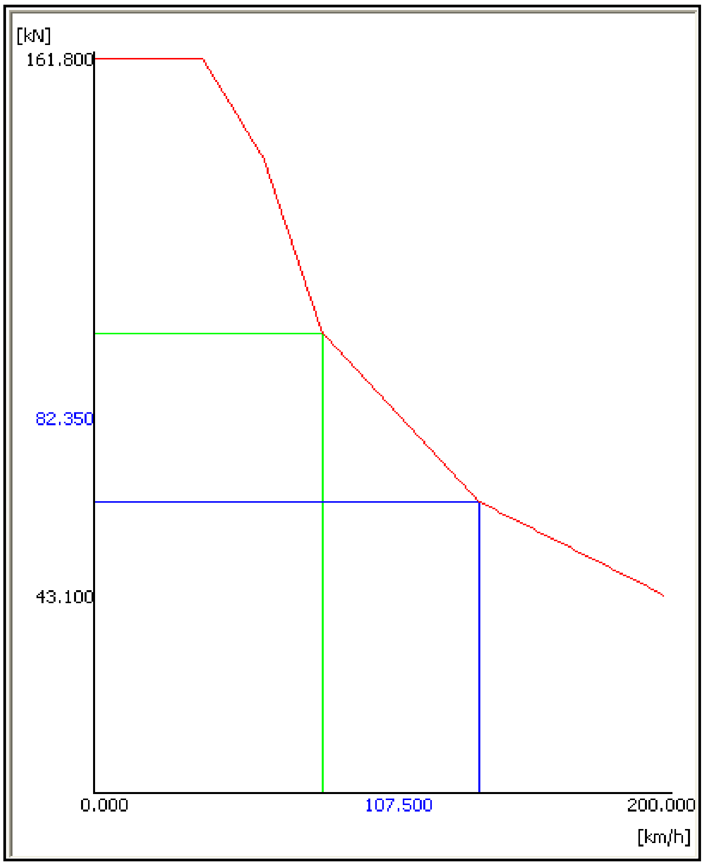
Length: 180 m.

Mass: 390 ton.

V_{max}: 160 km/h.

Max traction force: 215,82 kN.





X40 Regional train

Length: 162 m.

Mass: 216 ton.

V_{max}: 200 km/h.

Max traction force: 161,8 kN.

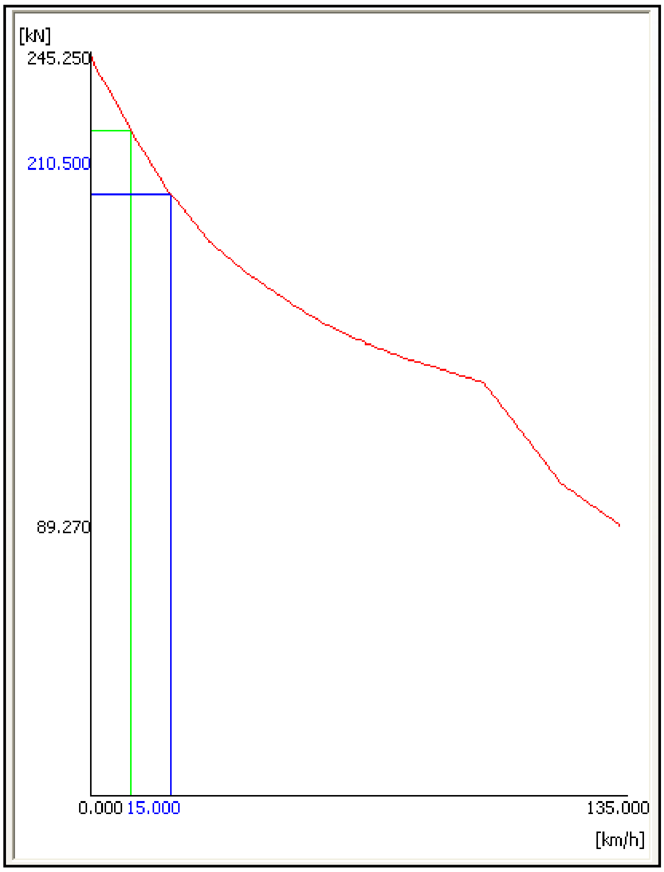
Rc4 Freight train

Length: 450 m.

Mass: 1200 ton.

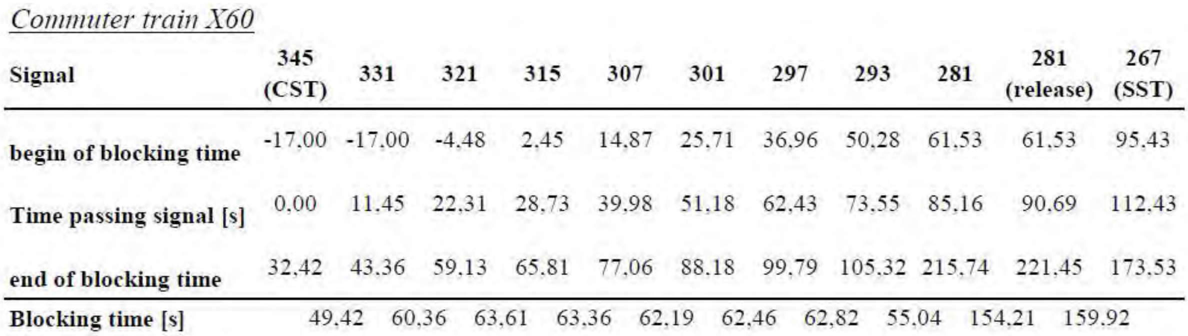
V_{max}: 135 km/h.

Max traction force: 245,25 kN.



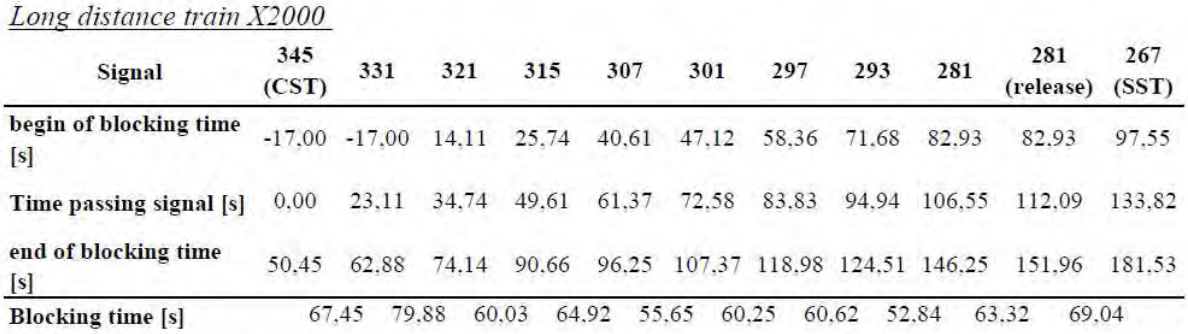
Appendix B. Blocking times

- ATC2



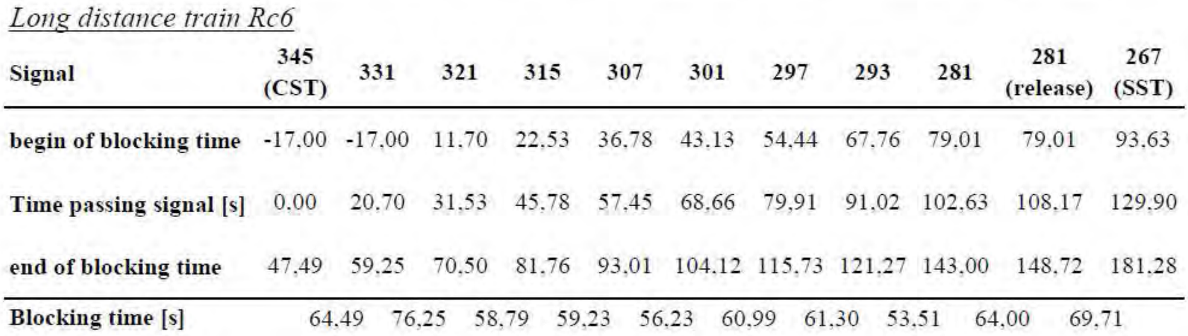
Commuter train X60

Signal	345 (CST)	331	321	315	307	301	297	293	281	281 (release)	267 (SST)
begin of blocking time	-17,00	-17,00	-4,48	2,45	14,87	25,71	36,96	50,28	61,53	61,53	95,43
Time passing signal [s]	0,00	11,45	22,31	28,73	39,98	51,18	62,43	73,55	85,16	90,69	112,43
end of blocking time	32,42	43,36	59,13	65,81	77,06	88,18	99,79	105,32	215,74	221,45	173,53
Blocking time [s]	49,42	60,36	63,61	63,36	62,19	62,46	62,82	55,04	154,21	159,92	



