



KTH Railway group

Transportation and Logistics

Master thesis

**Strategic analysis about railway signalling system
evolution to ETCS level 2 and 3**

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PREFACE

To accomplish this work I counted with the indispensable cooperation of some people that, direct or indirectly, contributed to the final result. To those people I must acknowledge my deep and sincere thanks.

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SUMMARY

The railway had an enormous importance in the last two centuries of human history as one of the most important elements in the industrial revolution, the late eighteenth century and during the nineteenth century. Around the railway stations were born and developed cities, which were linked to other cities, regions and countries. [1]

At the end of the twentieth century the railways were losing some notoriety for road and air transport. This was due, perhaps, the increased throughout the world of better roads, bigger and better supply of road vehicles and increased supply of air transport. It might be considered that the decreasing importance of rail transport was due to greater evidence of its weaknesses, as poor flexibility, inflexible schedules, high costs of maintenance and handling.

Today, beginning of twenty one century appears the energy concerns and sustainability, where rail can and should have greater importance, is expected to be again a reference to the different means of transport, because in the last years has evolved such which is considered a means of transport energy efficient, safe and reliable. Currently the train is considered the most environmentally choice as transportation.

Thus, the evolution of rail produced the emergence of new and more advanced control systems and operation of trains. With this evolution emerged new doubts about paths hereinafter to the rail modernization.

New and modern signalling systems are costly in the implementation, but in turn, lead to reduced costs of maintenance of such systems, providing increased speed of the trains and increasing the capacity of lines.

In many countries questions arise on this theme. Will it be feasible to modify existing lines, implementing new systems of train control, ETCS (European Train Control System)? Will be profitable, the costs of these new control systems by comparing them with their gains in capacity and speed of the lines? These new systems should be implemented on new lines or could also be implemented on existing lines? How should be the development of systems, ATC (Automatic Train Control) for ETCS level 2 or wait to be the trend for ETCS level 3?

The propose of this thesis was to answer these questions, after a strategic review of the evolution of an existing line with a conventional signalling system to a more modern system, ETCS Level 2, and then for, ETCS level 3.

This work aimed to analyse with some insight the impact of a rail signalling system alteration in an already existent line, Mjölby - Alvesta. It was therefore necessary to study an extensive literature of the different approached themes on this thesis, technical documentation of the Swedish railways, and the rail simulator RailSys 7.4.0 (RMCon) to accomplish a case of study.

In RailSys 7.4.0 (RMCon) simulator was constructed each of the solutions encountered during this thesis and was analyzed and recorded each outcome result.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Signalling systems	ATC	ATC	ATC	ATC	
	ETCS level2	ETCS level2	ETCS level2	ETCS level2	ETCS level2
	ETCS level3	ETCS level3	ETCS level3	ETCS level3	ETCS level3
Timetable	Timetable 1	Timetable 1	Timetable 1	Timetable 2	Timetable 2
				Timetable 3	Timetable 3
Train types	FT	FT	FT	RT	RT
	RT	RT	RT		
	LDT_Stop	LDT_Stop	LDT_Stop	LDT_Stop	LDT_Stop
	LDT_NonStop	LDT_NonStop	LDT_NonStop		
Máx. Speed permitted	200 km/h - ATC	200 km/h - ATC	200 km/h - ATC	200 km/h - ATC	320 km/h - ETCS level2(all line, dedicate line) 320 km/h - ETCS level3(all line, dedicate line)
	200 km/h - ETCS level2	320 km/h - ETCS level2	320 km/h - ETCS level2	320 km/h - ETCS level2	
	200 km/h - ETCS level3	320 km/h - ETCS level3	320 km/h - ETCS level3	320 km/h - ETCS level3	
Perturbation	No	No	Yes	No	No
Simulation time	1 day (1cycle)	1 day (1cycle)	365 days (365cycles)	1 day (1cycle)	1 day (1cycle)

Table 4.3 – Scenarios overview.

This thesis have also a basic description of railway signalling systems, describing the different levels of ETCS and explanation about the context of political and geographical importance, of the section Mjölby - Alvesta inserted in the Line Stockholm - Malmö.

The obtained results from diverse simulations in the case study, helps to answer the objectives in the present work and to understand that the replacement of the ATC for the ETCS level 2 and ETCS level 3 (even with the same speed limit) will reduce the train delays (smaller delay on the ETCS3). With the increase of speed in the track, only possible after the implementation of the ETCS level 2 and ETCS level 3, the delay differences between the different signalling systems are even more evident.

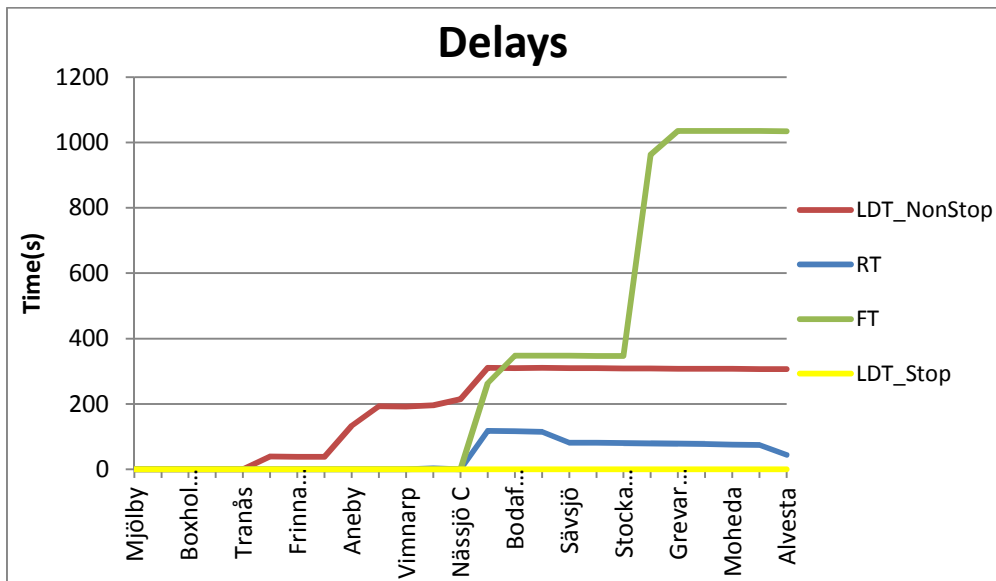


Figure 5.3 – Train delays operating on ATC – scenario 2.

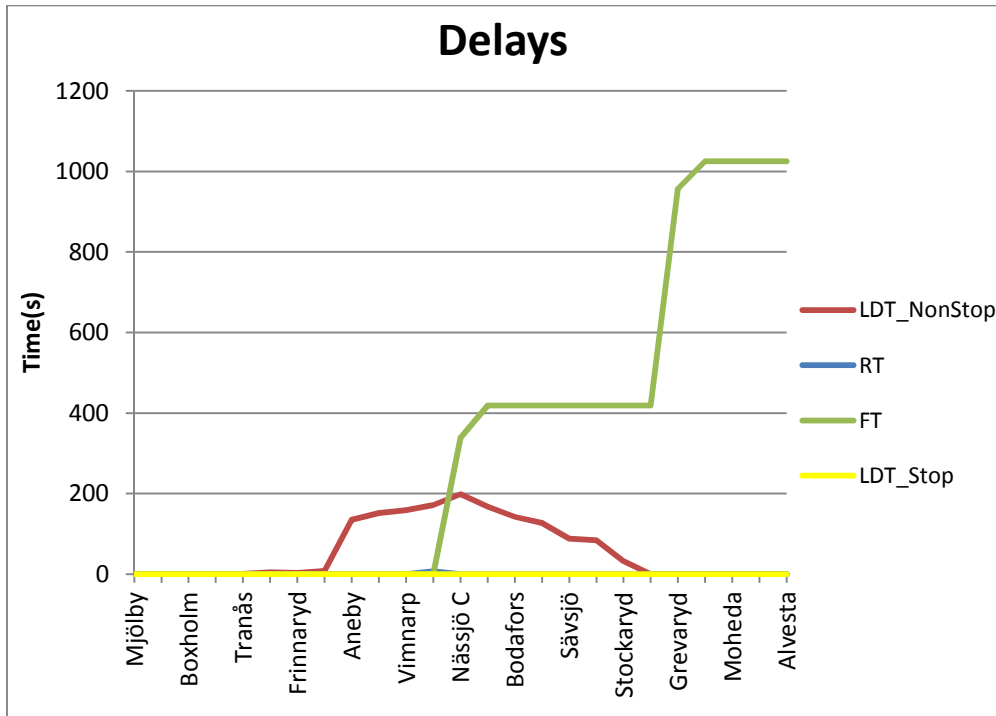


Figure 5.4 – Train delays operating on ETCS2 – scenario 2.

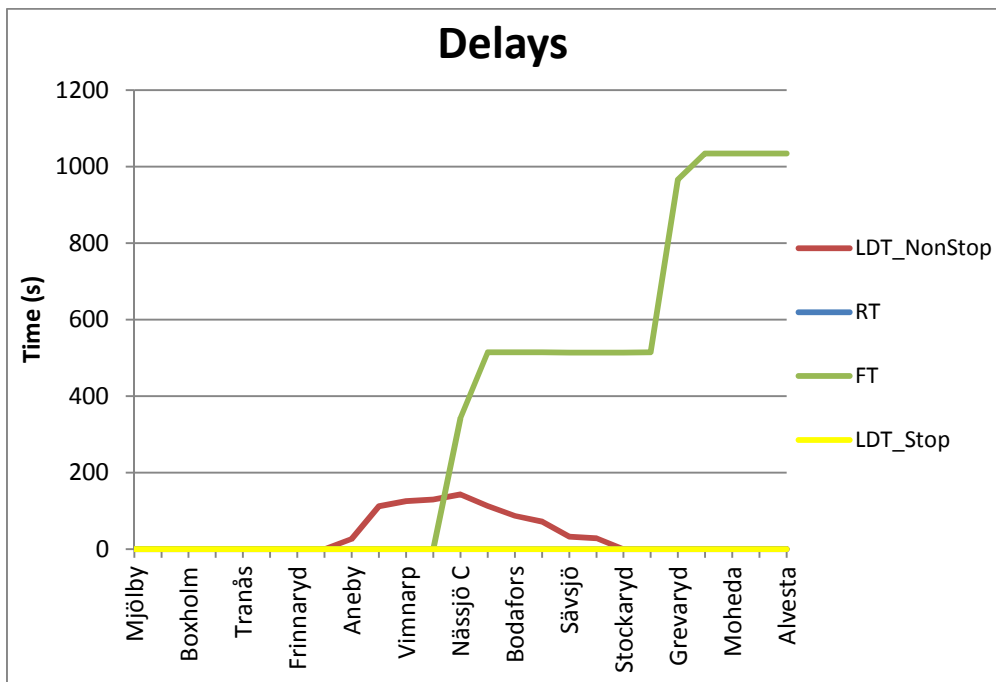


Figure 5.5 – Train delays operating on ETCS3 – scenario 2.

When the line is operated on a very busy daily timetable and some operation perturbations are added up to simulation for a period of one year, it is attested once again that the best performances in the average delays and punctuality rates are carried out by the ETCS level 2 and by the ETCS level 3.

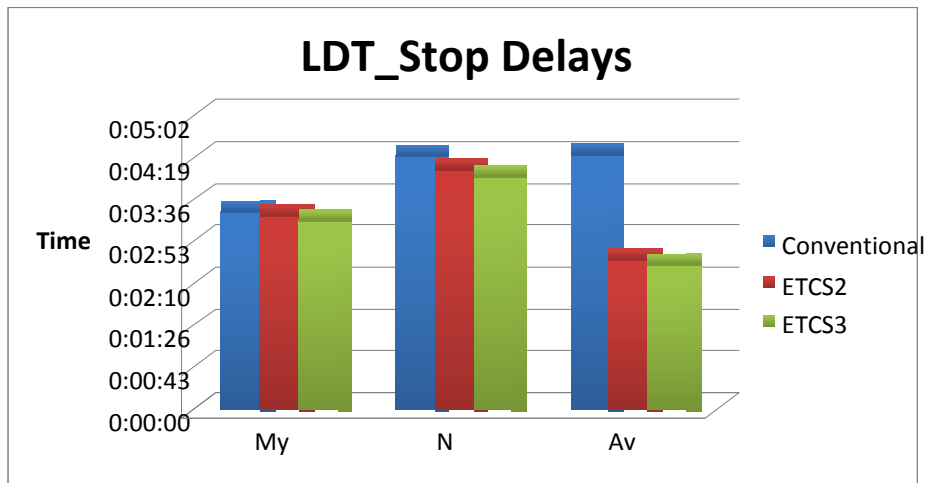


Figure 5.10 – LDT_Stop average delay, operating on a conventional system, an ETCS2 and an ETCS3, with the same timetable – scenario 3.

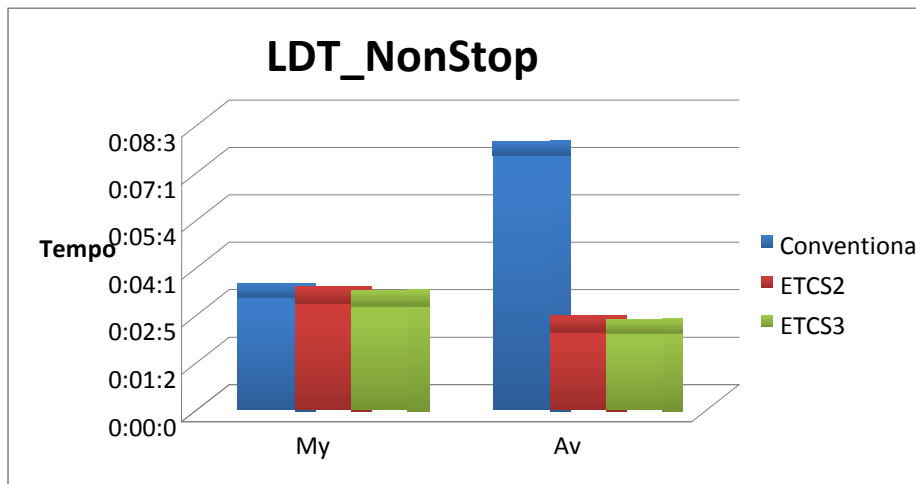


Figure 5.12 – LDT_NonStop average delay, operating on ATC, ETCS2 and ETCS3, with the same timetable – scenario 3.

The ETCS level 2 and the ETCS level 3, by increasing the speed limit on the line, reduces the journey duration when compared with the conventional system.

Regarding the line’s capacity, headway and number of vehicles operating at the same time, the ETCS level 3 stands out from the other two systems, because it allows a shorter headway and consequently, permits the circulation of a larger number of trains at the same time in the track.

LDT	Journey duration	Headway	Trains per hour
ETCS3	0:55:34	0:03:03	20
ETCS2	0:55:34	0:03:24	18
Conventional	1:03:35	0:03:15	19

Table 4.30 – LDT-Stop results in scenario 4.

RT	Journey duration	Headway	Trains per hour
ETCS3	1:16:53	0:02:45	22
ETCS2	1:16:48	0:05:16	12
Conventional	1:20:42	0:05:00	13

Table 4.31 – RT results in scenario 4.

As regards the maintenance costs of signalling systems, when comparing the contrast of expenses per year of the ATC with the ETCS level 2, the conclusions are quite clear: the ETCS level 2 has a quite smaller sum. But the ETCS level 3 figure is even smaller when compared with those two systems. The analysis of the maintenance costs of the three systems life cycle (30 years) supports the conclusion that the investment in the maintenance of the conventional system is quite higher when compared with the ETCS level 2 figures, but it is monumental relatively to the ETCS3 numbers.

In relation to the ETCS level 2, but especially to the ETCS level 3, one can also affirm that both systems have lower equipment failure rates, which means less flaws and perturbations in the rail track operation. This is proportional to the reduced maintenance costs because the number of existing track equipments will be very inferior when balanced against the conventional system.

Conventional	Maintenance costs
4,719,000 kr	Year
141,570,000 kr	Life cycle (30 years)

Table 5.8 – Maintenance costs calculation for the line Mjölby–Alvesta (ATC).

ETCS2	Maintenance costs
2,907,000 kr	Year
87,210,000 kr	Life cycle (30 years)

Table 5.9 – Maintenance costs calculation for the line Mjölby–Alvesta (ETCS2).

ETCS3	Maintenance costs
262,000 kr	Year
7,860,000 kr	Life cycle (30 years)

Table 5.10 – Maintenance costs calculation for the line Mjölby–Alvesta (ETCS3).

In conclusion, with the rail signalling ETCS level 2 and ETCS level 3 - especially due to the last system's greater results– one can increase the allowed maximum speed in the track and improve the line's interoperability and safety in the rail transport. But one can find more advantages in adopting these systems: the train delays are reduced, with or without line perturbations; the punctuality rate of the circulating trains is elevated; a higher number of vehicles operating the line at the same time are doable; improved headway; lower maintenance costs and fewer track equipments failures.

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GLOSSARY

ATC – Automatic Train Control

ATO – Automation Train Operation

ATP – Automatic Train Protection

ATS – Automatic Train Stop

AC – Alternating Current

DC – Direct Current

CTC – Centralized Traffic Control

EIRENE – European Integrated Radio Enhanced Network

ERA – European Railway Agency

ERRI – European Railways Research Institute

ERTMS – European Railway Traffic Management System

ETCS – European Train Control System

ETSI – European Telecommunications Standards Institute

EUROSIG – European Special Interest Group

GSM – Global System for Mobile Communication

GSM-R – Global System for Mobile Communication - Railway

KTH – Kungliga Tekniska högskolan

LCC – Life Cycle Cost

LEU – Lineside Electronic Unit

MMI – Man-Machine Interface

RAM – Reliability, Availability and Maintainability

RBC – Radio Block Centre

RMCon – Rail Management Consultants

STM – Specific Transmission Modules

TEN-T – Trans - European Transport Network

UIC – International Union of Railways

UNIFE – Association of the European Rail Industry

UNISIG – Union Industry of Signalling

1

INTRODUCTION

1.1. GROUNDING

Communication has been developing since prehistorically times, when man started to communicate through cave paintings and gestures. Due to the growing will and need in trading information and goods, man adopted tools witch aided and potencies the production process, sending and reception of the messages. The technology started to be part of the human communication as well as part in most of the activities developed by man along evolution.

In our global "flat world" virtual communications are as fast and fluid as if distance didn't exist. But when dealing with the transportation of people and goods, it seems difficult and slow in comparison. Furthermore, we witness an unprecedented environmental crisis that urges to solve.

Under this assumption, the rail transport could emerge as an extremely important answer to the current concerns of the world society. This mode of transport is fast, efficient, on-time, safe, free from jams or weather conditions, with centre-located and above all, none polluting and eco-friendly. [2-9]

To evidence the importance of the rail transport, we have to look in to its origin and history.

In 1804 Richard Trevithick [10] demonstrated the first locomotive-hauled train. Twenty-one years later, the English mechanic George Stephenson built the first public steam railway in the world, between Stockton and the mining area of Darlington, for goods and passengers. After 4 years was called to accomplish the railway between Liverpool and Manchester. [11, 12] This was followed by a period of fast expansion and development, spreading extraordinarily in many countries during the 19th century. [1] The railway became a symbol of progress.

The increasing of rail transport also increased safety problems in the movements of the trains along the railways. The traffic intensification and the growing speed caused several rail accidents, many of them which fatalities. Therefore, the need to control that same traffic in a safe way generated the emergence of the rail signalling.

The rail signalling exists mainly to prevent train collisions, regulating the circulation and good operation. Accidents continue to happen, although now in smaller scale, due to the evolution of the rail signalling and its implementation.

Although all trains circulate in rail tracks, with the evolution of the rail signalling different systems were implemented in different lands or even inside of the same country. This means that sometimes, a train equipped with a specific signalling system cannot circulate in a rail track supplied by a different system.

In 2000 arrives ERTMS (European Railway Traffic Management System), conceived to provide the interoperability between countries. It is considered unanimously the most advanced system of control in the world, bringing significant advantages in maintenance costs, safety, reliability, punctuality and traffic capacity.[13, 14]

The theme of this paper is related to the emergence of ETCS (European Train Control System), part of the ERTMS. It will address on how the change from the already existent systems to ETCS (level 2 or 3), should be executed.

Because ERTMS is considered the way to go regarding the evolution of railway, this transition represents the future of rail transport in Europe and even in the world. [14-16] Like any transition, gains and costs are involved. Projects should to be prioritized and ETCS levels should be chosen after a careful analysis of the geography and the type of the operation /role of the line.

1.2. GOALS

According with the work theme, the intention is to analyze the impact of the transition in an already existent line with signalling system ATC (Automatic Train Control) to an ETCS level 2 and level 3.

Consequently, the purpose of this work is:

- to simulate different scenarios for each proposed signal system for the line in study;
- to identify and compare the eventual differences on the traffic volume in the signal systems for the line in study;
- to identify and compare the potentials differences in time travel for each proposed signal systems for the line in study;
- to identify and to compare the potentials differences by increasing the circulation speed;
- to analyze the differences of maintenance costs for each signal system proposed;

1.3. METHODOLOGY

This work has six chapters. The first is the introductory where the analysis core, the goals to reach and the organization of the paper are defined.

In the second chapter, the general concepts of rail signalling are presented as well as their main operation guidelines and equipments.

In the third chapter, the ERTMS is presented and its appearance. Different levels of ETCS are presented and compared with signal systems previous to the emergence of ERTMS.

In the chapter four, different simulations are presented, executed with the help of the program RailSys 7.4.0 (RMCon). RailSys 7.4.0 is software of system analysis, planning and optimization of operational procedures for a rail network of any size. The operational procedures are microscopic descriptions of the real world in the model, displayed on the computer desktop and the analysis of the whole system as the solving of specific and local problems are easily accomplished. This program has been developed by the University of Hannover and RMCon (Rail Management Consultations). It has been applied with success in different projects such as the high-speed lines Cologne - Rhein/Main and Sydney - Canberra, the city railways of Munich, Sydney, Melbourne, etc, or the rail network of Berlin and Copenhagen. In this chapter is explaining the RailSys 7.4.0 composition.

These simulations were made in the already existent line Stockholm – Malmö, specifically the line Mjölby - Alvesta. In this chapter different operation criteria with several trains using the branch line simultaneously are simulated as well.

In the fifth chapter, the results of the different simulations are analyzed and compared. The maintenance costs to each signal system are also analyzed.

Finally, in the last chapter, the main conclusions are presented as well an ensemble of proposals for future developments.

2

RAIL SIGNALLING

2.1. RAIL SIGNALLING

The rail signalling is one of the essential elements of the rail transport, because it controls the movement of all of the trains of the network, it assures the safety of those same movements and it makes possible the administration of the trains during the operation.

Signalling main functions are: to guarantee the safe distance between two trains circulating in the same way, to stop the access to the same section of two vehicles circulating in opposite ways and to manage conflicts in railway junction with points. The rail signalling also supervises (and sometimes even replaces) the train driver, avoiding eventual human errors. It controls remotely the position of the circulating trains; it adjusts that same circulation to the existent traffic, providing a safe movement along the rail track. [17-19]

In a signalling, any anomaly should make the system evolve in to a more restrictive way. In rail signalling the systems are denominated as Fail-Safe. [20]



Figure 2.0 – Train station. [21]

2.2. SYSTEM EQUIPMENTS

It is important to mention the equipments which are relevant in a signalling system. Therefore, this paper will enumerate the devices most frequently used.

2.2.1. INTERLOCKING

When the first trains appeared, their speed was quite low. The driver's responsibility was mainly conduct the train, trusting his eye sight and not knowing what was happening along the track (also known as "Proceed-With-Care"). However, with this method the accidents were frequent. Therefore it was the need to find a way to control better the train circulation, especially when in conflict areas as train stations, junctions and level crossing.

The solution to these conflict areas was found by placing people whom with the help of a flag regulate the train's movements. Safety's system continually to evolve until some years later the first signals arrived, installed with the purpose of controlling the trains passage.

In 1840, the signals and points that controlled more problematic things are connected to a building called the signal box, where the Signalman controlled all the operations.

The next step was to protect the rail network circuit of eventual mistakes of the signalman: the first mechanical blocking was created. It prevented conflicting signals and assured the correct command was given to the points for the different itineraries in which trains circulated.

The functions of blocking went developing gradually, combining different mechanical options. Therefore was necessary to consider new dynamic aspects, like for instance the temporary blocks of points placed near after the signal. After inversion of the signal aspect, when the train is already very close of that signal, signal that instants before were permissive, it will be unsafe to move the points because that points are now in the braking curve of the train and consequently impossible to the train stop before reaching the points.

Appear small electric functions carried out by relay systems.

The electric connection between the blocking and rail track equipments allowed the use of electric signals and electric points.

In 1920, signalling engineers concluded that the method used in the mechanical interlocking could also be implemented by relay circuits. The electric interlocking came to life and a new concept emerge: the connection between the signalman and the objects in the track was substituted by the connection between the first signal and the last signal in the route.

Through the decades the complexity of the electric interlocking kept growing. Due to the geography of the rail network, more functions were needed. And in 1979, due to the increase of the use of the computers in industrial applications, the electronic interlocking was commissioned. The use of microprocessors gave the interlocking the final push needed, culminating in its use in the most important rail networks of the world. [22]

In our day interlocking assures safe rail transport along the rail network.

Interlocking incorporates three main functions: [23]

- Operation which includes the interface with the railway signalling and it can also include non vital automatic operational functions as automatic routes amongst others.
- Blocking which includes the vital functions of signal blocking, itineraries, points, blocking applications, etc.
- Control and information which includes command functions and information from and about all of the existent elements in the railway track as signals, points, line sections, level crossings, etc.

But time and a centrally located policy have altered the way we look at these functions. In nowadays an interlocking can operated from different places, separated from each other by several kilometres. [23]



Figure 2.1 – Electronic interlocking (Ebilock 950 R4 – Bombardier). [24]

2.2.2. CTC

Regarding the interlocking system, the latest news in a converging centre is the CTC (Centralized Traffic Control).

CTC allows the visualization and remotely control a branch line or a rail network. These systems allow traffic regulation, increasing its capacity and speed, reducing manpower in controlling operations and assure larger safety in the rail network, regarding schedules administration, record of events and system alarms. [25, 26]



Figure 2.2 – CTC (CCO Porto – REFER). [27]

2.2.3. TRAIN SAFETY

With the advent of rail signalling a new risk also emerged: the possibility of the driver ignore the safety signals or not observing them in an appropriate way. It is most uncommon for the drivers ignore deliberately the rail signals because they are the first ones to suffer the consequences. However to ignore signals by mistake or misunderstanding still occurs.

The two most common mistakes that the driver's can put the train in danger are the failure to observe a signal or failure controlling the train speed. The train safety system protects both situations.

The protection systems of more usual are the Automatic Train Stop (ATS), Automatic Train Protection (ATP) and Automatic Train Control (ATC).

Also exist, although in a lower scale, the Automatic Train Operation (ATO). This system is considered non-safe and assures partially or completely all of the driving functions. This means that it is possible to cut of the driver (although in the majority of the existent systems he continues to exist, to aid in eventual flaws in the system and emergencies).

ATS stops the train immediately in the occurrence of certain situations, like passing a red signal.

Train speed must be adjusted according to the railway conditions or the train's "movement authority". ATP supervises the train speed, stopping the train in case of lack of "movement authority" or if that same authority has been shortened after an unexpected occurrence by the signalling system. With the target speed indication we have a braking curve, the velocity calculations made by the train's safety system. By abiding to these calculations, the train will also comply with the movement authority assigned by the system of rail signalling.

We can say that ATP is safety system that assures that the train has the necessary safety's distance to stop without colliding with other train circulating on the same track line.

ATC is the most modern safety system which includes ATS, ATP and ATO. This system was adopted all over the world to describe the architecture of systems of automatic operation, being most usually used in subway system. [18, 28, 29]

2.2.4. RAIL TRACK EQUIPMENTS

2.2.4.1. Detecting trains

The detection devices most commonly used are the axle counter and the track circuit.

This type of equipments informs the position of the train along the railway, assuming a great importance in the network's design, safety, philosophy and form of operating.

The axel counter is a device on a railway that detects the passing of the train and its position. A detection point with two independent sensors compares the number of axes at the start and at the end of the section. It can also detect the direction of a train by the order in which the sensors are passed.

When passing through the first sensor, the counting increases and the section is busy. At the end of the section as the train passes a similar detection point, the counter decrements. If the net count is evaluated as zero, the section is presumed to be clear for a second train.



Figure 2.3 – Axle counter. [32]

The track circuit is a simple system using electric current on the tracks and a detection device – relay. The relay is placed at the end of the circuit and it functions as a switch. If the relay is energized it means that the section is free. When the train circulates it interrupts the electric current and creates a short circuit, making the relay contacts to fall and assuming the section as occupied.

Due to the different types of electric currents used in track circuits, we can differentiate them in three groups: Direct Current (DC), Alternating Current (AC) or Alternating Current with radio frequencies.

The track circuits can be used not only as devices for train detection, but also for transmitting information to the system of cabin signalling and train protection, between signals in the same section (from the exit signal to the entry signal) and the detection of continuity the tracks. [30, 31]

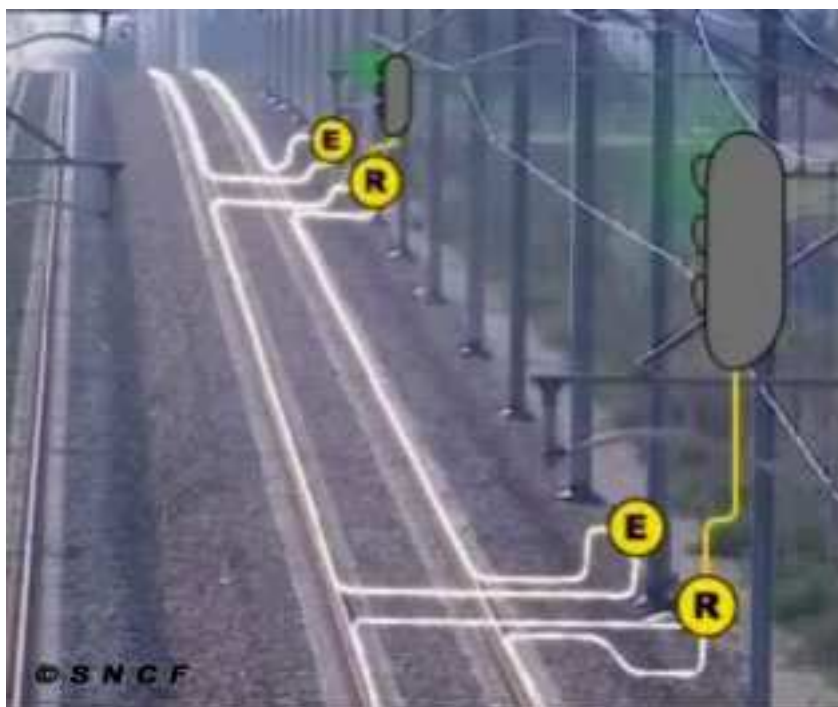


Figure 2.4 – Train track circuit. [33]

2.2.4.2. Signals

The purpose of the signals is to supply information and instructions to the driver and for the whole staff in the track. The signals are a liaison between the signalling system and the workers and can supply different types of information. By observing the signal, the machinist can apprehend the movement authority given to the train, the permitted speed, the route direction, departure authorization, position of the points, condition of the level crossing, command for testing the brakes, the beginning of electrified sections, kilometre positions, etc.

The signals should follow general requirements so the driver can recognize easily the message, interpretative the information in a correct form, understanding what does the signal means in a fast and unequivocal way. All the information transmitted by the signal should be given at the right time and always in the same way.

The signal should be considerate a failsafe device, because in the case of a technical flaw, the signal can never transmit a less restrictive indication than the original, but can give however a more restrictive information. [34, 35]



Figure 2.5 – Railway signals. [36]

2.2.4.3. Points

The purpose of the points is to allow a train to change from a track to another. The basic design of a point is similar in all the railways.

The points have three possible positions, two of them are considered as “final” and the remaining one as “intermediate” position. The final positions are classified as the normal (+) position and the inverse (-) position, so called in agreement with the position used more frequently for the rail network. Nowadays it is also used “Left” and “Right”, instead of normal and inverse, after observing the point blades in the same direction as the points. [37, 38]

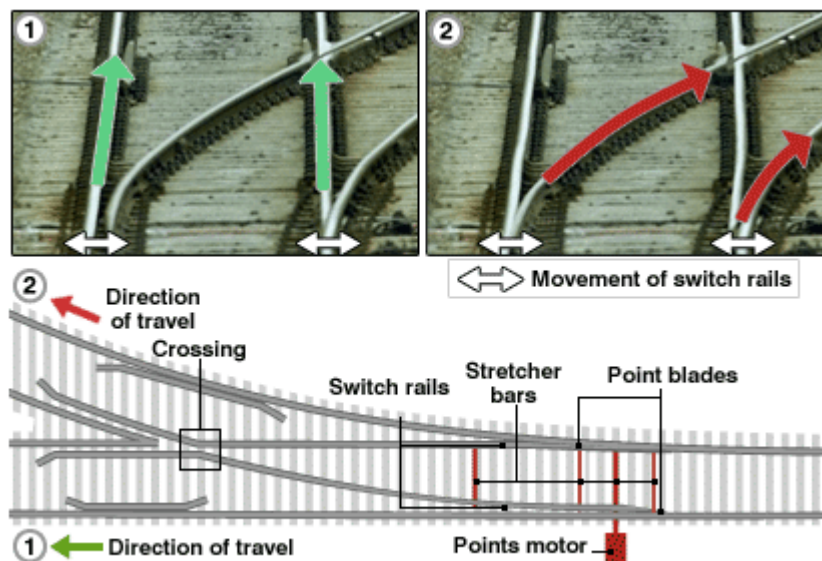


Figure 2.6 – Railway points [39]

2.2.4.4. Level crossing

Level crossings, the intersection places between the railway and the roadway, are the primary location of collisions between trains and other vehicles due to their different characteristics. This situation is difficult to administrate. The train's inability in braking in a short distance when it comes across an obstacle, combined with low orderliness in the roadway, explains 1/3 of the train crashes. These same accidents, which are mainly caused by inappropriate behaviours of the car drivers, represent less than 1% of all road accidents.

To increase the safety in one level crossing, many countries are abandoning its use in favour of other options. However, the number of level crossings still operating is very high and no changes are waited in a nearby future.

After comparing braking distances between railway and road transport, the right of way was given to the trains and the tracks should not be obstructed by its passage through the level crossing.

With the approaching of the train, the roadway vehicles have to be informed so they could be able to stop before arriving to the level crossing. The road traffic can be aware of train's proximity by a direct form (optical or acoustic) or by the observation of signals installed in the level crossing.

The system operating at the level crossing should be Fail-Safe in case of failure. This means that the level crossing has to continue to operate in a safe way or signalize the system flaw, so that both means of transport don't have permission to cross it in normal operation.

The European Railway Agency (ERA) classifies the level crossings as:

- **Passive level crossings**, where there is no information regarding the train's arrival. Therefore the vehicle's driver has to apprehend by itself if the approaching train and make the decision of crossing;
- **Active level crossings**, that indicate if it a train is coming or not.

Unlike the passive level crossings, quite simple and easy of comprehend, the active level crossings must obey to defined safety requirements not only regarding the type of the warning that indicates the train's approach, but also how it prevents road vehicles from go across the railway.

The most common equipments used in an active level crossing, are:

- Colour light signals: depending on the countries, they can be a plain red light, a flashing red light or two red lights flashing alternately.
- Mechanical roadway block, usually by crossing gates (with boom barriers).
- Crossing bells, ring continuously before the boom barriers are closed until the train is gone.
- A flagman. This "equipment" is basically a person who manually alerts the closing of the level crossing or manually closes the boom barriers. Either way, this solution is only used in degraded areas or in temporary solutions.

One of the greatest concerns in the operation of active level crossings is the warning period. The period is defined as the time from which the level crossing is activated (when the warning signals begin to function) until the arrival of the train to the intersection.

The duration of the warning depends on the chosen solution for the closing and opening of the level crossing. It should not be too short to give the possibility of the vehicles drivers stop before the arrival of the train to the level crossing, but it should not also be too long, which might lead to road indiscipline and therefore reducing the level crossing's safety. [40-42]



Figure 2.7 – Level crossing. [43]

2.3. FUNCTIONAL PHILOSOPHIES OF SYSTEM

2.3.1. TRAIN SEPARATION

A train braking distance exceeds considerably the driver's visual field. Therefore, during regular movements, procedures of train separation are taking in action regardless the driver's visual field.

There are three theoretical train separation principles:

- Train separation by relative braking distance;
- Train separation by absolute braking distance;
- Train separation by fixed blocks distance.

2.3.1.1. Train separation by relative braking distance

The relative braking distance uses a separation length calculated by adding the braking distance disparity between the two trains to the safety's gap. The two vehicle's braking distances are measured by the correlation of each train braking curve and their corresponding speeds.

This train separation theory permits using the rail track at its maximum capacity, but this operating model also brings relevant problems.