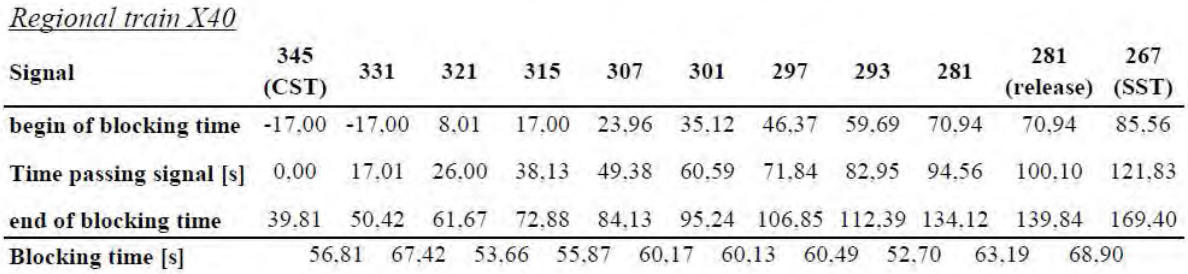
Long distance train X2000

Signal	345 (CST)	331	321	315	307	301	297	293	281	281 (release)	267 (SST)
begin of blocking time [s]	-17,00	-17,00	14,11	25,74	40,61	47,12	58,36	71,68	82,93	82,93	97,55
Time passing signal [s]	0,00	23,11	34,74	49,61	61,37	72,58	83,83	94,94	106,55	112,09	133,82
end of blocking time [s]	50,45	62,88	74,14	90,66	96,25	107,37	118,98	124,51	146,25	151,96	181,53
Blocking time [s]	67,45	79,88	60,03	64,92	55,65	60,25	60,62	52,84	63,32	69,04	



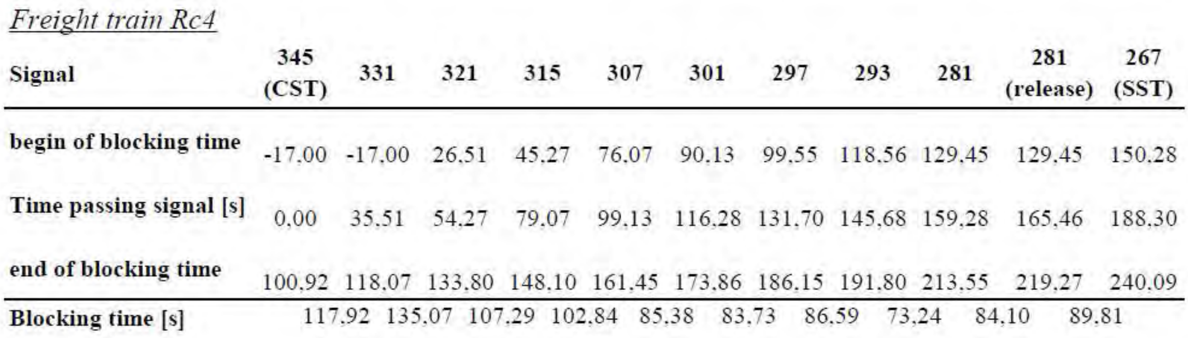
Long distance train Rc6

Signal	345 (CST)	331	321	315	307	301	297	293	281	281 (release)	267 (SST)
begin of blocking time	-17,00	-17,00	11,70	22,53	36,78	43,13	54,44	67,76	79,01	79,01	93,63
Time passing signal [s]	0,00	20,70	31,53	45,78	57,45	68,66	79,91	91,02	102,63	108,17	129,90
end of blocking time	47,49	59,25	70,50	81,76	93,01	104,12	115,73	121,27	143,00	148,72	181,28
Blocking time [s]	64,49	76,25	58,79	59,23	56,23	60,99	61,30	53,51	64,00	69,71	



Regional train X40

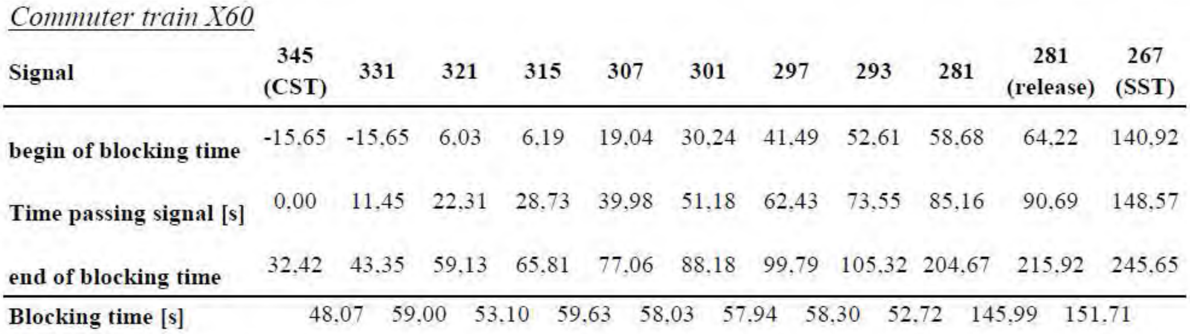
Signal	345 (CST)	331	321	315	307	301	297	293	281	281 (release)	267 (SST)
begin of blocking time	-17,00	-17,00	8,01	17,00	23,96	35,12	46,37	59,69	70,94	70,94	85,56
Time passing signal [s]	0,00	17,01	26,00	38,13	49,38	60,59	71,84	82,95	94,56	100,10	121,83
end of blocking time	39,81	50,42	61,67	72,88	84,13	95,24	106,85	112,39	134,12	139,84	169,40
Blocking time [s]	56,81	67,42	53,66	55,87	60,17	60,13	60,49	52,70	63,19	68,90	



Freight train Rc4

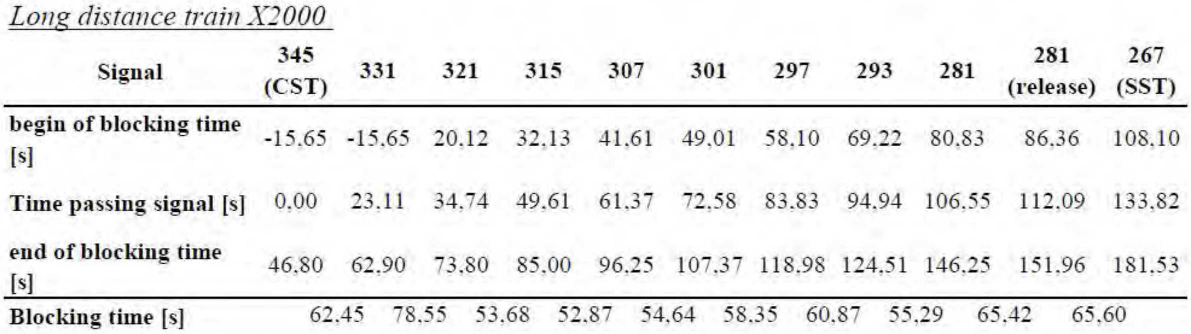
Signal	345 (CST)	331	321	315	307	301	297	293	281	281 (release)	267 (SST)
begin of blocking time	-17,00	-17,00	26,51	45,27	76,07	90,13	99,55	118,56	129,45	129,45	150,28
Time passing signal [s]	0,00	35,51	54,27	79,07	99,13	116,28	131,70	145,68	159,28	165,46	188,30
end of blocking time	100,92	118,07	133,80	148,10	161,45	173,86	186,15	191,80	213,55	219,27	240,09
Blocking time [s]	117,92	135,07	107,29	102,84	85,38	83,73	86,59	73,24	84,10	89,81	