With this method it's not possible to move the points located between the two trains. To be able the move the point, it would be necessary for the gap between the switch and the train to be larger than the braking distance. Another potential problem would be if an accident occurred with the first train, it will be impossible for the second to avoid a collision.

$$d = d_{\text{brake},2} - d_{\text{brake},1} + S$$

- d distance between trains
- $d_{\text{brake},1}$ braking distance of train 1
- $d_{\text{brake},2}$ braking distance of train 2
- S safety distance

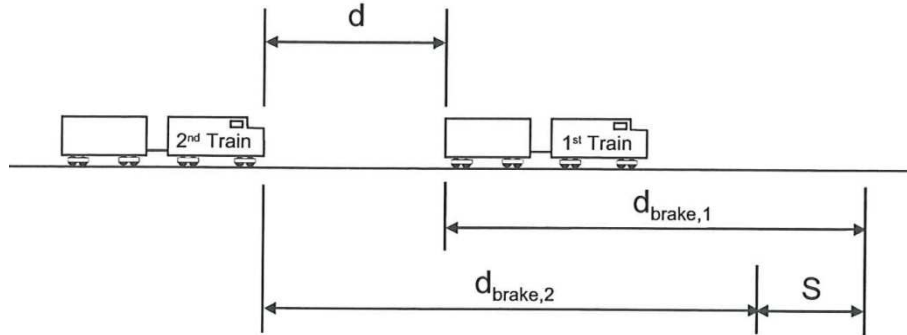


Figure 2.8 – Train separation by relative braking distance. [44]

Due to these important functional problems, this operational solution is just a theoretical idea and therefore, not implemented in rail transport.

2.3.1.2. Train separation by absolute braking distance

Train separation by absolute braking distance, as the name shows, uses the full braking distance of the second train plus the safety's distance.

It is considered the best solution for train separation, having as only downside (that is keeping it from being implemented) the technological difficulty of tracking the trains in an exact and secure way.

However, with the development of operations based in radio technology, it is expected in a close by future a wide implementation of the Moving Block method (name for which it is known).

$$d = d_{\text{brake},2} + S$$

- d distance between trains
- $d_{\text{brake},2}$ braking distance of train 2
- S safety distance

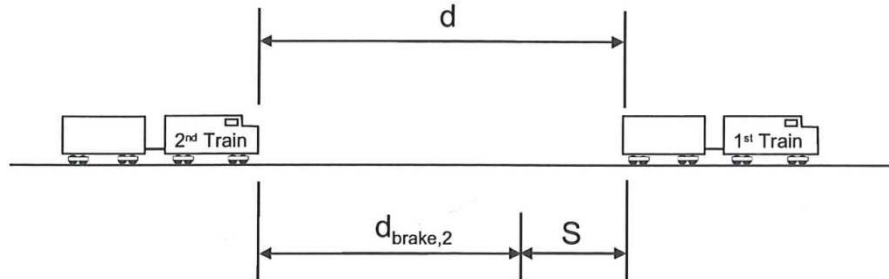


Figure 2.9 – Train separation by absolute braking distance. [45]

In a Moving Block system, the section behind the train is liberated according with the gaps of location of the train. Tighter the intervals are, closer can a train be followed.

2.3.1.3. TRAIN SEPARATION BY FIXED BLOCKS

The railways where this model is used are divided by sections: they can only be occupied by one train at the same time and the gap between two trains is calculated by adding the braking distance, plus the block (section) length, plus the safety distance.

$$d = d_{\text{brake,max}} + l_{\text{block}} + S$$

- d distance between trains
- $d_{\text{brake,max}}$ maximum braking distance
- l_{block} length of the block section
- S safety distance

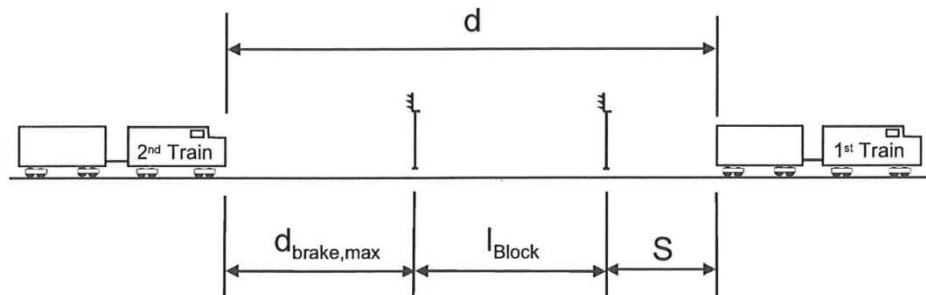


Figure 2.10 – Train separation by fixed blocks.[46]

In nowadays, train separation by fixed blocks is the most used solution in rail transport all over the world. [47]

2.3.2. Operating by Fixed blocks or Moving Block

It is now relevant to elaborate a little more the train separation method by fixed blocks.

In this kind of operation, it is most common to use rail signals to mark out the sections. However, in hopes to increase the safety, a growth in the use of train cabin systems (Cab Signal Systems) is becoming more evident (especially in the high-speed lines) due to possible negligence in observing the railway signalling. [48]

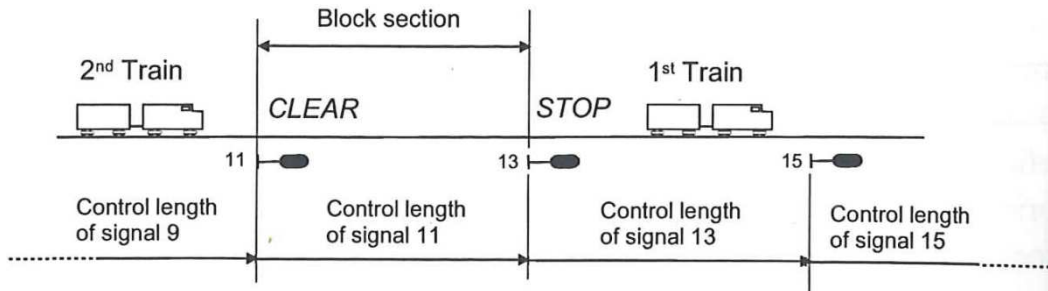
2.3.2.1. Regulation in operations with fixed blocks

This system uses fixed blocks sections protected by railway or cab signals. For a signal to allow of train passage in to the section's entrance, some requirements must be satisfied:

- The train that circulates ahead, liberates the section;
- The train that circulates ahead, liberated the overlap (only in lines where the block overlap is used);
- The train that circulates ahead, is protected from the following with a stop signal;
- The train is protected against opposed movements.

The systems where the block overlaps are not required, the signal control's length and the section distance are the same.

a) Line without block overlaps



b) Line with block overlaps

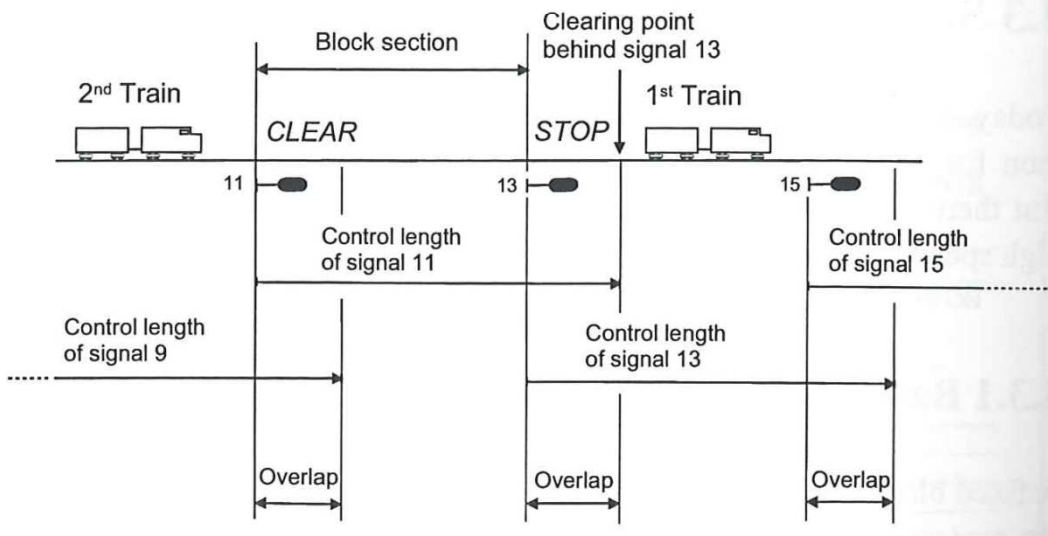


Figure 2.11 – Train operations with fixed blocks. [49]

The reserved area belonging to the following section is called overlap[50] because the first signal's control length overtake the next section and it's signal. The purpose of overlaps is to give an additional protection in case of the driver is unable to stop the train before the stop signal. A signal cannot give the following train permission to go, until the whole section controlled by that signal (Control length), it is free. [48]

2.3.2.2. Blocking time theory and Headway

The headway is the period of time between two sequential trains in which the minimum headway in the line with fixed blocks system depends on the blocking time. Blocking time is the interval of time in which each section (block) is exclusively allocated to a train and as a consequence, blocked to other trains. As a result, blocking time endures until the first train liberates the section and the second train receives the movement authority over that same block. Usually the blocking period of the first train is higher than occupation time in the section. In a branch line in which the railway signals secure the sections, for a train without a programmed stop, the blocking duration results in the sum of the following intervals of time, figure 2.12:

- The time to release the signal;
- The time necessary for the driver to see the liberation of permissive aspect in the advanced signal;
- The time between when the block sign gives movement authority and the advanced signal of that same section gives that same indication to the driver;
- The time between block signals;
- The time to "clean" the block and if requested, to "clean" the overlap, with the fully passage of the first train;
- The time of release the blocking system.

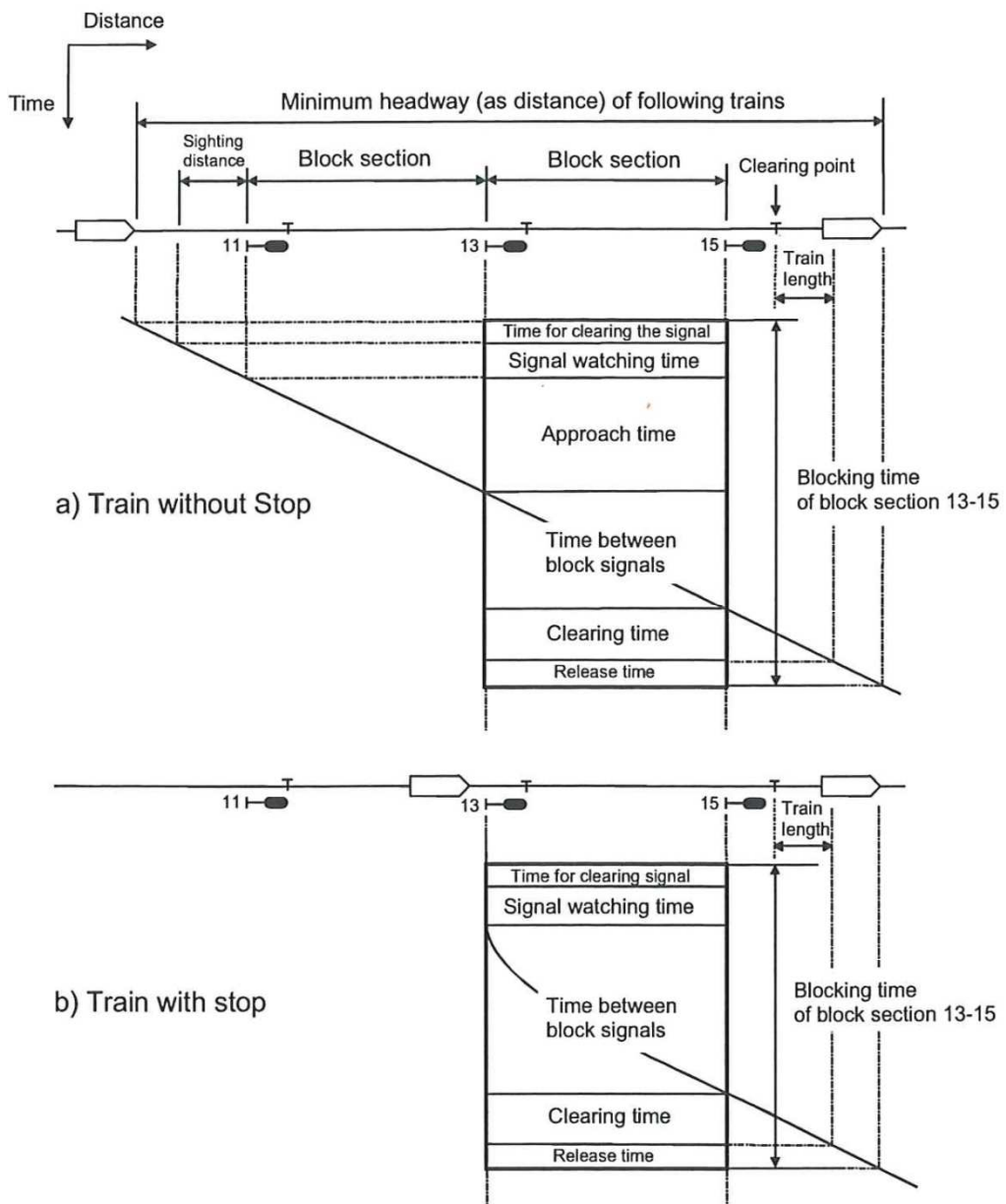


Figure 2.12 – Blocking time of a fixed block system. [51]

If the train is scheduled to stop before the signal that indicates beginning of the block, the time that goes between the movement authority given by the block signal and the moment that same information is given to the driver, will not be considered. In this same case, the time for the driver to see the “proceed” in the advanced signal will be applied in the block signal. In a branch line in which the delimitation of the blocks is made by cab signalling, the time of approach is the period in which the train travels through the braking distance, signalled by the on-board system.

Applying the blocking times of all sections, a train raises in a time / distance diagram, called "blocking time stairway", figure 2.13. The blocking time stairway diagram represents, in the most accurate way, the operational line use.

With the diagram blocking time stairway it is possible to determine the minimum headway of two trains, figure 2.14. The line headway is the minimum headway between two trains, not only for a specific block but to all of the line blocks.

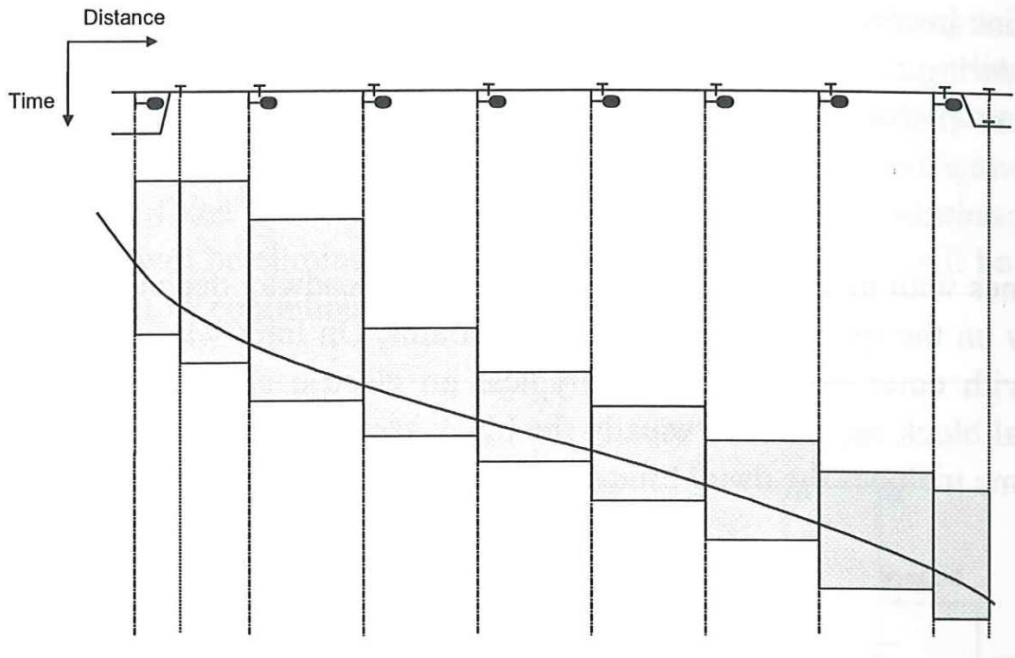


Figure 2.13 – Blocking Time Stairway. [52]

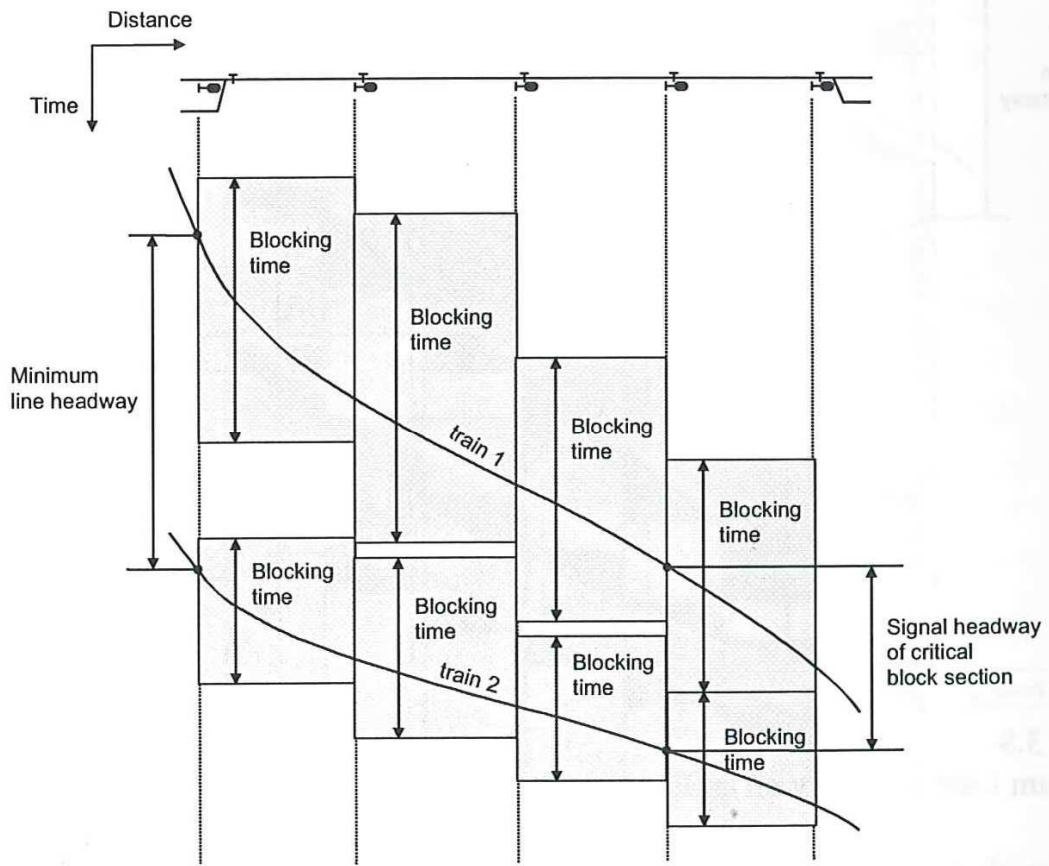


Figure 2.14 – Sections Headway and line Headway. [52]

In lines operated by the moving block system, the blocking time of the line itself can also be determined. In a moving block line, the length of the section is reduced to zero which means that the time between block signals is eliminated, but all the other aspects of the blocking time can be found in the moving block.