- ETCS Level 2



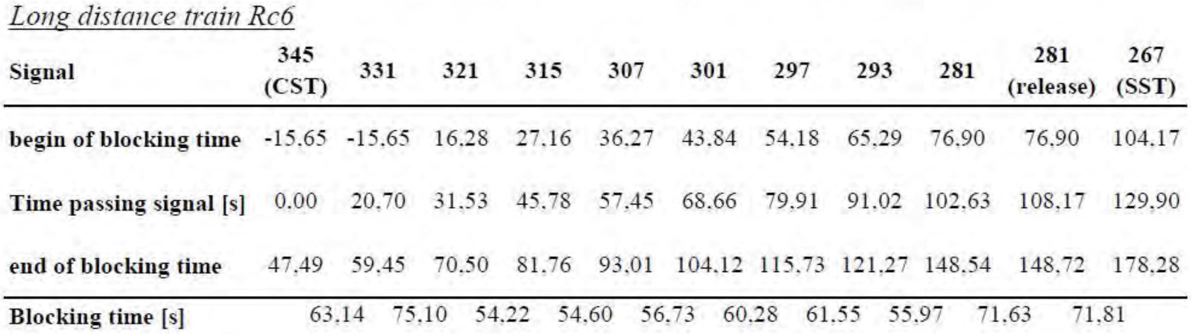
Commuter train X60

Signal	345 (CST)	331	321	315	307	301	297	293	281	281 (release)	267 (SST)
begin of blocking time	-15,65	-15,65	6,03	6,19	19,04	30,24	41,49	52,61	58,68	64,22	140,92
Time passing signal [s]	0,00	11,45	22,31	28,73	39,98	51,18	62,43	73,55	85,16	90,69	148,57
end of blocking time	32,42	43,35	59,13	65,81	77,06	88,18	99,79	105,32	204,67	215,92	245,65
Blocking time [s]	48,07	59,00	53,10	59,63	58,03	57,94	58,30	52,72	145,99	151,71	



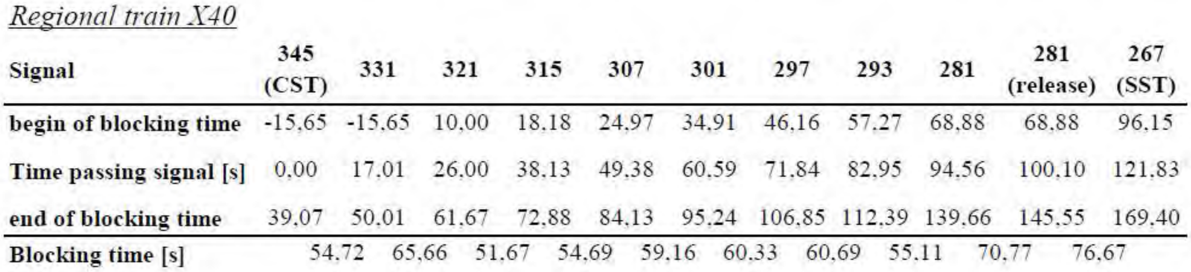
Long distance train X2000

Signal	345 (CST)	331	321	315	307	301	297	293	281	281 (release)	267 (SST)
begin of blocking time [s]	-15,65	-15,65	20,12	32,13	41,61	49,01	58,10	69,22	80,83	86,36	108,10
Time passing signal [s]	0,00	23,11	34,74	49,61	61,37	72,58	83,83	94,94	106,55	112,09	133,82
end of blocking time [s]	46,80	62,90	73,80	85,00	96,25	107,37	118,98	124,51	146,25	151,96	181,53
Blocking time [s]	62,45	78,55	53,68	52,87	54,64	58,35	60,87	55,29	65,42	65,60	



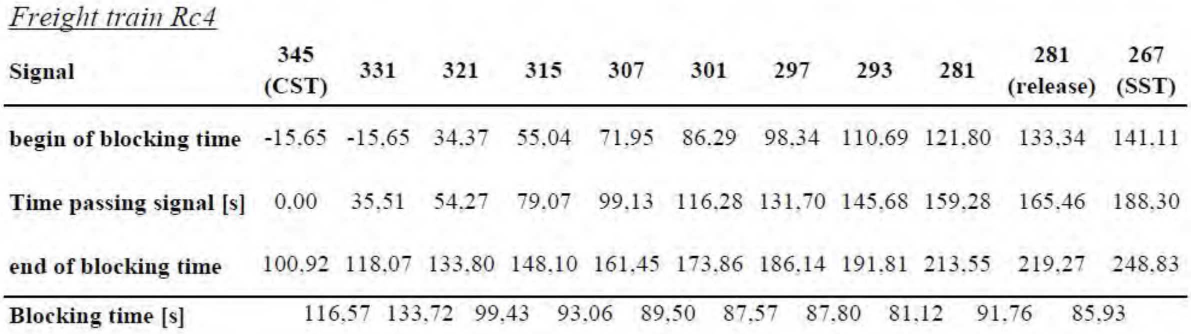
Long distance train Rc6

Signal	345 (CST)	331	321	315	307	301	297	293	281	281 (release)	267 (SST)
begin of blocking time	-15,65	-15,65	16,28	27,16	36,27	43,84	54,18	65,29	76,90	76,90	104,17
Time passing signal [s]	0,00	20,70	31,53	45,78	57,45	68,66	79,91	91,02	102,63	108,17	129,90
end of blocking time	47,49	59,45	70,50	81,76	93,01	104,12	115,73	121,27	148,54	148,72	178,28
Blocking time [s]	63,14	75,10	54,22	54,60	56,73	60,28	61,55	55,97	71,63	71,81	



Regional train X40

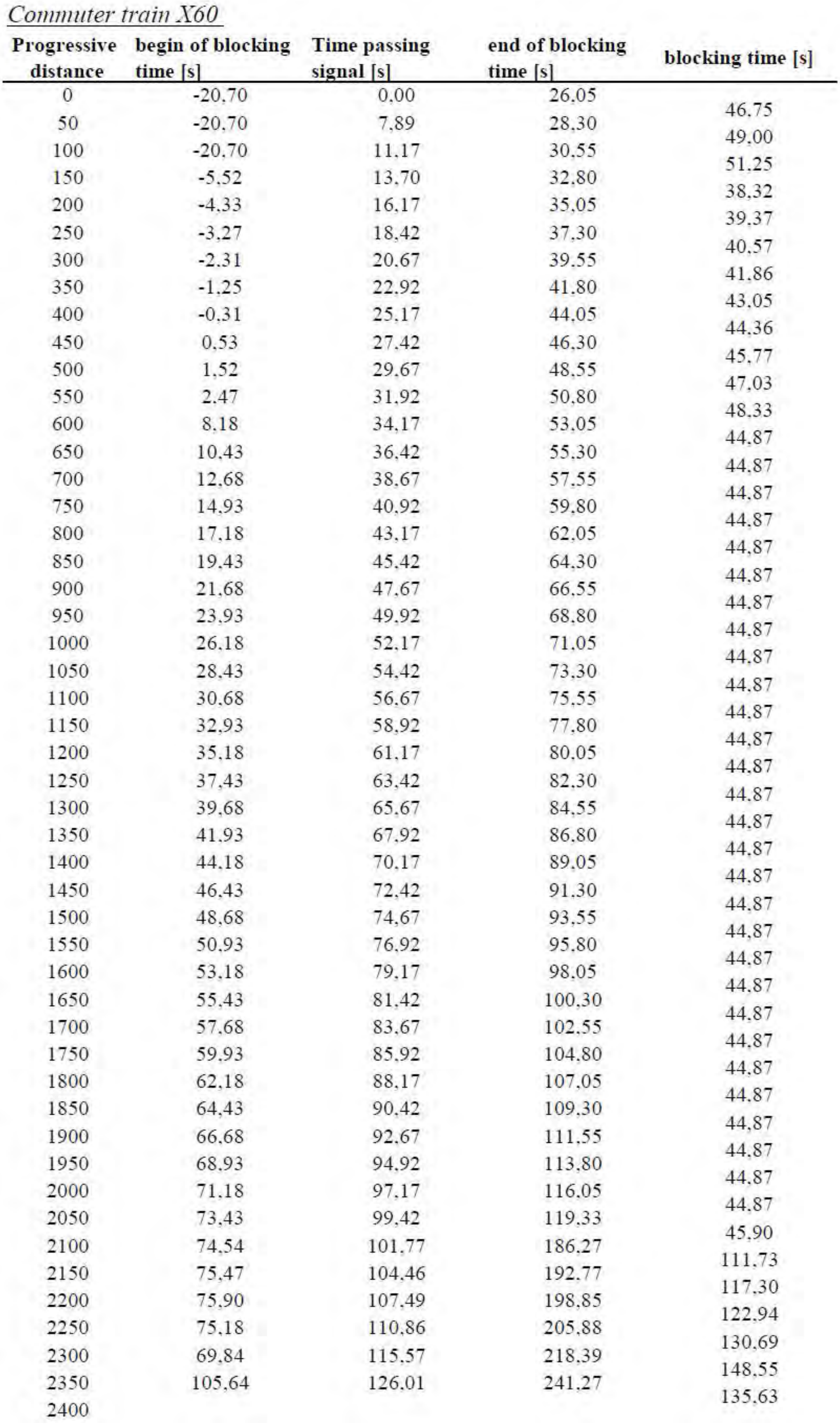
Signal	345 (CST)	331	321	315	307	301	297	293	281	281 (release)	267 (SST)
begin of blocking time	-15,65	-15,65	10,00	18,18	24,97	34,91	46,16	57,27	68,88	68,88	96,15
Time passing signal [s]	0,00	17,01	26,00	38,13	49,38	60,59	71,84	82,95	94,56	100,10	121,83
end of blocking time	39,07	50,01	61,67	72,88	84,13	95,24	106,85	112,39	139,66	145,55	169,40
Blocking time [s]	54,72	65,66	51,67	54,69	59,16	60,33	60,69	55,11	70,77	76,67	



Freight train Rc4

Signal	345 (CST)	331	321	315	307	301	297	293	281	281 (release)	267 (SST)
begin of blocking time	-15,65	-15,65	34,37	55,04	71,95	86,29	98,34	110,69	121,80	133,34	141,11
Time passing signal [s]	0,00	35,51	54,27	79,07	99,13	116,28	131,70	145,68	159,28	165,46	188,30
end of blocking time	100,92	118,07	133,80	148,10	161,45	173,86	186,14	191,81	213,55	219,27	248,83
Blocking time [s]	116,57	133,72	99,43	93,06	89,50	87,57	87,80	81,12	91,76	85,93	

- ETCS Level 3



Commuter train X60

Progressive distance	begin of blocking time [s]	Time passing signal [s]	end of blocking time [s]	blocking time [s]
0	-20,70	0,00	26,05	46,75
50	-20,70	7,89	28,30	49,00
100	-20,70	11,17	30,55	51,25
150	-5,52	13,70	32,80	38,32
200	-4,33	16,17	35,05	39,37
250	-3,27	18,42	37,30	40,57
300	-2,31	20,67	39,55	41,86
350	-1,25	22,92	41,80	43,05
400	-0,31	25,17	44,05	44,36
450	0,53	27,42	46,30	45,77
500	1,52	29,67	48,55	47,03
550	2,47	31,92	50,80	48,33
600	8,18	34,17	53,05	44,87
650	10,43	36,42	55,30	44,87
700	12,68	38,67	57,55	44,87
750	14,93	40,92	59,80	44,87
800	17,18	43,17	62,05	44,87
850	19,43	45,42	64,30	44,87
900	21,68	47,67	66,55	44,87
950	23,93	49,92	68,80	44,87
1000	26,18	52,17	71,05	44,87
1050	28,43	54,42	73,30	44,87
1100	30,68	56,67	75,55	44,87
1150	32,93	58,92	77,80	44,87
1200	35,18	61,17	80,05	44,87
1250	37,43	63,42	82,30	44,87
1300	39,68	65,67	84,55	44,87
1350	41,93	67,92	86,80	44,87
1400	44,18	70,17	89,05	44,87
1450	46,43	72,42	91,30	44,87
1500	48,68	74,67	93,55	44,87
1550	50,93	76,92	95,80	44,87
1600	53,18	79,17	98,05	44,87
1650	55,43	81,42	100,30	44,87
1700	57,68	83,67	102,55	44,87
1750	59,93	85,92	104,80	44,87
1800	62,18	88,17	107,05	44,87
1850	64,43	90,42	109,30	44,87
1900	66,68	92,67	111,55	44,87
1950	68,93	94,92	113,80	44,87
2000	71,18	97,17	116,05	44,87
2050	73,43	99,42	119,33	45,90
2100	74,54	101,77	186,27	111,73
2150	75,47	104,46	192,77	117,30
2200	75,90	107,49	198,85	122,94
2250	75,18	110,86	205,88	130,69
2300	69,84	115,57	218,39	148,55
2350	105,64	126,01	241,27	135,63
2400				

Long distance train X2000

Progressive distance	begin of blocking time [s]	Time passing signal [s]	end of blocking time [s]	blocking time [s]
0	-20,70	0,00	40,09	60,79
50	-20,70	7,89	43,81	64,51
100	-20,70	11,17	47,17	67,87
150	9,54	13,70	50,30	40,76
200	12,95	16,17	53,23	40,28
250	15,97	18,42	55,99	40,02
300	18,80	20,67	58,62	39,82
350	21,09	22,92	61,13	40,04
400	23,60	25,17	63,53	39,93
450	25,68	27,42	65,11	39,43
500	27,99	29,67	67,61	39,62
550	29,99	31,92	69,99	39,99
600	31,79	34,17	72,27	40,48
650	33,75	36,42	75,45	41,69
700	35,48	38,67	76,74	41,27
750	37,25	40,92	78,99	41,74
800	38,92	43,17	81,24	42,33
850	40,53	45,42	83,49	42,96
900	42,25	47,67	85,74	43,50
950	43,73	49,92	87,99	44,26
1000	45,22	52,17	90,24	45,02
1050	46,90	54,42	92,49	45,59
1100	47,29	56,67	94,74	47,45
1150	49,54	58,92	96,99	47,45
1200	51,79	61,17	99,24	47,45
1250	54,04	63,42	101,49	47,45
1300	56,29	65,67	103,74	47,45
1350	58,54	67,92	105,99	47,45
1400	60,79	70,17	108,24	47,45
1450	63,04	72,42	110,49	47,45
1500	65,29	74,67	112,74	47,45
1550	67,54	76,92	114,99	47,45
1600	69,79	79,17	117,24	47,45
1650	72,04	81,42	119,49	47,45
1700	74,29	83,67	121,74	47,45
1750	76,54	85,92	123,99	47,45
1800	78,79	88,17	126,24	47,45
1850	81,04	90,42	128,49	47,45
1900	83,29	92,67	130,74	47,45
1950	85,54	94,92	132,99	47,45
2000	87,79	97,17	135,24	47,45
2050	90,04	99,42	137,49	47,45
2100	92,29	101,77	139,74	47,45
2150	94,54	104,46	141,99	47,45
2200	96,79	107,49	144,24	47,45
2250	99,04	110,86	146,49	47,45
2300	101,29	115,57	148,74	47,45
2350	103,54	126,01	150,99	47,45
2400				

Long distance train Rc6

Progressive distance	begin of blocking time [s]	Time passing signal [s]	end of blocking time [s]	blocking time [s]
0	-20,70	0,00	38,11	58,81
50	-20,70	14,15	41,49	62,19
100	-20,70	20,19	44,60	65,30
150	6,01	24,90	47,53	41,52
200	9,32	28,91	50,27	40,95
250	11,97	32,49	52,86	40,89
300	14,47	35,76	55,34	40,87
350	16,85	38,78	57,71	40,85
400	19,01	41,61	59,99	40,98
450	21,11	44,29	61,98	40,86
500	23,11	46,83	64,41	41,30
550	25,07	49,26	66,74	41,67
600	26,83	51,59	69,05	42,22
650	28,53	53,90	71,25	42,72
700	30,11	56,15	73,50	43,39
750	31,85	58,40	75,75	43,90
800	33,38	60,65	78,00	44,62
850	34,97	62,90	80,25	45,28
900	36,56	65,15	82,50	45,94
950	37,97	67,40	84,75	46,78
1000	39,34	69,65	87,00	47,66
1050	41,12	71,90	89,25	48,13
1100	43,37	74,15	91,50	48,13
1150	45,62	76,40	93,75	48,13
1200	47,87	78,65	96,00	48,13
1250	50,12	80,90	98,25	48,13
1300	52,37	83,15	100,50	48,13
1350	54,62	85,40	102,75	48,13
1400	56,87	87,65	105,00	48,13
1450	59,12	89,90	107,25	48,13
1500	61,37	92,15	109,50	48,13
1550	63,62	94,40	111,75	48,13
1600	65,87	96,65	114,00	48,13
1650	68,12	98,90	116,25	48,13
1700	70,37	101,15	118,50	48,13
1750	72,62	103,40	120,75	48,13
1800	74,87	105,65	123,00	48,13
1850	77,12	107,90	125,25	48,13
1900	79,37	110,15	127,50	48,13
1950	81,62	112,40	129,75	48,13
2000	83,87	114,65	132,00	48,13
2050	86,12	116,90	134,25	48,13
2100	88,37	119,15	136,50	48,13
2150	90,62	121,40	138,75	48,13
2200	92,87	123,65	141,00	48,13
2250	95,12	125,90	143,25	48,13
2300	97,37	128,15	145,50	48,13
2350	99,62	130,40	147,75	48,13
2400				