In many lines, the sum of these other components is even bigger than the part of the time of block that can be eliminated in the moving block. The difference in a line of fixed blocks is the "steps" of the blocking time stairway diagram, that will be eliminated and the diagram will be transformed in a continuous time channel, figure 2.15. [48]

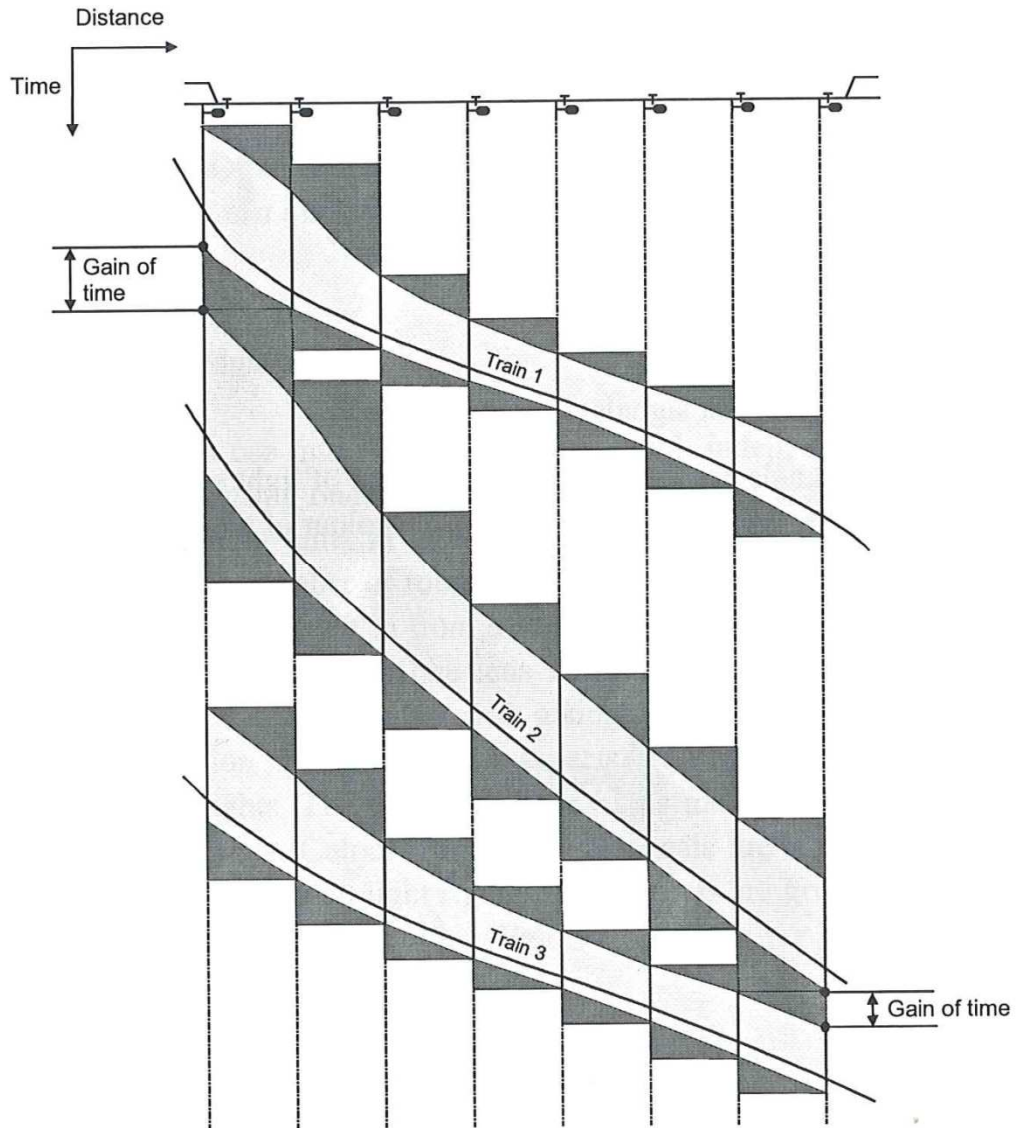


Figure 2.15 – Blocking time comparison between Moving and Fixed Block. [53]

3

ERTMS/ETCS

3.1. GENESIS

The European Railway Traffic Management System (ERTMS) took shape after the European Union (EU) became aware that the problematic interoperability in and between different European railway networks was caused by a multiplicity of signalling systems.

One of the biggest obstacles to the development of the international rail transport lies in the existence, in Europe only, of more than twenty different signalling systems.

In nowadays the trains are equipped with more than seven navigation systems; which is extremely expensive and unbearable in case of space volume for all those equipments. For example, a train travelling between two countries must, before the actual crossing, to switch operational system or even to change the locomotive for one adjusted to signalling system operating the destination country. This engineering represents a waste of time, operational problems and high maintenance costs.

For all these reasons, during the 1980's the creation of a common system in Europe began to be discussed. Following the 1989 findings of the Ministry of Transportation, the EEC (European Economic Community as known by that time) began to analyse the signalling and control problems of the trains. By the end of 1990, the European Railways Research Institute (ERRI) created a commission formed by accredited railway technicians, with the purpose of developing the European Train Control System (ETCS). In June of 1991, the European Special Interest Group (EUROSIG) and the International Union of Railways (UIC) established the cooperation principles for the system development.

In 1993, the European Commission raised the problem of the interoperability directive and the decision to create a structure of technical standards was set. In 1995, the EU laid down general rules for the trans-European networks funding and defined a global strategy for the development of the ERTMS.

“Derived from the Treaty provisions relating to trans-European networks (Title XV, Articles 154, 155 and 156), Directive 96/48/EC establishes a legal framework requiring in particular, since November 2002, the use of ERTMS on any new high-speed line in the trans-European network or when the signalling system is to be renewed. For conventional rail, similar requirements will take effect six months after the entry into force of a decision relating to the technical specifications for interoperability (TSIs) adopted pursuant to Directive 2001/16/EC. The use of ERTMS will in particular be compulsory for any new installation or renewal of signalling in the priority projects listed in Decision 884/2004/EC”. [54]

In 1998, was created the Union Industry of Signalling (UNISIG) to conclude the system requirements, official's on the 25th of April 2000. ERTMS had arrived finally, bringing a substantial improvement to the railway's performance levels.

The technical standards were constantly reconsidered to include additional functions and in 2008 they were formally adopted. To assure that ERTMS is adjusted to the real needs of the railway in a permanent way, the technique standards are set and controlled by the European Railway Agency (ERA) in cooperation with the industry of rail signalling and their stakeholders.

Alongside with the standards setting, the European Union and the member states made an effort to finance the implementation of ERTMS / ETCS. Two settlements were signed in 2005 and 2008 between the EU and the stakeholders of the rail signalling industry, which seeks to implement ERTMS in the European rail transport system.

ERTMS is a gigantic European project (very similar to the Galileo for satellite navigation or SESAR for air traffic management) that accommodates the European Union's exporting growth of new opportunities and technical systems. The ERTMS was implemented in several countries, namely in the Asian Southwest, proving that ERTMS is the right path in to effective signalling and speed control in the rail transport network. [54-57]

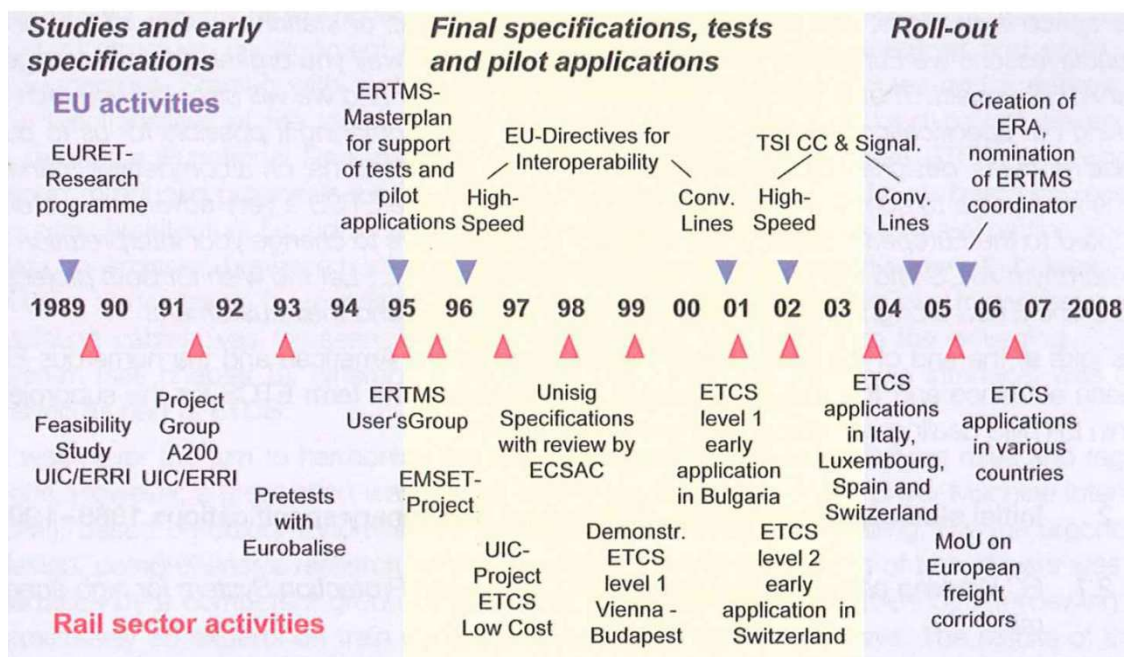


Figure 3.0 – ERTMS time line. [58]

3.2. CHANGE FACTORS

The extension and the impact of the railway sector fragmentation presses EU to act; to unite forces and cut down the costs of developing, testing and validating incompatible systems in each member state that, ironically, have the same purpose.

Looking it to the European Rail Traffic Management System (ERTMS) timeline it is clear that in the last decades, the different traffic management systems have suffered legal, operational, technical and economic changes. In the hope of accomplish new benefits with the implementation of ERTMS, different factors compelled the change in these operational systems.

3.2.1. INTEROPERABILITY

The circulation of people and of goods between different countries has been increasing in a gradual and sustained way. Therefore, the interoperability (initially a military term) is a fundamental requirement and presupposes that trains, including locomotives, can circulate freely in different railway networks.

There is a distinction between the functional interoperability and the technical interoperability. The technical interoperability is the precondition that enables trains to cross the border; the functional interoperability, by the other hand, eases of the management and manpower in trains circulating in different countries.

The interoperability it is not restricted only to signals and train control. There are other factors to take in consideration and to be standardized for interoperability becomes a reality.

In Europe is possible to find at least six gauge types. The standard model (and therefore most usual) is the 1435 mm gauge, but there exist five more different gauge types, like for example the Iberian gauge of 1668 mm (as shown in figure 3.1). The standardization of the gauge in the European rail network is imperative to achieve the interoperability.

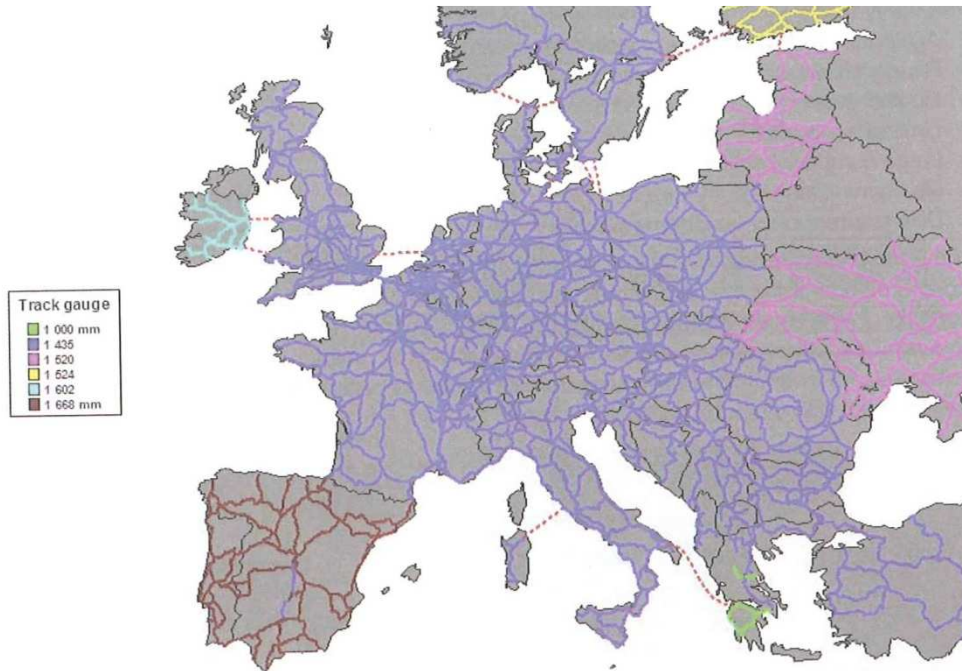


Figure 3.1 –Different track gauge in Europe. [59]

Another difference that can find in the European rail network is the safety envelope, also found in six different versions, as attested in the figure 3.2. Due to commercial reasons, the tendency was to increase trains length, what naturally causes great impact in the rail network. The solution is to find a standard template.

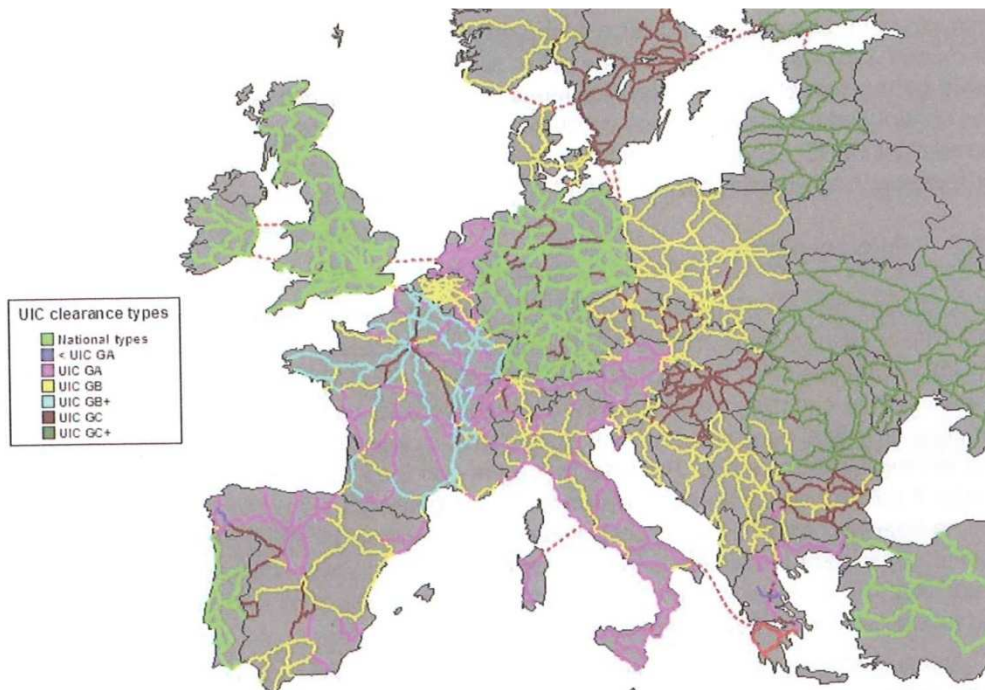


Figure 3.2 – UIC safety envelope types. [59]

Regarding the railway electrification system, one can find in Europe only, nine different types of current (Figure 3.3). This issue should also be standardized, but it is not as urgent as the last two factors. Due to the spectacular progress of the electrically propelled locomotives sector in the last two decades, trains that can run with more than a type of current are a reality. The train Thalys operates with four different types of electric traction.

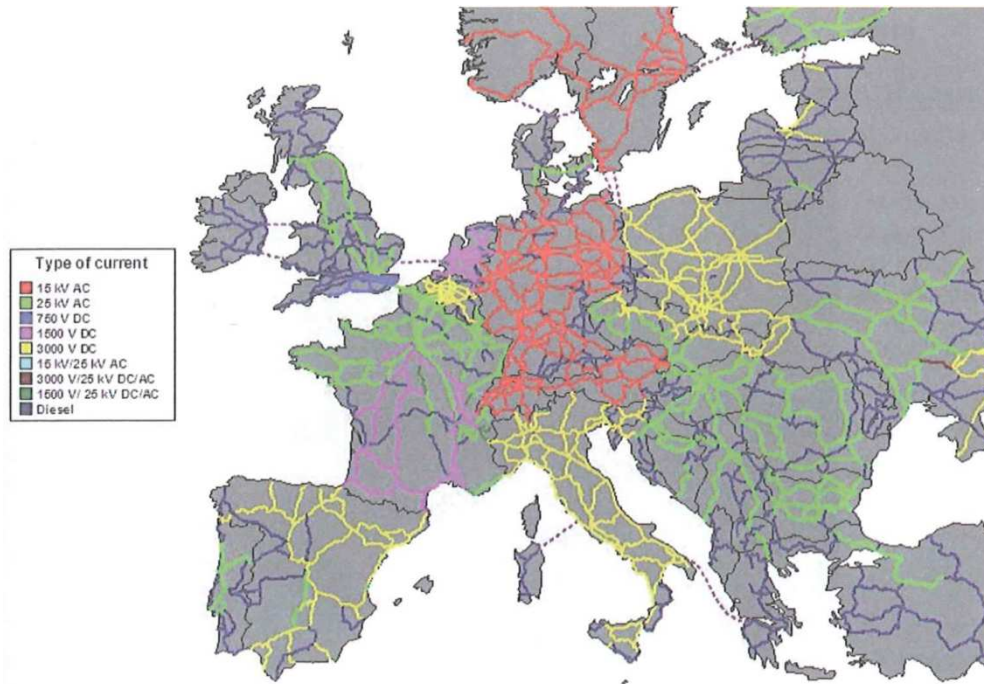


Figure 3.3 – Types of electric current. [60]

Besides all differences already mentioned, one can also point out the train control and the rail signalling as the most problematic systems in the network. The multiplicity is enormous and one can find more than twenty different and incompatible structures operating. The classical solution to assure the interoperability is to equip the train so it can be control by different systems in parallel. The expenses of this procedure increases the locomotives total costs in 20% to 25%, not mentioning the several problems of mechanical and electromagnetic in installing the different national systems of cab signalling, Figure 3.4.