Regional train X40

Progressive distance	begin of blocking time [s]	Time passing signal [s]	end of blocking time [s]	blocking time [s]
0	-20,70	0,00	31,50	52,20
50	-20,70	11,53	34,33	55,03
100	-20,70	16,58	36,94	57,64
150	1,61	20,51	39,38	37,77
200	3,63	23,84	41,72	38,09
250	5,50	26,80	43,78	38,27
300	7,36	29,49	46,26	38,90
350	8,93	31,97	48,58	39,65
400	10,59	34,29	51,12	40,53
450	12,10	36,83	53,37	41,27
500	13,58	39,08	55,62	42,03
550	15,11	41,33	57,87	42,76
600	16,52	43,58	60,12	43,59
650	17,83	45,83	62,37	44,53
700	19,35	48,08	64,62	45,27
750	20,53	50,33	66,87	46,34
800	22,05	52,58	69,12	47,07
850	24,10	54,83	71,37	47,27
900	26,35	57,08	73,62	47,27
950	28,60	59,33	75,87	47,27
1000	30,85	61,58	78,12	47,27
1050	33,10	63,83	80,37	47,27
1100	35,35	66,08	82,62	47,27
1150	37,60	68,33	84,87	47,27
1200	39,85	70,58	87,12	47,27
1250	42,10	72,83	89,37	47,27
1300	44,35	75,08	91,62	47,27
1350	46,60	77,33	93,87	47,27
1400	48,85	79,58	96,12	47,27
1450	51,10	81,83	98,37	47,27
1500	53,35	84,08	100,62	47,27
1550	55,60	86,33	102,87	47,27
1600	57,85	88,58	105,12	47,27
1650	60,10	90,83	107,37	47,27
1700	62,35	93,08	109,62	47,27
1750	64,60	95,33	111,87	47,27
1800	66,85	97,58	114,12	47,27
1850	69,10	99,83	116,37	47,27
1900	71,35	102,08	118,62	47,27
1950	73,60	104,33	120,87	47,27
2000	75,85	106,58	123,12	47,27
2050	78,10	108,83	125,37	47,27
2100	80,35	111,08	127,62	47,27
2150	82,60	113,33	129,87	47,27
2200	84,85	115,58	132,12	47,27
2250	87,10	117,83	134,37	47,27
2300	89,35	120,08	136,62	47,27
2350	91,60	122,33	138,87	47,27
2400				

Freight train Rc4

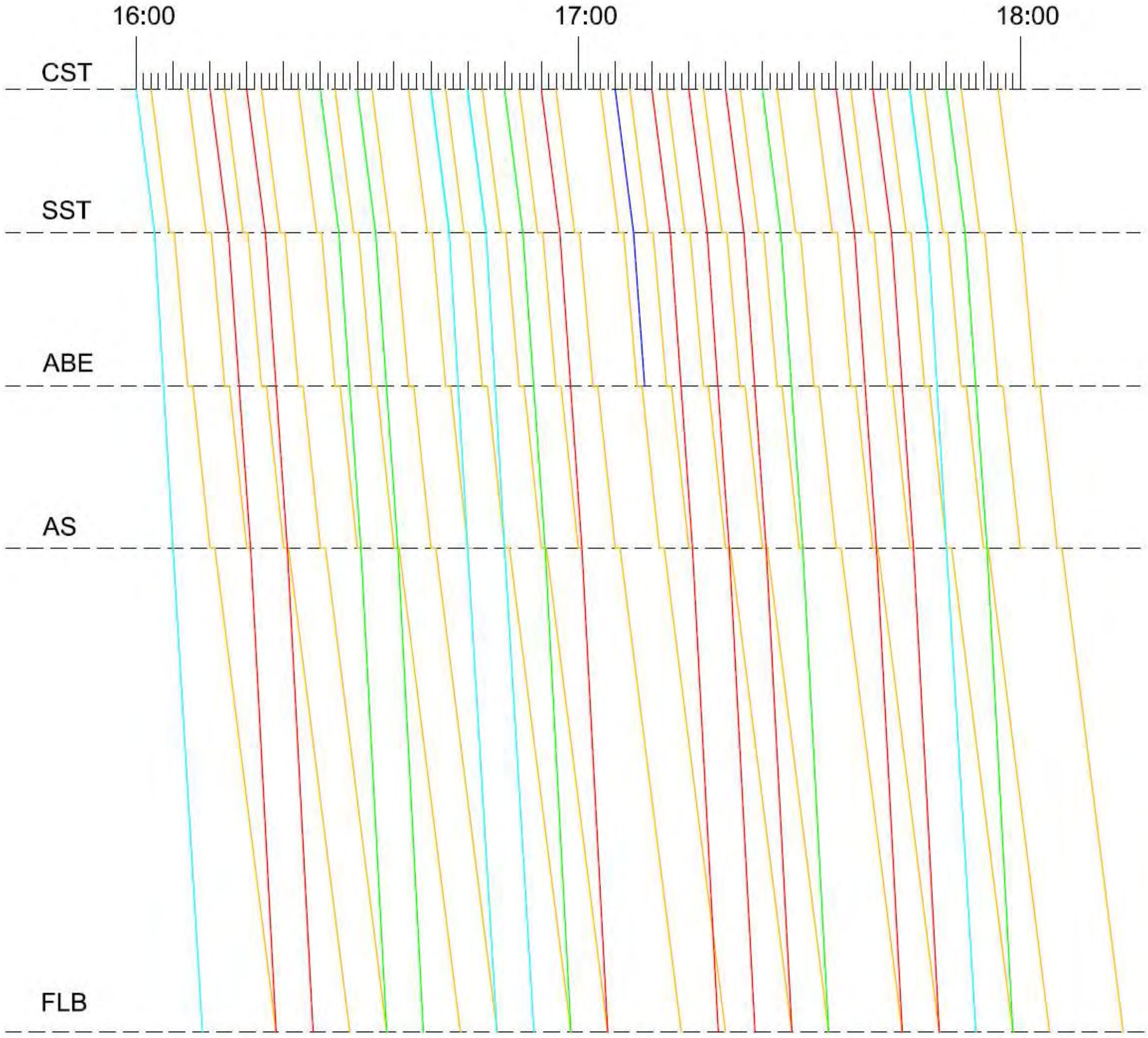
Progressive distance	begin of blocking time [s]	Time passing signal [s]	end of blocking time [s]	blocking time [s]
0	-20,70	0,00	87,90	108,60
50	-20,70	24,26	92,15	112,85
100	-20,70	34,73	96,24	116,94
150	21,13	42,89	100,29	79,16
200	25,50	49,87	104,12	78,61
250	30,96	56,09	107,81	76,85
300	36,54	61,78	111,41	74,87
350	39,77	67,04	114,91	75,14
400	44,61	71,99	118,32	73,71
450	48,56	76,66	121,65	73,09
500	51,79	81,11	124,91	73,12
550	54,89	85,37	128,09	73,20
600	58,84	89,46	131,21	72,37
650	61,23	93,40	134,27	73,05
700	65,80	97,22	137,28	71,47
750	68,45	100,91	140,23	71,78
800	71,54	100,19	143,65	72,11
850	74,37	107,99	146,00	71,63
900	76,81	111,40	148,81	72,01
950	79,19	114,73	151,58	72,39
1000	82,66	117,98	154,32	71,65
1050	84,94	121,16	157,02	72,08
1100	87,89	124,28	159,67	71,78
1150	90,78	127,34	162,30	71,52
1200	92,21	130,35	164,90	72,69
1250	95,34	133,30	167,46	72,11
1300	98,07	136,20	169,98	71,91
1350	100,10	139,06	172,49	72,39
1400	102,74	141,87	174,96	72,22
1450	105,01	144,64	177,42	72,41
1500	107,25	147,37	179,84	72,59
1550	109,77	150,07	182,24	72,47
1600	111,64	152,73	184,61	72,98
1650	113,49	155,36	186,97	73,48
1700	116,50	157,95	189,29	72,79
1750	118,00	160,50	191,60	73,60
1800	120,36	163,03	193,90	73,54
1850	122,98	165,54	196,17	73,18
1900	124,14	168,01	198,42	74,29
1950	126,41	170,46	200,67	74,26
2000	128,95	172,88	202,93	73,98
2050	130,90	175,28	205,19	74,29
2100	133,38	177,66	207,44	74,06
2150	134,73	180,01	209,69	74,96
2200	136,63	182,34	211,95	75,32
2250	139,30	184,65	214,20	74,90
2300	140,35	186,94	216,45	76,10
2350	142,71	189,21	218,71	76,00
2400				

Appendix C. Graphical timetables

Timetable 2008

Legend:

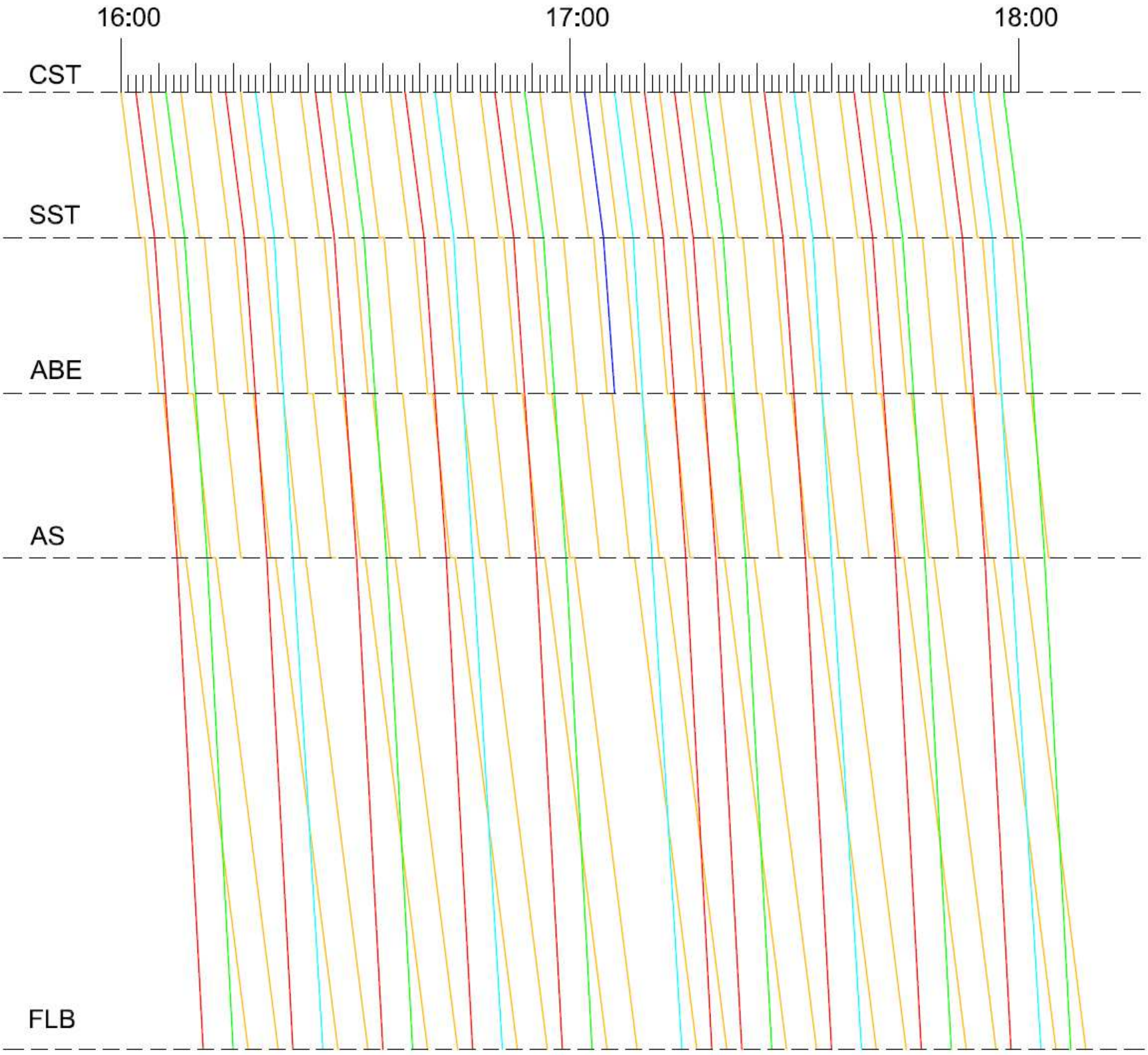
—	Commuter train X60
—	Long distance train X2000
—	Long distance train Rc6
—	Regional train X40
—	Freight train Rc4



Timetable New 1

Legend:

— Commuter train X60
— Long distance train X2000
— Long distance train Rc6
— Regional train X40
— Freight train Rc4



Timetable New 2

Legend:

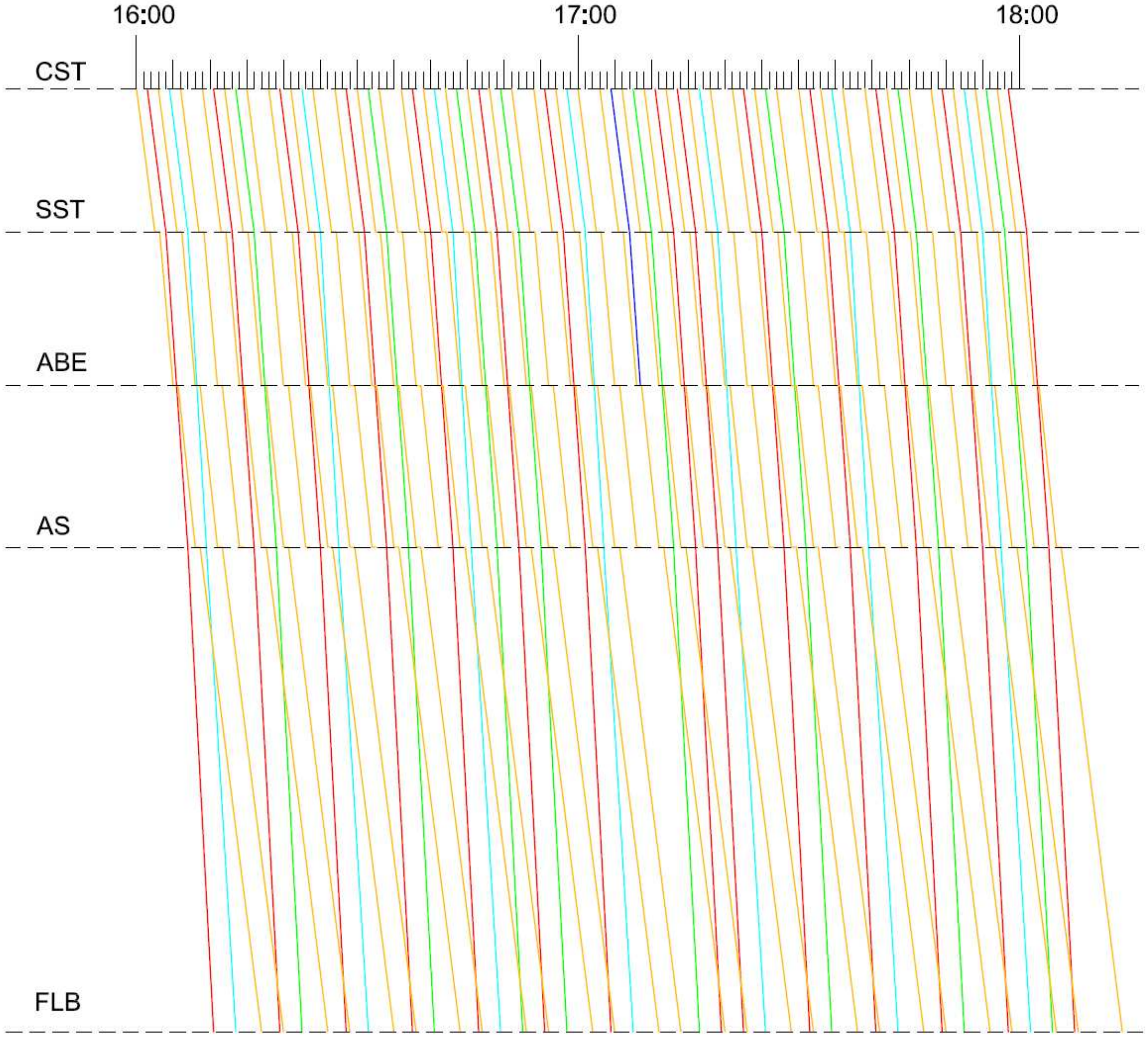
— Commuter train X60

— Long distance train X2000

— Long distance train Rc6

— Regional train X40

— Freight train Rc4



Appendix D. Entry delay distributions

Commuter train X60

Lateness [s]	Number of trains
0	9
6	322
11	293
16	312
21	327
25	269
30	344
34	278
38	279
42	278
47	343
51	268
56	324
61	309
66	291
71	273
77	306
84	330
90	260
98	318
106	288
115	293
126	320
137	285
150	296
166	311
184	294
206	295
235	303
273	296
323	298
397	301
538	298
1058	299
3720	91