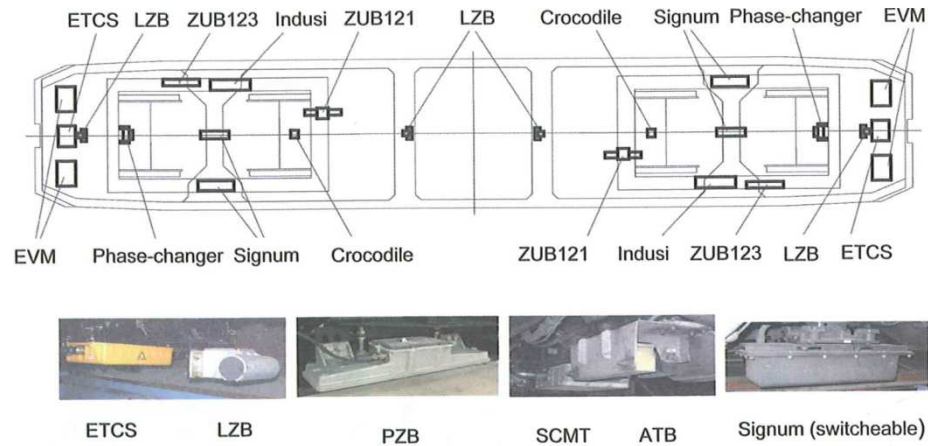


Figure 3.4 – Signalling devices from the different systems installed on the train. [61]

Another restrictive factor is the requirement of different displays in the train cabin, so driver can receive the information and operate in the different systems installed, as for example, in the cabin of the Thalys (figure 3.5).[55, 62]



Figure 3.5 – Cab of the train Thalys. [61]

3.2.2. COMPETITION IN THE SYSTEMS SUPPLY

The acquisition based on an open tender, it is a fundamental requirement for any public sector. But with the lack of standard requirements or system, this principle had no economic strength.

With the development of ERTMS, the customers can acquire equipments from all ERTMS supplying companies and all those same companies will also be able to make their offers. Track equipments as well as on-board equipments can be acquired from any one of the six ERTMS supplying companies, making the market more competitive. [62]

3.2.3. QUALITY AND SAFETY SERVICE

The rail transportation demands restricted safety specifications but the traditional signalling and traffic control systems have some limitations. Contrarily to the road transport, the rail transport move along tracks and needs a considerable braking distance, especially while travelling in high-speed. The reason is pure physics: the weak adhesion of the metal with the train wheels and the enormous amount of weight of the vehicle makes an immediate stop impossible.

In many track lines there is a need of substituting the old systems for more modern, safer and reliable ones. This requirement is even more important in high-speed lines, where on-board signalling is mandatory. Without a control system with complete supervision, it wouldn't be possible to circulate in high speed in a safe way.

Modern technologies (used in ERTMS) offer the possibility to improve the quality of the rail operation, by supporting the drivers and the rail traffic controllers with the information needed. ERTMS was developed to operate at the speed of 500 Km/h, in hoping that in a nearby future all the trains can circulate at that speed in a safe and reliable way. [62]

3.2.4. THE INCREASE OF TRANSPORT CAPACITY

The pressure and the need to increase the rail transport capacity is a reality. This can be achieved by improving the existent track lines and by creating new ones. Given the fact that these two options are quite expensive and slow, the best option is to entrust the existent lines with more of transport capacity: This can be accomplished by exploring of the vast potential of the railway signalling and of the new technologies in traffic control.

Therefore, the key for traffic's capacity increasing is changing from the traditional operating method of Fixed Blocking to Moving Blocking. [62]

3.2.5. . COST REDUCTION OF THE SYSTEM'S LIFE TIME

Economical studies show that the maintenance and reparation costs of the rail signalling systems are unbearable for certain track lines. As a result, some of those same lines have been closed.

In the last decades, communication technology and computers had an enormous progress in price/performance relationship.

With the ERTMS, maintenance costs are lower when compared with the traditional signalling systems. In fact from level 2 of ERTMS, when some track signalling equipments stop being necessary, the maintenance and reparation costs are substantially reduced. [62]

3.3. ERTMS

The European Railway Traffic Management System (ERTMS) is a massive industrial project developed by six members of UNIFE (Alstom Transport, Ansaldo STS, Bombardier Transportation, Invensys Rail Group, Siemens Mobility and Thales), in cooperation with the European Union, other railway entities and the industry of GSM-R.

ERTMS is constituted by two components:

- The GSM-R (Global System for Mobile Communication - Railway) a wireless radio system based on the GSM technology. This is a voice and data communication system between railway operational staff and station controllers, using restricted frequencies bands for railway applications and other advanced features. [56]
- The European Train Control System (ETCS) allows transmitting to the driver the movement authority information and the authorized speed; it also allows controlling constantly the driver performance, if he respects the indications and permissions given to him.

3.3.1. GSM-R

GSM-R is essential for the ETCS data transmission, assuring to the network a high capacity and a high quality service. The GSM-R requirements are subject to constant revision and its standard specifications given by EIRENE (European Integrated Radio Enhanced Network) are updated every 2 years.

According to European directive 91/440 on the development of the Community's railways, a new system of rail communications must:

- be open and standardized;
- promote national and international interoperability;
- suitable for international rail traffic;
- approved for the open competition between national/international operators;
- support new requirements of systems of rail signalling normalized (ETCS);
- up-to-date;
- be able to provide a safe platform in the voice communications and other rail functionalities;
- To be capable to support the commercial needs of the titleholders and network operators.

GSM-R's core is an ETSI GSM standard specially developed for the railway, with a GSM specifications and a reserved frequency band.

GSM-R includes the following railway functionalities:

- All the calls, emergency radio calls and ETCS, have priority;
- The calls for the users are made by a functional number management;
- The calls between the drivers and the rail traffic controllers are made by using the transmission of Long Line Public Address;
- The possibility of Voice Group Call System, for groups predefined;
- Emergency calls are possible in predefined, using the fast calls programming (in less than two seconds).

3.3.2. ETCS

Due to the nature of its requested functions, the ERTMS / ETCS have to be implemented partially in the train and the rest on the track and subsequently two subsystems are defined: the on-board subsystem and the track subsystem.

There also exist external systems to the track which are a part of ERTMS / ETCS, but on which interoperability requirements do not apply like for instance the interlocking, control centers, etc.

3.3.2.1. On-board subsystems

Depending on the level of ERTMS / ETCS, the on-board systems may have:

- ERTMS / ETCS on-board equipment;
- GSM-R on-board radio system;
- STM (Specific Transmission Modulate) for the national operating systems of the train.

The ERTMS / ETCS on-board equipment is computer system that supervises the movements of the train, based on the information shared with the track subsystem.

The interoperability requirements for the ERTMS / ETCS equipments are related with the functionality and the data communication between the on-board and track subsystems and also between the driver and the cabin sub subsystem, the train and the STM modules.

The GSM-R radio on-board system is used for the bidirectional transmission of information between the train and Radio Infill Unit (RBC).

3.3.2.2. TRACK SUBSYSTEMS

Also depending on the ERTMS / ETCS level, the track subsystems may have:

- Balises;
- Lineside Electronic Unit (LEU);
- Radio communication (GSM-R);
- Radio Block Centre (RBC);
- Euroloop;
- Radio Infill Unit.

The balise is transmission device, which sends “telegrams” from the track subsystem to on-board subsystem. It provides the up-link with fixed messages or, when connected the one LEU, the messages can be altered, depending on the present conditions regarding the track, the allowed speed, the movement authority, etc.

The balises are installed in groups: every balise transmits a telegram and the combination of those telegrams, defines the message sent by each group.

The LEUs are electronic devices that generate telegrams, be sent by the balises, with the received information of the external systems to the track.

The GSM-R it is used for the bidirectional change of information between the on-board subsystem and the RBC or RIU.

The RBC is a system based on a computer that creates the messages to be sent to the train, compiled with the received information of the external systems to the track and with the information shared with the on-board subsystems. The main goal of these messages is to supply movement authority, so the may circulate trains in the rail network in a secure way in the RBC area.

The RBC interoperability requirements concern the information shared between RBC and the on-board subsystem.

The Euroloop subsystem operates in the lines with ERTMS level 1, supplying in advance the signalling information regarding the next signal that the train will find. It combines the on-board functionalities and parts of the track.

The Radio In-fill Unit subsystem also operates in lines with ERTMS level 1, supplying in advance the signalling information regarding the next signal that the train will find. It combines the on-board functionalities and parts of the track. [63-65]

3.4. ERTMS LEVELS

The different possible correlations between the track and the train are reflected in the existence of several levels of ERTMS / ETCS.

The definition of the level depends on how the track is equipped, in which way the information is transmitted to the on-board equipments and how it is processed.

The different levels were defined in a way that allows each railway company to choose the ERTMS / ETCS level fitting their strategies, infrastructure and chosen operation performance.

One must also take in consideration that in the different levels, it's allowed an interaction between individual signalling systems and rail traffic control with ERTMS / ETCS.

The authorities that systematize the ERTMS/ETCS standard technical requirements have created an ERTMS / ETCS level 0 that is used to operate in lines not equipped with ERTMS / ETCS or in lines in commissioning.

The levels 3, 2 and 1 are compatible in a descending system. This means that a train equipped with ERTMS / ETCS level 3 can be operated in lines with level 1 and 2, and that a train equipped with level 2 can be operated in lines with level 1. [64, 66, 67]

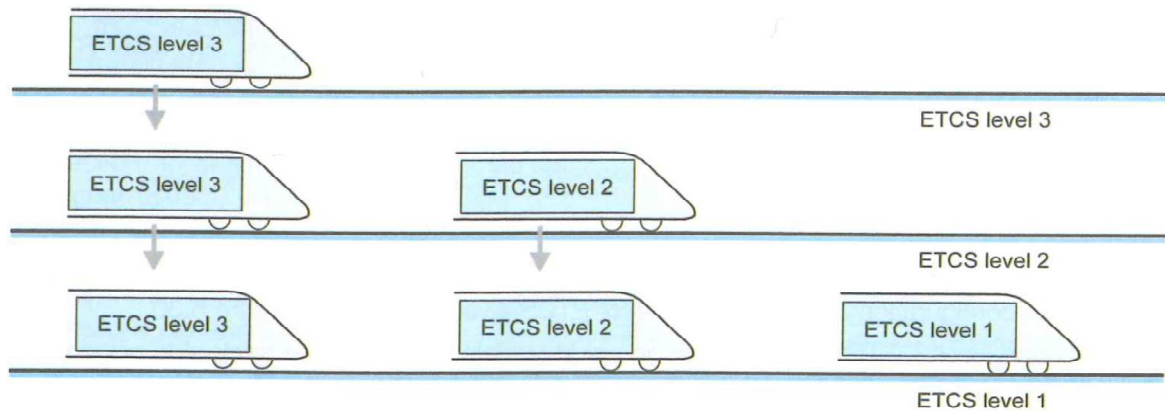


Figure 3.6 – Compatibility between the different ETCS levels. [68]

3.4.1. LEVEL 0

The level 0 corresponds to ERTMS / ETCS vehicles operating in non-ETCS route or in lines that are in commissioning. In this level of operation the movement authority is given to the driver through trackside signals whether optical or other signalling equipments external to ERTMS / ETCS.

The ERTMS / ETCS onboard equipment doesn't supervise the train movement, with the exception of the maximum speed allowed of that the line or specific line sections.

The supervision of the train's integrity and detection is made by a rail signalling system external to the ERTMS / ETCS scope.

In level 0, there isn't any communication between the track and the train, with the exception of Eurobalises, which announce and command the signalling level transition. Consequently, the train continues to read the Eurobalises but ignores all the receiving information, with exception of some special data.

In the Man-Machine Interface (MMI), the only information shown regarding the supervision of the vehicle's movement is the allowed speed. [69]

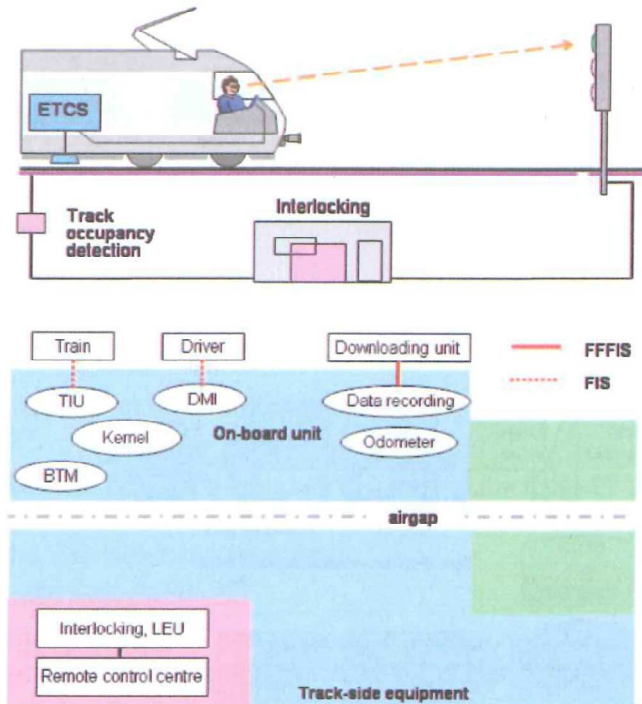


Figure 3.7 – Level 0. [70]

ERTMS / ETCS track equipments:

- Nonexistent track equipments, with the exception of Eurobalises for detecting level transition.

Main functions of the ERTMS / ETCS track equipments:

- None.

ERTMS / ETCS onboard equipments:

- Onboard equipment, with the Eurobalise payload data.

Main functions of the ERTMS / ETCS onboard system:

- To monitor the maximum speed;
- To monitor the maximum speed in a restricted area;
- To read the payload data in search for level transition or special commands;
- Nonexistent onboard signalling. [69]

3.4.2. STM LEVEL

The level STM is used when trains equipped with ERTMS / ETCS are operating in track lines equipped with nationwide signalling and supervision systems.

The payload data to be transmitted is produced by the national signalling system and which is sent to the train by the standard channels of that same system. When receiving the information, the train converts it on-board, making it intelligible for the ERTMS / ETCS. Depending on the functionality and performance of the national signalling system, the optical signals may be exempt.

STM (Specific Transmission Module) is the device that allows the ERTMS / ETCS on-board equipment to receive the nationwide signalling transmission. The monitoring level is similar to the nationwide system, in which the management of the trains detection and integrity is executed by external equipment to the ERTMS / ETCS.

This level of operation does not use ERTMS / ETCS transmissions between the rail track and the train, with the exception of the information from the Eurobalises regarding the level transition or other specific commands. However, the Eurobalises must be read. The on-board ERTMS / ETCS supervision functions are supported. The use of the on-board ERTMS / ETCS functionality may diverge, depending on the configuration of the STM level.

The information given to the driver depends on the functionality of the nationwide system, in which the report of active STM is a part of the payload data. The train should possess the data so it avoid stopping during level transitions and supervise the maximum permissible speed. [71]

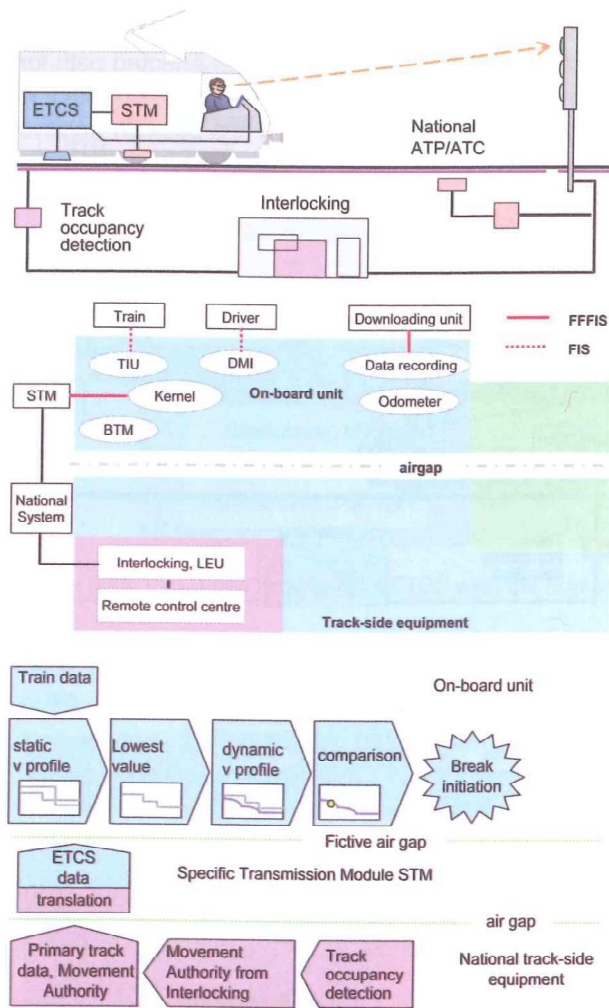


Figure 3.8 – STM level. [70]

ERTMS / ETCS track equipments:

- The level STM uses the transmission from the nationwide signalling system, which does not belong to ERTMS / ETCS. Usage of Eurobalises to announce the level transition.

Main functions of the ERTMS / ETCS track equipments:

- None.

ERTMS / ETCS onboard equipments:

- Onboard equipment, with Eurobalise transmission;
- STM compatible with the nationwide signalling system.

Main functions of the ERTMS / ETCS onboard system:

- Depends on the nationwide signalling system and the STM implementation;
- To read the Eurobalises to detect the level transition or special commands;
- On-board signalling depends on the nationwide signalling system. [71]

3.4.3. LEVEL 1

ERTMS / ETCS Level 1 is a cab signalling system that can be superimposed on the existing signalling system. The movement authority is generated by the track equipment and transmitted to the train by the Eurobalises.

This level of ERTMS / ETCS provides a continues supervision of the train speed and also avoid against the violation of the movement authority. The vehicle detection and the train integrity supervision is accomplished by track equipments of the adjacent nationwide system (track circuits, blocking, etc), being these systems aliens to the ERTMS / ETCS scope. The track equipment does not know to which train is sending out the information.

During an operation in an ERTMS / ETCS level 1, if a signal changes to “clear” mode, the approaching train does not receive that information until passing over the group of Eurobalises. For that same reason, the driver will have to observe the signal to know when the train can proceed. After passing the Eurobalises group and its respective signal, the train have permission to proceed of the next stopping place, in a maximum safe speed.

Additional Eurobalises can be install between main signals, with the purpose of transmitting intermediate information. As a result, the convoy will receive new data before reaching the signal.

It can also be installed a semi-continuous infill using Euroloop or Radio infill way, allowing the train to inform the driver continuously, as soon as the data is available. The signals are required in ERTMS / ETCS level 1, except if it is being operated in a semi-continuous infill way.