Long distance train X2000

Lateness [s]	Number of trains
0	108
4	317
7	307
10	298
13	289
17	371
20	268
23	260
27	333
31	318
35	304
39	290
43	277
48	327
52	248
58	349
63	270
69	302
75	278
82	296
90	303
99	301
110	316
122	288
137	292
158	310
186	298
223	293
283	303
355	296
497	300
706	301
1416	300
3720	292

Long distance train Rc6

Lateness [s]	Number of trains
0	895
5	311
10	330
14	275
19	355
23	291
27	295
31	297
35	297
39	296
43	292
47	287
51	280
56	336
61	319
65	240
71	336
77	309
83	282
90	298
98	301
107	292
118	295
132	291
153	303
183	292
217	301
266	299
355	300
549	300
1137	299
3720	105

Regional train X40

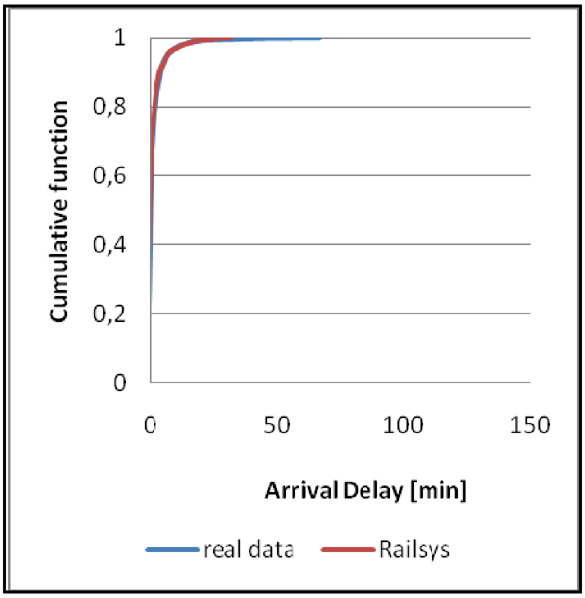
Lateness [s]	Number of trains
0	864
6	302
12	321
17	279
23	344
28	291
33	292
38	290
43	285
49	332
54	265
60	300
67	319
74	288
82	295
92	323
102	280
115	312
129	288
146	299
167	307
192	299
222	297
256	295
296	302
351	299
421	300
519	298
684	300
1061	299
2017	300
3720	136

Freight train Rc4

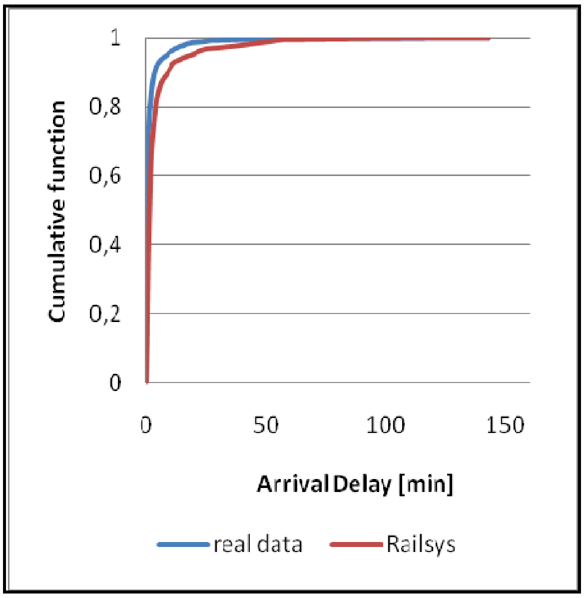
Lateness [s]	Number of trains
0	5849
12	319
72	284
103	298
132	308
171	296
220	298
265	298
333	299
449	301
596	300
940	299
1578	300
2643	300
7320	251

Appendix E. Validation

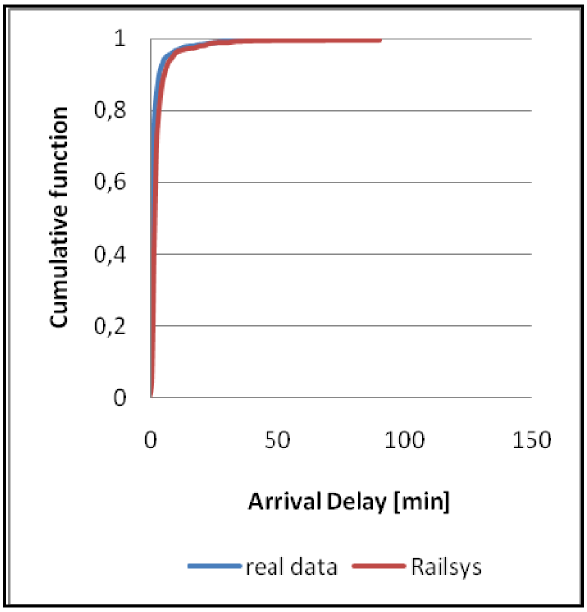
Commuter train X60



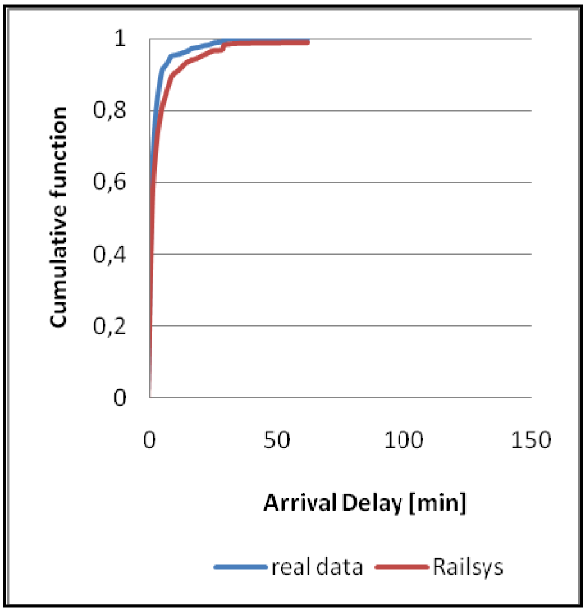
Long distance train X2000



Long distance train Rc6

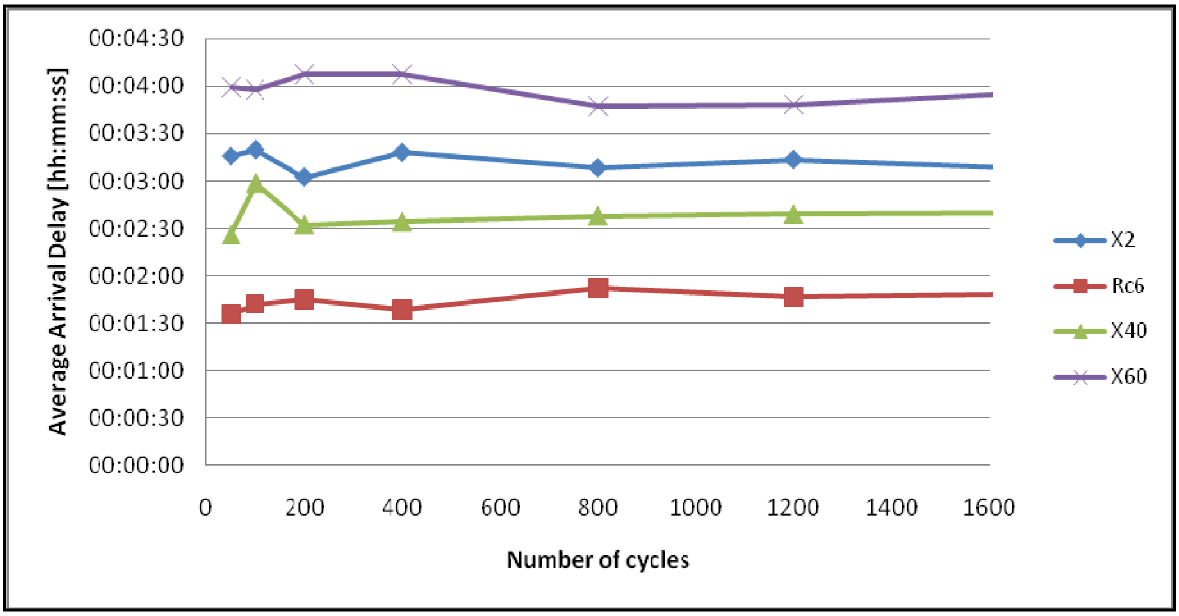


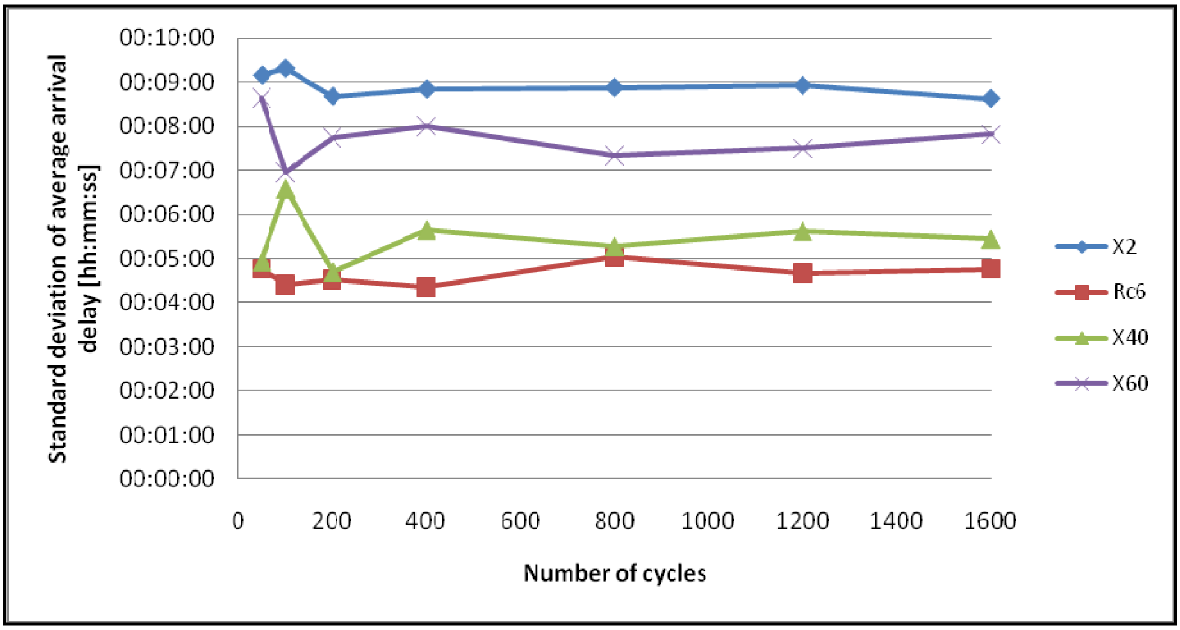
Regional train X40



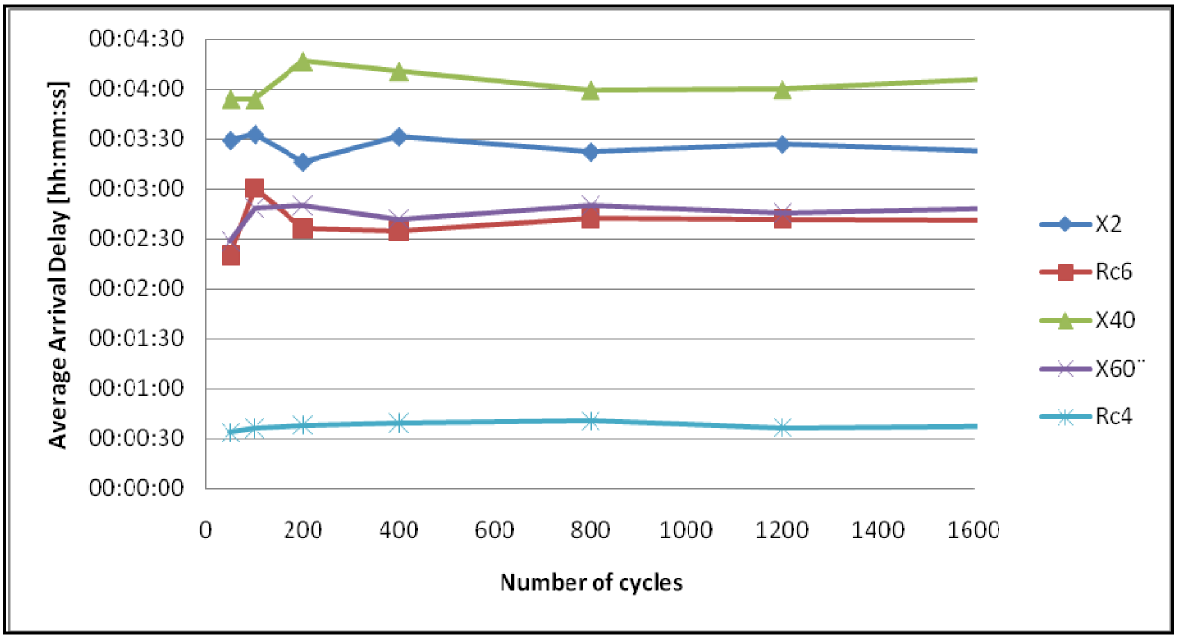
Appendix F. Number of replications

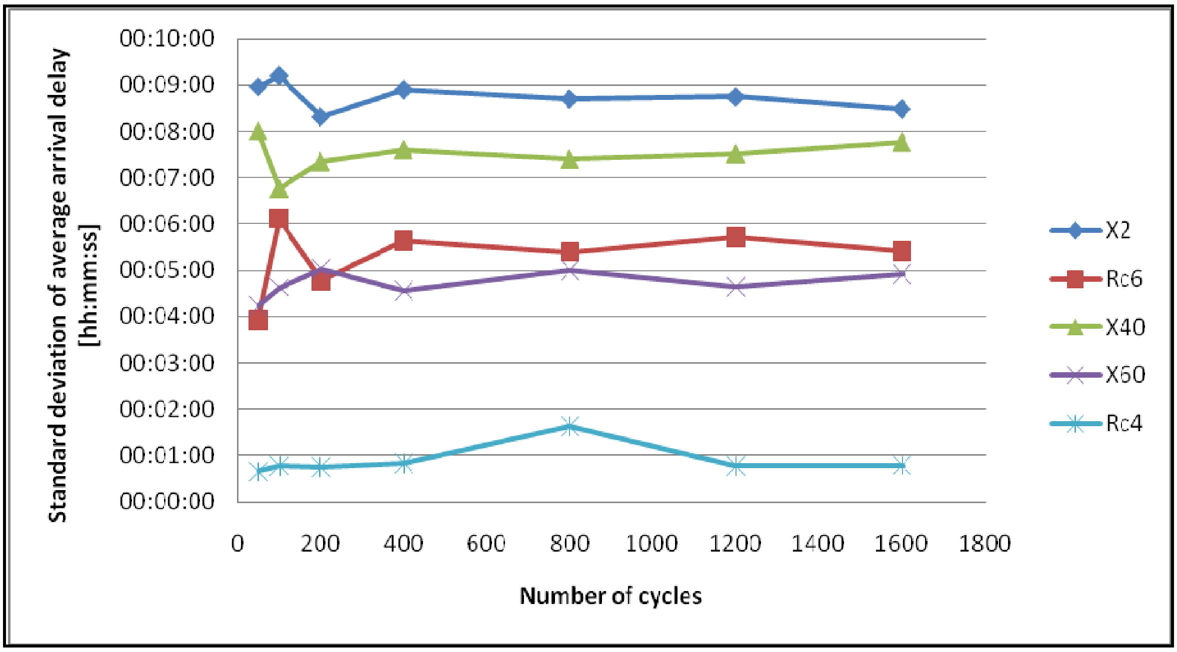
In Flemingsberg





In Stockholm South Station


Average Arrival Delay [hh:mm:ss]
00:04:30
00:04:00
00:03:30
00:03:00
00:02:30
00:02:00
00:01:30
00:01:00
00:00:30
00:00:00
0
200
400
600
800
1000
1200
1400
1600
Number of cycles
X2
Rc6
X40
X60¨
Rc4


Standard deviation of average arrival delay [hh:mm:ss]
00:10:00
00:09:00
00:08:00
00:07:00
00:06:00
00:05:00
00:04:00
00:03:00
00:02:00
00:01:00
00:00:00
0
200
400
600
800
1000
1200
1400
1600
1800
Number of cycles
X2
Rc6
X40
X60
Rc4

TEC-MT 10-010

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