Euroloop or radio infill improves the safety of the ERTMS / ETCS level 1 and allows operating without the maximum safe speed when approaching an already “clear” signal. [72]

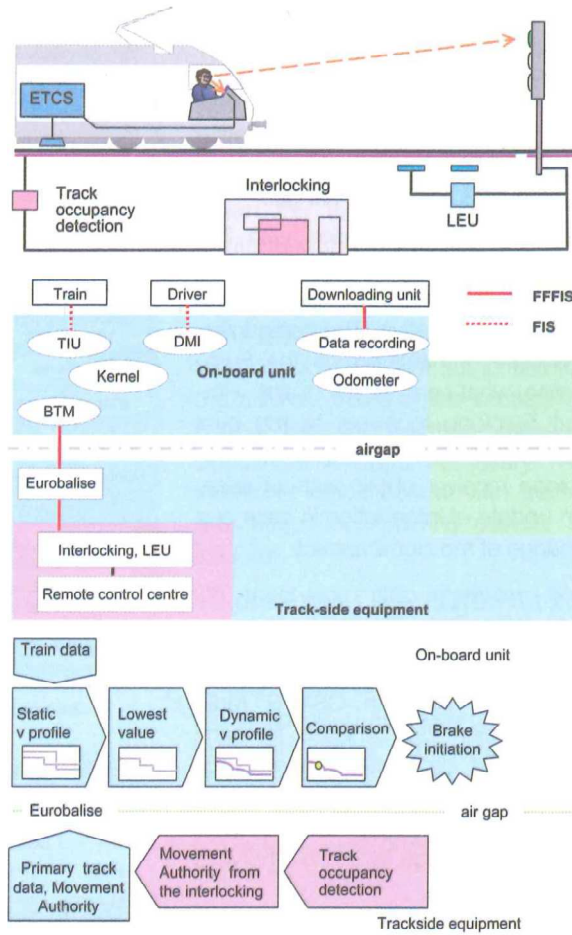


Figure 3.9 – ERTMS/ETCS level 1. [73]

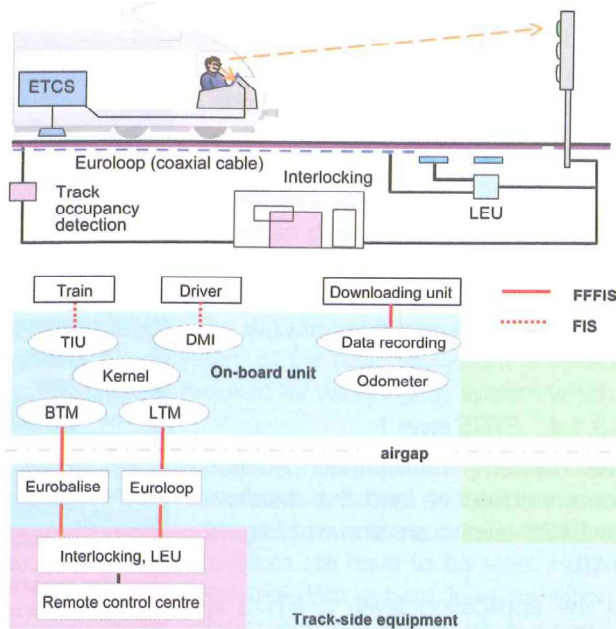


Figure 3.10 – ERTMS/ETCS level 1 with Euroloop in-fill. [74]

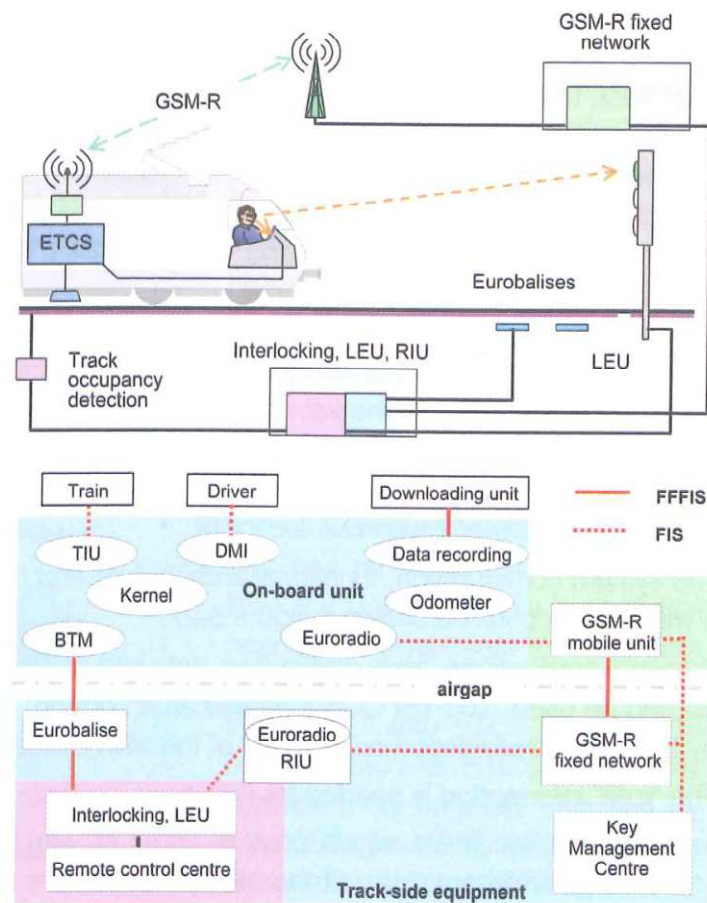


Figure 3.11 – ERTMS/ETCS level 1 with GSM-R in-fill. [74]

ERTMS / ETCS track equipments:

- Eurobalises to transmit information from the track to the train;
- Eurobalises should be able to transmit different data;
- Semi-continuous infill transmission using Euroloop or Radio in-fill.

Main functions of the ERTMS / ETCS track equipments:

- To determine movement authorities according with the adjacent signalling system;
- To transmit movement authority and information from the track to the train.

ERTMS / ETCS onboard equipments:

- On-board equipment, with Eurobalises transmission;
- Euroloop transmission if an Euroloop system is required;
- Radio infill transmission if a radio infill system is required.

Main functions of the ERTMS / ETCS onboard system:

- To receive the movement authority and the route information from the track transmitted by the groups of Eurobalises;
- To select, from all maximum safe speeds permitted, the most restrictive for the line ahead;
- To calculate the safe speed profile, taking in consideration the acceleration / braking of the train and the route characteristics;
- To compare of the train actual speed with the permitted one and the braking command, in case of need;
- Onboard signalling for the driver. [72]

3.4.4. LEVEL 2

ERTMS / ETCS level 2 is a radio-based signal and train control system that is superimposed on the existing signalling system. The movement authority is generated by the track equipment and transmitted to the train by Euroradio.

ERTMS / ETCS level 2 continually monitors the train speed, protecting against the infraction of the movement authority by the trains. The vehicle detection of the vehicles and the train integrity supervision is executed by the track equipment of the underlying national system (track circuits, blocking, etc), being these systems outsiders to the ERTMS / ETCS scope.

This level of ERTMS / ETCS is a Euroradio-based system for the communication between track and train. Eurobalises are also used as main equipment to report the trains exact position and direction. The Radio Block Center, which sends out the data to the trains, knows exactly which vehicle controlled by this system, through the ERTMS / ETCS train's identity, provided by its onboard equipment.

In this level the use of trackside signalling may be exempt. [75]

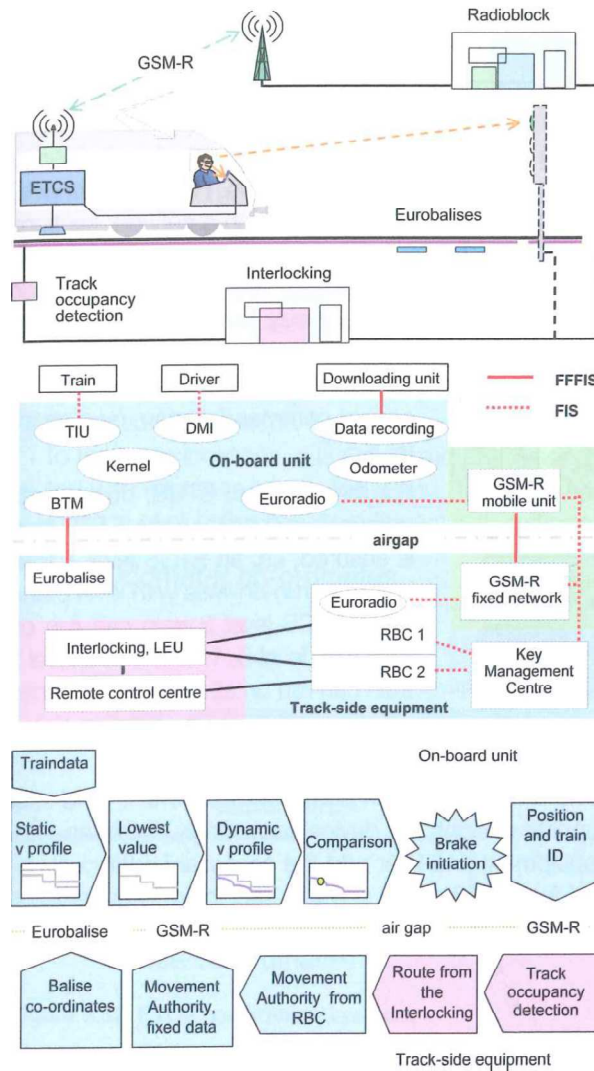


Figure 3.12 – ERTMS/ETCS level 2. [76]

ERTMS / ETCS track equipment:

- RBC (Radio Block Center);
- Euroradio for bi-directional communication between track and train;
- Eurobalises as main reference for train location.

Main functions of the ERTMS / ETCS track equipment:

- To acknowledge each train operating in ERTMS / ETCS in the RBC area, through the ERTMS / ETCS train identity;
- To follow in a RBC area each ERTMS / ETCS train location controller;
- To determine movement authorities according to the underlying signalling system;
- To transmit movement authority and route information for each train individually;
- To turn over the train control in the limits area of different RBC.

ERTMS / ETCS onboard equipment:

- On-board equipment, with Eurobalises and Euroradio transmission.

Main functions of the ERTMS / ETCS onboard system:

- To read the Eurobalises and report the train's position to the RBC, according with detected balises;
- To receive the movement authority and route information transmitted by Euroradio;
- To select, from all maximum safe speeds permitted, the most restrictive for the line ahead;
- To calculate the safe speed profile, taking in consideration the acceleration / braking of the train and the route characteristics;
- To compare of the train actual speed with the permitted one and the braking command, in case of need;
- Onboard signalling for the driver. [75]

3.4.5. LEVEL 3

ERTMS / ETCS level 3 is a radio-based train control system. The movement authority is given by the track equipment and transmitted to the train by Euroradio.

ERTMS / ETCS level 3 continually monitors the train speed, protecting against the infraction of the movement authority by the trains. The vehicle detection of the vehicles and the train integrity supervision is accomplished by RBC in cooperation with the train, which reports on its position and integrity.

This level of ERTMS / ETCS is a Euroradio-based system for the communication between track and train. Eurobalises are also used as main equipment to report the trains exact position and direction. The Radio Block Center, which sends out the data to the trains, knows exactly which vehicle controlled by this system, through the ERTMS / ETCS train's identity, provided by its onboard equipment.

In this level the use of trackside signalling is not considered. [77]

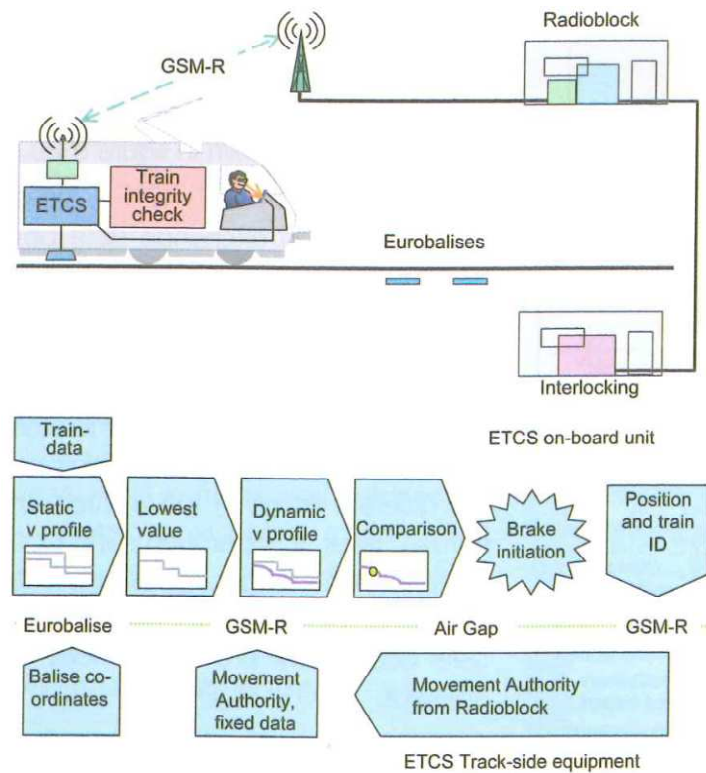


Figure 3.13 – ERTMS/ETCS level 3. [68]

ERTMS / ETCS track equipment:

- RBC (Radio Block Center);
- Euroradio for bi-directional communication between track and train;
- Eurobalises as main reference for train location.

Main functions of the ERTMS / ETCS track equipment:

- To acknowledge each train operating in ERTMS / ETCS in the RBC area, through the ERTMS / ETCS train identity;
- To follow in a RBC area each ERTMS / ETCS train location controller;
- To determine movement authorities according to the underlying signalling system;
- To transmit movement authority and route information for each train individually;
- To turn over the train control in the limits area of different RBC.

ERTMS / ETCS onboard equipment:

- Onboard equipment, with Eurobalises and Euroradio transmission.
- Train integrity system.

Main functions of the ERTMS / ETCS onboard system:

- To read the Eurobalises and report the train's position to the RBC, according with detected becons;
- To monitor the train's integrity (outsider function to the ERTMS/ETCS) and to sent out to the RBC;
- To receive the movement authority and route information transmitted by Euroradio;
- To select, from all maximum safe speeds permitted, the most restrictive for the line ahead;
- To calculate the safe speed profile, taking in consideration the acceleration / braking of the train and the route characteristics;
- To compare of the train actual speed with the permitted one and the braking command, in case of need;
- On-board signalling for the driver. [77]

4

ERTMS IMPLEMENTATION ON THE MJÖLBY - ALVESTA LINE

4.1. INTRODUCTION

In this chapter a study will be presented, supported on simulations of different railway signalling solutions, including ERTMS level 2 and level 3, in the Mjölby - Alvesta line, part of the route Stockholm – Malmö.

In this study, it is intended to know which are the best development strategy, the more functional and the economical approach more viable to the line in analysis.

4.2. MJÖLBY – ALVESTA LINE

After the decision of the European Commission in 26 of October of 2006, by which create the executive Agency of the network trans-european of transport in application of the Regulation (CE) n° 58/2003 of the Council (2007/60/CE), all the member states of the European Union should present a plan of ERTMS implementation to answer to the requirements of TSI 2006/860/EC (Control command and signalling subsystem of the trans-European high speed rail system) and TSI 2006/679/EC (Control command and signalling subsystem of the trans-European conventional rail system).

The Swedish strategy for implementation of ERTMS in the infrastructure can be summed up in the following order of priority [78]

- 1) New and/or essentially upgraded routes or line;
- 2) Routes or lines without signalling system, centralized traffic control and ATP systems;
- 3) Routes or lines with major reinvestment needs for existing signal plants;
- 4) Routes or lines included in the corridors pointed out by the European Union used by freight trains crossing borders;
- 5) The remaining parts of the routes in TEN-T and after that other parts of the railway network;

ERTMS is planned to be implemented on the Swedish part of Corridor B before 2020 and in Swedish railway TEN routes by 2035. [78]

The line Mjölby - Alvesta was chosen for this study because it is a part to the Southern Main Line, between Malmö and Stockholm. The Southern Main Line is one of the most important routes in Sweden for several reasons: it connects two main cities of the country; it ties the Swedish capital to the south of the country and also very important, it connects of two northern European capitals: Stockholm and Copenhagen.

In this line circulate freight trains, regional trains and long distance trains.



Figure 4.0 – Line Mjölby – Alvesta.

In this academic work, different scenarios will be simulated using all the three signalling types proposed for this study: ATC (conventional signalling, the current signalling system in the line), ETCS level 2 and ETCS level 3.

The line environment (geography, speed restrictions, line sections, etc) used in these simulations is faithful to the current state of the line study (Mjölby - Alvesta line, part of the route Stockholm – Malmö).

4.3. SOFTWARE USED IN THE SIMULATIONS

To simulate all proposed scenarios for the line in study, it was used Railsys 7.0., a program of infrastructures and timetable management.

RailSys 7.0 is software of system analysis, planning and optimization of operational procedures for a rail network of any size. The operational procedures are microscopic descriptions of the real world in the model, displayed on the computer desktop and the analysis of the whole system as the solving of specific and local problems are easily accomplished.

This program has been developed by the University of Hannover and RMCon (Rail Management Consultations). It has been applied with success in different projects such as the high-speed lines Cologne - Rhein/Main and Sydney - Canberra, the city railways of Munich, Sydney, Melbourne, etc, or the rail network of Berlin and Copenhagen.

RailSys consists of three modules:

- *Infrastructure Manager*
- *Timetable and Simulation Manager*
- *Evaluation Manager*

4.3.1. INFRASTRUCTURE MANAGER

Infrastructure Manager Function is, as the own name indicates, is to model the existing infrastructure and to build up different infrastructure variants. It includes ail signals, pointers, train stations, routes, and contain attributes about track parameters like length, gradient, maximum speed. The information can be inserted on a graphic or in table form.

4.3.2. TIMETABLE AND SIMULATION MANAGER

Thanks to the Timetable and Simulation Manager it is possible to set exact routes and different alternatives for every train in the rail network created by the Infrastructure Manager.

The main task of the program is the optimal allocation of locomotives in large lines or networks, showing inconsistencies such as unfeasible connection times, not enough headways and conflicts with other trains. To be able to do this, the program uses several functions as the continuous conflict recognition in the rail net and the continuous calculation of the minimum journey duration.

Nominal or perturbed simulations can be carried out: the nominal simulation serves normally to check that everything is working fine the perturbed simulation, it is necessary to emulate real train operations because of the complex relationship when a train is late.

4.3.3. EVALUATION MANAGER

This model has been developed to evaluate the impact of the infrastructure or timetable alternatives. It evaluates the performance of the simulated operational program, by means of preparing and analysing the delay data. To identifying the most favourable option, comparisons should be made.

The results can be displayed as performance of the whole network, for lines only, in stations, for the total amount of trains or for different patterns. Different parameters can be analyzed: arrival and departure delays, additionally generated delays (which could identify critical sections), on time running performance at stations, number of delayed trains, number of operational manoeuvres, block occupation, etc. [79, 80]

4.4. TRAINS

For this study 3 types of trains were chosen, each one operated with different ends, a reproduction of the actual line: a long distance trains, a regional train and a freight trains.

LDT– Long distance train



Figure 4.1 – Zefiro (X32). [81]

Maximum speed: 320 (km/h)

Acceleration: 1.2 (m/s²)

Length: 155 (m)

Weight: 360 (t)

RT – Regional train



Figure 4.2 – Regina X52, photo: Oskar Fröidh.

Maximum speed: 200 (km/h)

Acceleration: 1.0 (m/s²)

Length: 54 (m)

Weight: 135 (t)

FT – Freight train



Figure 4.3 – Green Cargo Rc4, foto: Oskar Fröidh.

Maximum speed: 100 (km/h)

Acceleration: 1.0 (m/s²)

Length: 400 (m)

Weight: 1000 (t)

4.5. TIMETABLES

In these scenarios the following timetables will be used (a document where all the trains and the time schedule is they are presented). [82]

Stations		Train type			
		FT	RT	LDT_Stop	LDT_NonStop
Mjölby	(My)		Stop	Stop	
Lindekullen	(Lkn)				
Boxholm	(Bx)		Stop		
Sommen	(Smn)				
Tranås	(Tns)		Stop		
Gripenberg	(Gp)				
Frinaryd	(Frd)				
Ralingsås	(Ras)				
Aneby	(Any)		Stop		
Flisby	(Fls)				
Vimnarp	(Vim)				
Gamlarp	(Gmp)				
Nässjö C	(N)		Stop	Stop	
Grimstorp	(Gt)				
Bodafors	(Bdf)				
Ulvstorp	(Utp)				
Sävsjö	(Sä)		Stop		
Aleholm	(Ahm)				
Stockaryd	(Sy)				
Rörvik	(Rk)				
Grevaryd	(Grd)				
Lidnäs	(Lns)				
Moheda	(Mo)				
Gåvetorp	(Gåp)				
Alvesta	(Av)		Stop	Stop	

Table 4.0 – Timetable 1.

Stations		Type of train
		LDT_Stop
Mjölby	(My)	Stop
Lindekullen	(Lkn)	
Boxholm	(Bx)	
Sommen	(Smn)	
Tranås	(Tns)	
Gripenberg	(Gp)	
Frinaryd	(Frd)	
Ralingsås	(Ras)	
Aneby	(Any)	
Flisby	(Fls)	
Vimnarp	(Vim)	
Gamlarp	(Gmp)	
Nässjö C	(N)	Stop
Grimstorp	(Gt)	
Bodafors	(Bdf)	
Ulvstorp	(Utp)	
Sävsjö	(Sä)	
Aleholm	(Ahm)	
Stockaryd	(Sy)	
Rörvik	(Rk)	
Grevaryd	(Grd)	
Lidnäs	(Lns)	
Moheda	(Mo)	
Gåvetorp	(Gåp)	
Alvesta	(Av)	Stop

Table 4.1 – Timetable 2.

Stations		Type of train
		RT
Mjölby	(My)	Stop
Lindekullen	(Lkn)	
Boxholm	(Bx)	Stop
Sommen	(Smn)	
Tranås	(Tns)	Stop
Gripenberg	(Gp)	
Frinaryd	(Frd)	
Ralingsås	(Ras)	
Aneby	(Any)	Stop
Flisby	(Fls)	
Vimnarp	(Vim)	
Gamlarp	(Gmp)	
Nässjö C	(N)	Stop
Grimstorp	(Gt)	
Bodafors	(Bdf)	
Ulvstorp	(Utp)	
Sävsjö	(Sä)	Stop
Aleholm	(Ahm)	
Stockaryd	(Sy)	
Rörvik	(Rk)	
Grevaryd	(Grd)	
Lidnäs	(Lns)	
Moheda	(Mo)	
Gåvetorp	(Gåp)	
Alvesta	(Av)	Stop

Table 4.2 – Timetable 3.

4.6. SCENARIOS

4.6.1. SCENARIOS OVERVIEW

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Signalling systems	ATC	ATC	ATC	ATC	
	ETCS level2	ETCS level2	ETCS level2	ETCS level2	ETCS level2
	ETCS level3	ETCS level3	ETCS level3	ETCS level3	ETCS level3
Timetable	Timetable 1	Timetable 1	Timetable 1	Timetable 2	Timetable 2
				Timetable 3	Timetable 3
Train types	FT	FT	FT	RT	RT
	RT	RT	RT		
	LDT_Stop	LDT_Stop	LDT_Stop	LDT_Stop	LDT_Stop
	LDT_NonStop	LDT_NonStop	LDT_NonStop		
Máx. Speed permitted	200 km/h - ATC	200 km/h - ATC	200 km/h - ATC	200 km/h - ATC	320 km/h - ETCS level2(all line, dedicate line) 320 km/h - ETCS level3(all line, dedicate line)
	200 km/h - ETCS level2	320 km/h - ETCS level2	320 km/h - ETCS level2	320 km/h - ETCS level2	
	200 km/h - ETCS level3	320 km/h - ETCS level3	320 km/h - ETCS level3	320 km/h - ETCS level3	
Perturbation	No	No	Yes	No	No
Simulation time	1 day (1cycle)	1 day (1cycle)	365 days (365cycles)	1 day (1cycle)	1 day (1cycle)

Table 4.3 – Scenarios overview.

4.6.2. SCENARIO 1

In this scenario, the three different trains are inserted in the same timetable, timetable1 and the line operation in each signalling system takes in consideration the maximum speed allowed of 200 km/h. The operation occurs during 1 day (1 cycle).

4.6.2.1. Assumptions

The main line infrastructure is used in the simulator is the current infrastructure in the Southern Main Line Stockholm - Malmö. The speeds of every track section are the present-day ones with the speed limit of 200 Km/h.

All three different trains are presented in the timetable1 used in scenario 1. However, the long distance train (LDT) is operated in two different ways and therefore has two different schedules:

- LDT_Stop - it begins to operate at 7:00:00, has a frequency of 60 minutes and the last train leaves at 21:00:00. Fifteen trains are operated per day.
- LDT_NonStop - it begins to operate at 7:30:00, has a frequency of 60 minutes and the last train leaves at 19:30:00. Thirteen trains are operated per day.
- RT (Regional train) – it begins to operate at 5:03:00, has a frequency of 20 minutes and the last train leaves at 23:23:00. Fifty trains are operated per day;
- FT (Freight train) - it begins to operate at 4:07:00, has a frequency of 60 minutes and the last train leaves at 22:07:00. Nineteen trains are operated per day.

4.6.2.2. Results

Stations		Delay			
		FT	RT	LDT_Stop	LDT_NonStop
Mjölby	(My)	0	0	0	0
Lindekullen	(Lkn)	0	0	0	0
Boxholm	(Bx)	0	0	0	0
Sommen	(Smn)	0	0	0	0
Tranås	(Tns)	0	0	0	0
Gripenberg	(Gp)	0	0	0	40
Frinnaryd	(Frd)	0	0	0	39
Ralingsås	(Ras)	0	0	0	39
Aneby	(Any)	0	0	0	134
Flisby	(Fls)	0	0	0	193
Vimnarp	(Vim)	0	0	0	192
Gamlarp	(Gmp)	0	3	0	196
Nässjö C	(N)	0	0	0	215
Grimstorp	(Gt)	264	118	0	311
Bodafors	(Bdf)	348	117	0	310
Ulvstorp	(Utp)	348	115	0	311
Sävsjö	(Sä)	348	82	0	310
Aleholm	(Ahm)	347	82	0	310
Stockaryd	(Sy)	347	81	0	309
Rörvik	(Rk)	963	80	0	309
Grevaryd	(Grd)	348	79	0	308
Lidnäs	(Lns)	1035	78	0	308
Moheda	(Mo)	1035	76	0	308
Gåvetorp	(Gåp)	1035	75	0	307
Alvesta	(Av)	1034	45	0	307

Table 4.4 – Train delays operating in a conventional system – scenario 1.

Stations		Delays			
		FT	RT	LDT_Stop	LDT_NonStop
Mjölby	(My)	0	0	0	0
Lindekullen	(Lkn)	0	0	0	0
Boxholm	(Bx)	0	0	0	0
Sommen	(Smn)	0	0	0	0
Tranås	(Tns)	0	0	0	2
Gripenberg	(Gp)	0	0	0	7
Frinnaryd	(Frd)	0	0	0	8
Ralingsås	(Ras)	0	0	0	12
Aneby	(Any)	0	0	0	138
Flisby	(Fls)	0	0	0	156
Vimnarp	(Vim)	0	0	0	164
Gamlarp	(Gmp)	0	7	0	176
Nässjö C	(N)	335	0	0	204
Grimstorp	(Gt)	415	0	0	205
Bodafors	(Bdf)	415	0	0	204
Ulvstorp	(Utp)	415	0	0	205
Sävsjö	(Sä)	415	0	0	205
Aleholm	(Ahm)	414	0	0	205
Stockaryd	(Sy)	414	0	0	205
Rörvik	(Rk)	415	0	0	204
Grevaryd	(Grd)	958	0	0	204
Lidnäs	(Lns)	1025	0	0	205
Moheda	(Mo)	1026	0	0	204
Gåvetorp	(Gåp)	1025	0	0	204
Alvesta	(Av)	1025	0	0	204

Table 4.5 – Train delays operating in ETCS2 - scenario1.

Stations		Delay			
		FT	RT	LDT_Stop	LDT_NonStop
Mjölby	(My)	0	0	0	0
Lindekullen	(Lkn)	0	0	0	0
Boxholm	(Bx)	0	0	0	0
Sommen	(Smn)	0	0	0	0
Tranås	(Tns)	0	0	0	0
Gripenberg	(Gp)	0	0	0	0
Frinnaryd	(Frd)	0	0	0	0
Ralingsås	(Ras)	0	0	0	0
Aneby	(Any)	0	0	0	30
Flisby	(Fls)	0	0	0	112
Vimnarp	(Vim)	0	0	0	127
Gamlarp	(Gmp)	0	7	0	131
Nässjö C	(N)	0	0	0	143
Grimstorp	(Gt)	515	0	0	144
Bodafors	(Bdf)	515	0	0	143
Ulvstorp	(Utp)	515	0	0	144
Sävsjö	(Sä)	514	0	0	144
Aleholm	(Ahm)	514	0	0	144
Stockaryd	(Sy)	514	0	0	144
Rörvik	(Rk)	515	0	0	143
Grevaryd	(Grd)	966	0	0	143
Lidnäs	(Lns)	1035	0	0	144
Moheda	(Mo)	1035	0	0	144
Gåvetorp	(Gåp)	1035	0	0	143
Alvesta	(Av)	1035	0	0	143

Table 4.6 – Train delays operating on ETCS3 - scenario1.

4.6.3. SCENARIO 2

In this scenario, the three different trains are inserted in the same timetable, timetable1. The vehicles were operated in an ETCS level 2 with the maximum speed of 320 Km/h and in an ETCS level 3, with the maximum speed of 320 km/h. The operation occurs during 1 day (1 cycle).

4.6.3.1. Assumptions

The main line infrastructure is used in the simulator is the current infrastructure in the Southern Main Line Stockholm - Malmö. The speeds of every track section are the present-day ones, with the exception of the speeds that previously were greater than or equal to 200 Km/h are now of 320 Km/h.

All three different trains are presented in the timetable1 used in scenario 1. However, the long distance train (LDT) is operated in two different ways and therefore has two different schedules:

- LDT_Stop - it start to operate at 7:00:00, has a frequency of 60 minutes and the last train leaves at 21:00:00. Fifteen trains are operated per day.
- LDT_NonStop - it start to operate at 7:30:00, has a frequency of 60 minutes and the last train leaves at 19:30:00. Thirteen trains are operated per day.
- RT - it starts to operate at 5:03:00, has a frequency of 20 minutes and the last train leaves at 23:23:00. Fifty-six trains are operated per day.
- FT - it starts to operate at 4:07:00, has a frequency of 60 minutes and the last train leaves at 22:07:00. Nineteen trains are operated per day.

4.6.3.2. Results

Stations		Delay			
		FT	RT	LDT_Stop	LDT_NonStop
Mjölby	(My)	0	0	0	0
Lindekullen	(Lkn)	0	0	0	0
Boxholm	(Bx)	0	0	0	0
Sommen	(Smn)	0	0	0	0
Tranås	(Tns)	0	0	0	1
Gripenberg	(Gp)	0	0	0	5
Frinnaryd	(Frd)	0	0	0	3
Ralingsås	(Ras)	0	0	0	8
Aneby	(Any)	0	0	0	135
Flisby	(Fls)	0	0	0	152
Vimnarp	(Vim)	0	0	0	159
Gamlarp	(Gmp)	0	7	0	172
Nässjö C	(N)	339	0	0	199
Grimstorp	(Gt)	419	0	0	168
Bodafors	(Bdf)	419	0	0	142
Ulvstorp	(Utp)	419	0	0	127
Sävsjö	(Sä)	419	0	0	88
Aleholm	(Ahm)	419	0	0	84
Stockaryd	(Sy)	419	0	0	33
Rörvik	(Rk)	419	0	0	0
Grevaryd	(Grd)	957	0	0	0
Lidnäs	(Lns)	1025	0	0	0
Moheda	(Mo)	1025	0	0	0
Gåvetorp	(Gåp)	1025	0	0	0
Alvesta	(Av)	1025	0	0	0

Table 4.7 – Train delays operating on ETCS2 – scenario2.

Stations		Delay			
		FT	RT	LDT_Stop	LDT_NonStop
Mjölby	(My)	0	0	0	0
Lindekullen	(Lkn)	0	0	0	0
Boxholm	(Bx)	0	0	0	0
Sommen	(Smn)	0	0	0	0
Tranås	(Tns)	0	0	0	0
Gripenberg	(Gp)	0	0	0	0
Frinnaryd	(Frd)	0	0	0	0
Ralingsås	(Ras)	0	0	0	0
Aneby	(Any)	0	0	0	27
Flisby	(Fls)	0	0	0	112
Vimnarp	(Vim)	0	0	0	126
Gamlarp	(Gmp)	0	0	0	130
Nässjö C	(N)	343	0	0	143
Grimstorp	(Gt)	515	0	0	113
Bodafors	(Bdf)	515	0	0	87
Ulvstorp	(Utp)	515	0	0	72
Sävsjö	(Sä)	514	0	0	33
Aleholm	(Ahm)	514	0	0	29
Stockaryd	(Sy)	514	0	0	0
Rörvik	(Rk)	515	0	0	0
Grevaryd	(Grd)	966	0	0	0
Lidnäs	(Lns)	1035	0	0	0
Moheda	(Mo)	1035	0	0	0
Gåvetorp	(Gåp)	1035	0	0	0
Alvesta	(Av)	1035	0	0	0

Table 4.8 – Train delays operating on ETCS3 – scenario2.

4.6.4. SCENARIO 3

In this scenario were inserted in timetable1 not only are all three different trains, but also perturbations in track line. The line operation with the existent conventional signalling took in consideration the maximum speed allowed in the line (200 km/h) and the ETCS level 2 and ETCS Level 3 were operated at the maximum speed of 320 km/h. The operation occurs during 365 days (365 cycles).

4.6.4.1. Assumptions

The main line infrastructure is used in the simulator is the current infrastructure in the Southern Main Line Stockholm - Malmö. The speeds of every track section are the present-day ones, with the exception of the speeds that previously were greater than or equal to 200 Km/h are now of 320 Km/h.

All three different trains are presented in the timetable1 used in scenario 1. However, the long distance train (LDT) is operated in two different ways and therefore has two different schedules:

- LDT_Stop - it start to operate at 7:00:00, has a frequency of 60 minutes and the last train leaves at 21:00:00. Fifteen trains are operated per day.
- LDT_NonStop - it start to operate at 7:30:00, has a frequency of 60 minutes and the last train leaves at 19:30:00. Thirteen trains are operated per day.
- RT - it starts to operate at 5:03:00, has a frequency of 20 minutes and the last train leaves at 23:23:00. Fifty-six trains are operated per day.
- FT - it starts to operate at 4:07:00, has a frequency of 60 minutes and the last train leaves at 22:07:00. Nineteen trains are operated per day.

And with the following perturbations:

Train	Station	Perturbation
FT	Mjölby	Train delay at the arrival
FT	Boxholm	Driver's failure / Signalling failure
FT	Ralingsås	Driver's failure / Signalling failure
FT	Ulvstorp	Driver's failure / Signalling failure
FT	Lidnäs	Driver's failure / Signalling failure
RT	Mjölby	Train delay at the arrival
RT	Boxholm	Driver's failure / Signalling failure
RT	Tranås	Delay in passengers exit and entering
RT	Ralingsås	Driver's failure / Signalling failure
RT	Aneby	Delay in passengers exit and entering
RT	Nässjö C	Delay in passengers exit and entering
RT	Ulvstorp	Driver's failure / Signalling failure
RT	Sävsjö	Delay in passengers exit and entering
RT	Lidnäs	Driver's failure / Signalling failure
LDT	Mjölby	Train delay at the arrival
LDT	Boxholm	Driver's failure / Signalling failure
LDT	Ralingsås	Driver's failure / Signalling failure
LDT	Nässjö C	Delay in passengers exit and entering
LDT	Ulvstorp	Driver's failure / Signalling failure
LDT	Lidnäs	Driver's failure / Signalling failure

Table 4.9 – Perturbations.

4.6.4.2. Results

Freight Trains

Station	Arrival delay	Departure delay	Punctuality [%]
My	00:05:18	00:05:28	81.0
Av	00:21:07	00:21:07	6.2

Table 4.10 – Arrival/departure delays and punctuality of FT on ATC.

Regional Trains

Station	Arrival delay	Departure delay	Punctuality [%]
My	00:02:15	00:01:51	91.0
Bx	00:01:48	00:01:31	92.2
Tns	00:01:29	00:01:39	93.1
Any	00:01:40	00:01:50	92.9
N	00:01:54	00:01:47	92.6
Sä	00:02:01	00:02:10	92.1
Av	00:02:18	00:01:58	91.4

Table 4.11 – Arrival/departure delays and punctuality of RT on ATC.

Long Distance Train_Stop

Station	Arrival delay	Departure delay	Punctuality [%]
My	00:03:25	00:03:04	83.5
N	00:04:23	00:04:08	77.7
Av	00:04:25	00:03:37	77.2

Table 4.12 – Arrival/departure delays and punctuality of LDT_Stop on ATC.

Long Distance Train_NonStop

Station	Arrival delay	Departure delay	Punctuality [%]
My	00:03:27	00:03:27	84.0
Av	00:07:46	00:07:46	29.0

Table 4.13 – Arrival/departure delays and punctuality of LDT_NonStop on ATC.

Freight trains

Station	Arrival delay	Departure delay	Punctuality [%]
My	00:05:08	00:05:19	80.9
Av	00:18:33	00:18:33	9.1

Table 4.14 – Arrival/departure delays and punctuality of FT on ETCS2.

Regional Trains

Station	Arrival delay	Departure delay	Punctuality [%]
My	00:02:15	00:01:52	90.8
Bx	00:01:53	00:01:35	91.8
Tns	00:01:35	00:01:45	92.6
Any	00:01:47	00:01:56	92.3
N	00:02:03	00:01:50	91.9
Sä	00:01:55	00:02:04	92.1
Av	00:02:09	00:01:48	91.5

Table 4.15 – Arrival/departure delays and punctuality of RT on ETCS2.

Long Distance Train _Stop

Station	Arrival delay	Departure delay	Punctuality [%]
My	00:03:22	00:03:01	83.9
N	00:04:10	00:03:56	78.2
Av	00:02:37	00:02:13	80.5

Table 4.16 – Arrival/departure delays and punctuality of LDT_Stop on ETCS2.

Long Distance Train _NonStop

Station	Arrival delay	Departure delay	Punctuality [%]
My	0:03:18	0:03:18	84.3
Av	0:02:26	0:02:26	88.6

Table 4.17 – Arrival/departure delays and punctuality of LDT_NonStop on ETCS2.

Freight Train

Station	Arrival delay	Departure delay	Punctuality [%]
My	00:05:13	00:05:18	81.7
Av	00:16:32	00:16:32	17.3

Table 4.18 – Arrival/departure delays and punctuality of FT on ETCS3.

Regional Train

Station	Arrival delay	Departure delay	Punctuality [%]
My	00:02:12	00:01:48	91.3
Bx	00:01:49	00:01:31	92.2
Tns	00:01:32	00:01:42	93.1
Any	00:01:45	00:01:54	92.7
N	00:01:59	00:01:45	92.4
Sä	00:01:49	00:01:58	92.0
Av	00:02:11	00:01:49	91.3

Table 4.19 – Arrival/departure delays and punctuality of RT on ETCS3.

Long Distance Train _Stop

Station	Arrival delay	Departure delay	Punctuality [%]
My	00:03:17	00:02:56	84.7
N	00:04:02	00:03:48	78.7
Av	00:02:32	00:02:07	80.8

Table 4.20 – Arrival/departure delays and punctuality of LDT_Stop on ETCS3.

Long Distance Train _NonStop

Station	Arrival delay	Departure delay	Punctuality [%]
My	00:03:13	00:03:13	84.9
Av	00:02:22	00:02:22	88.7

Table 4.21 – Arrival/departure delay and punctuality of LDT_NonStop in the ETCS3.

If we consider the increase of the maximum speed allowed in ETCS2 and ETCS3, it is possible to cut down the journey duration of trains able to circulate in a speed higher than 200 Km/h. By shortening the journey duration, the route is improved and new schedules are stipulated for the operating trains.

Because the trains delays and punctuality is a result from the comparison of their time of arrival at the stations, the new schedules affects the results from the ETCS2 and the ETCS3.

Freight Trains

Station	Arrival delay	Departure delay	Punctuality [%]
My	00:05:20	00:05:30	81.0
Av	00:26:03	00:26:03	6.6

Table 4.22 – Arrival/departure delays and punctuality of FT on ETCS2, with new timetables and shorter journey duration.

Regional Trains

Station	Arrival delay	Departure delay	Punctuality [%]
My	00:02:15	00:01:51	91.0
Bx	00:01:53	00:01:35	91.8
Tns	00:01:35	00:01:45	92.9
Any	00:01:48	00:01:57	92.5
N	00:02:04	00:03:21	92.1
Sä	00:03:32	00:03:41	74.0

Table 4.23 – Arrival/departure delays and punctuality of RT on ETCS2, with new timetables and shorter journey duration.

Long Distance Train _Stop

Station	Arrival delay	Departure delay	Punctuality [%]
My	0:03:31	0:03:10	83.5
N	0:04:30	0:04:15	78.3
Av	0:05:04	0:04:13	67.4

Table 4.24 – Arrival/departure delays and punctuality of LDT_Stop on ETCS2, with new timetables and shorter journey duration.

Long Distance Train _NonStop

Station	Arrival delay	Departure delay	Punctuality [%]
My	00:03:20	00:03:20	84.0
Av	00:07:07	00:07:07	52.8

Table 4.25 – Arrival/departure delays and punctuality of LDT_NonStop on ETCS2, with new timetables and shorter journey duration.

Freight Trains

Station	Arrival delay	Departure delay	Punctuality [%]
My	00:05:13	00:05:18	81.7
Av	00:20:24	00:20:24	9.4

Table 4.26 – Arrival/departure delays and punctuality of FT on ETCS3, with new timetables and shorter journey duration.

Regional Trains

Station	Arrival delay	Departure delay	Punctuality [%]
My	00:02:12	00:01:48	91.3
Bx	00:01:49	00:01:31	92.2
Tns	00:01:32	00:01:42	93.0
Any	00:01:45	00:01:54	92.7
N	00:01:59	00:03:05	92.4
Sä	00:03:07	00:03:15	76.0
Av	00:03:30	00:03:08	75.6

Table 4.27 – Arrival/departure delays and punctuality of RT on ETCS3, with new timetables and shorter journey duration.

Long Distance Train _Stop

Station	Arrival delay	Departure delay	Punctuality [%]
My	0:03:17	0:02:56	84.7
N	0:04:14	0:03:58	78.5
Av	0:04:50	0:03:58	70.6

Table 4.28 – Arrival/departure delays and punctuality of LDT_Stop on ETCS3, with new timetables and shorter journey duration.

Long Distance Train _NonStop

Station	Arrival delay	Departure delay	Punctuality [%]
My	00:03:13	00:03:13	84.9
Av	00:06:30	00:06:30	59.5

Table 4.29 – Arrival/departure delays and punctuality of LDT_NonStop on ETCS3, with new timetables and shorter journey duration.

4.6.5. SCENARIO 4

In this scenario two timetables are considered: timetable2 where operates the LDT and timetable3 where the RT operates. The line operation with the existent conventional signalling took in consideration the maximum speed allowed in the line (200 km/h) and the ETCS level 2 and ETCS Level 3 were operated at the maximum speed of 320 km/h. The operation occurs during 1 day (1 cycle).

4.6.5.1. Assumptions

The main line infrastructure is used in the simulator is the current infrastructure in the Southern Main Line Stockholm - Malmö. The speeds of every track section are the present-day ones, with the exception of the speeds that previously were greater than or equal to 200 Km/h are now of 320 Km/h.

The timetable2 used in this scenario includes the LDT with the following schedule:

- LDT_Stop – From the 7:00:00 and for a period of an hour, the trains departure with minimum headway, so they won't interfere with the following vehicles.

The timetable3 used in this scenario includes the RT with the following schedule:

- RT – From the 7:00:00 and for a period of an hour, the trains departure with minimum headway, so they won't interfere with the following vehicles.

4.6.5.2. Results

LDT	Journey duration	Headway	Trains per hour
ETCS3	0:55:34	0:03:03	20
ETCS2	0:55:34	0:03:24	18
Conventional	1:03:35	0:03:15	19

Table 4.30 – LDT-Stop results in scenario 4.

RT	Journey duration	Headway	Trains per hour
ETCS3	1:16:53	0:02:45	22
ETCS2	1:16:48	0:05:16	12
Conventional	1:20:42	0:05:00	13

Table 4.31 – RT results in scenario 4.

4.6.6. SCENARIO 5

In this scenario two timetables are considered: timetable2 where operates the LDT and timetable3 where RT operates. The line operation took in consideration in the ETCS level 2 and the ETCS Level 3 the maximum speed of 320 km/h. The operation occurs during 1 day (1 cycle).

4.6.6.1. Assumptions

The main line infrastructure is used in the simulator is the current infrastructure in the Southern Main Line Stockholm - Malmö. The permitted speeds of all line sections were altered to 320 Km/h (track addressed to high-speed trains).

The timetable2 used in this scenario includes the LDT with the following schedule:

- LDT_Stop – From the 7:00:00 and for a period of an hour, the trains departure with minimum headway, so they won't interfere with the following vehicles.

The timetable3 used in this scenario includes the RT with the following schedule:

- RT – From the 7:00:00 and for a period of an hour, the trains departure with minimum headway, so they won't interfere with the following vehicles.

4.6.6.2. Results

LDT	Journey duration	Headway	Trains per hour
Dedicated_track_ETCS3	0:41:29	0:04:49	13
Dedicated_track_ETCS2	0:41:28	0:05:06	12

Table 4.32 – LDT_Stop's results in scenario 5.

RT	Journey duration	Headway	Trains per hour
Dedicated_track_ETCS3	1:11:46	0:03:44	17
Dedicated_track_ETCS2	1:11:42	0:04:17	15

Table 4.33 – RT's results in scenario 5.

5

RESULTS ANALYSIS

5.1. INTRODUCTION

In this chapter will be analyze the results of the study of the previous chapter, as well as the maintenance costs of the life cycle of the different signalling systems in the line in study.

5.2. RESULTS ANALYSIS

5.2.1. DELAYS AND PUNCTUALITY

Scenario 1

In the scenario 1, timetable1 is applied and the line is limited to the maximum speed of 200 Km/h. The only variation in this simulation is the operation with the three different signalling systems in study.

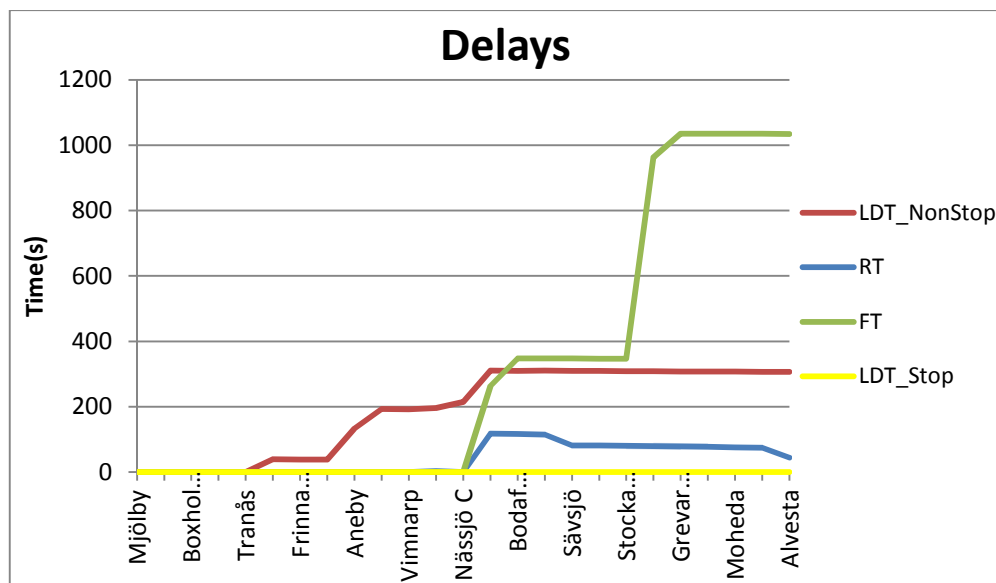


Figure 5.0 – Trains delays operating on ATC – scenario 1.

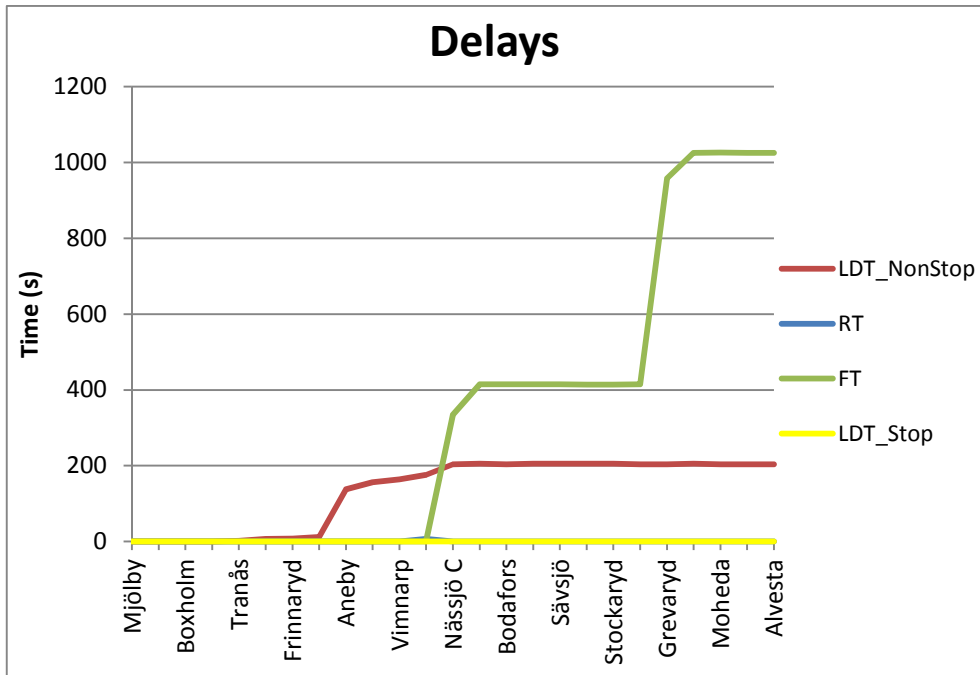


Figure 5.1 – Trains delays operating on ETCS2 - scenario1.

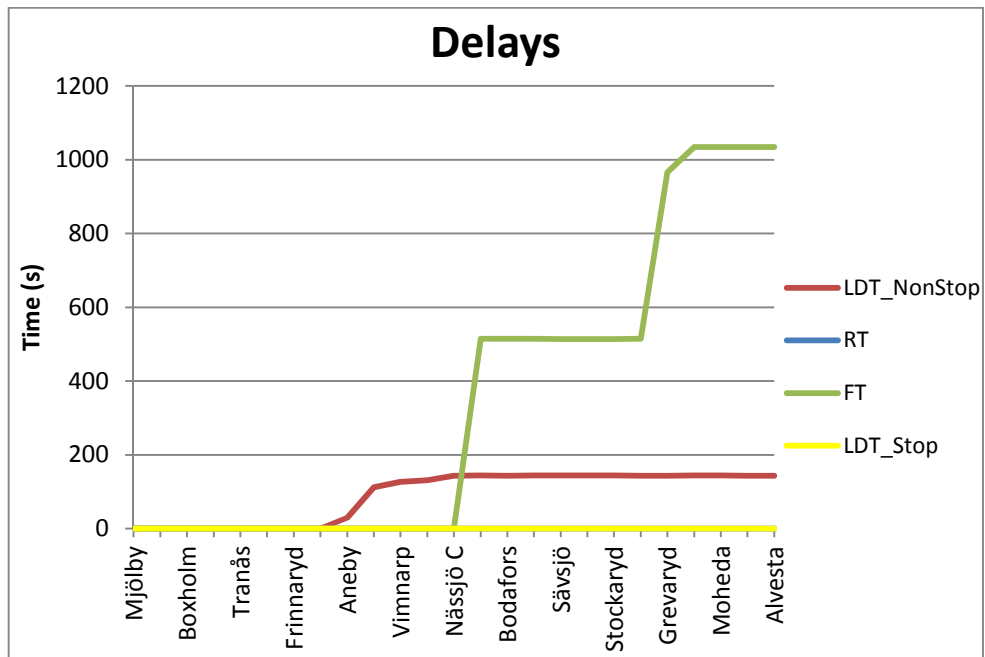


Figure 5.2 – Trains delays operating on ETCS3 - scenario1.

Results analysis of the delays registered in the scenario 1

After analysing the figures 5.0, 5.1 and 5.2, is evident that the largest number of delays (in three types of trains) occur in the conventional system: the freight trains reaches a delay of 1035 seconds; the regional trains begin the register delays in the Gamlarp station (3s), reach their peak at Grimstorp Station (118s) and they arrive to the Alvesta station with a 45s delay. The long distance trains without programmed stops, reach their first delay at the Gripenberg station (40s), reach their peak at the Grimstorp and Ulvstorp stations (311s), and arrive to Alvesta station with a 307s delay. The long distance trains with programmed stops do not register any delay.

While operating in the ETCS2, the freight trains register a maximum delay of 1025 seconds (inferior value to the registered on the conventional system); the regional trains register a delay only in Gamlarp Station (7s) and arrives to Alvesta station on-time. The long distance trains without programmed stops are late for the first time at the Tranås station (2s), reach their maximum figures in the stations of Grimstorp, Ulvstorp, Sävsjö, Aleholm and Stockaryd (205s, inferior to the delay registered on the conventional system), and arrive to Alvesta station with a delay of 204 seconds (inferior to the delay registered on the conventional system). The long distance trains with programmed stops register no delays.

While operating in the ETCS3, the freight trains registers a maximum delay of 1035 seconds (same value registered on the conventional system) and the regional trains register no delays. The long distance trains without programmed stops are late for the first time at the Aneby station (30s), reach their maximum delay in the stations of Grimstorp, Ulvstorp, Sävsjö, Aleholm, Stockaryd, Lidnäs and Moheda (144s, inferior to the delay registered on the conventional system and on the ETCS2), and arrive to Alvesta with a 143s delay (inferior to the delays registered on the conventional system and on the ETCS2). The long distance trains with programmed stops register no delays.

Scenario 2

In scenario 2, alterations were introduced: The speed limitation was increased from 200 km/h to 320 km/h for the ETCS2 and ETCS3, with the exception of the conventional system which only allows the maximum speed of 200 Km/h. All three systems operated with the timetable1.

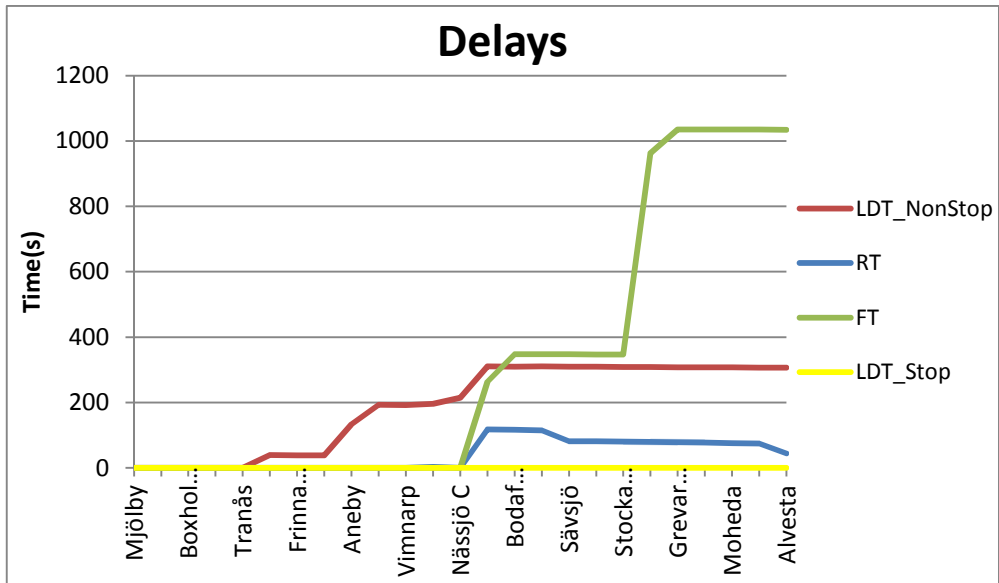


Figure 5.3 – Train delays operating on ATC – scenario 2.

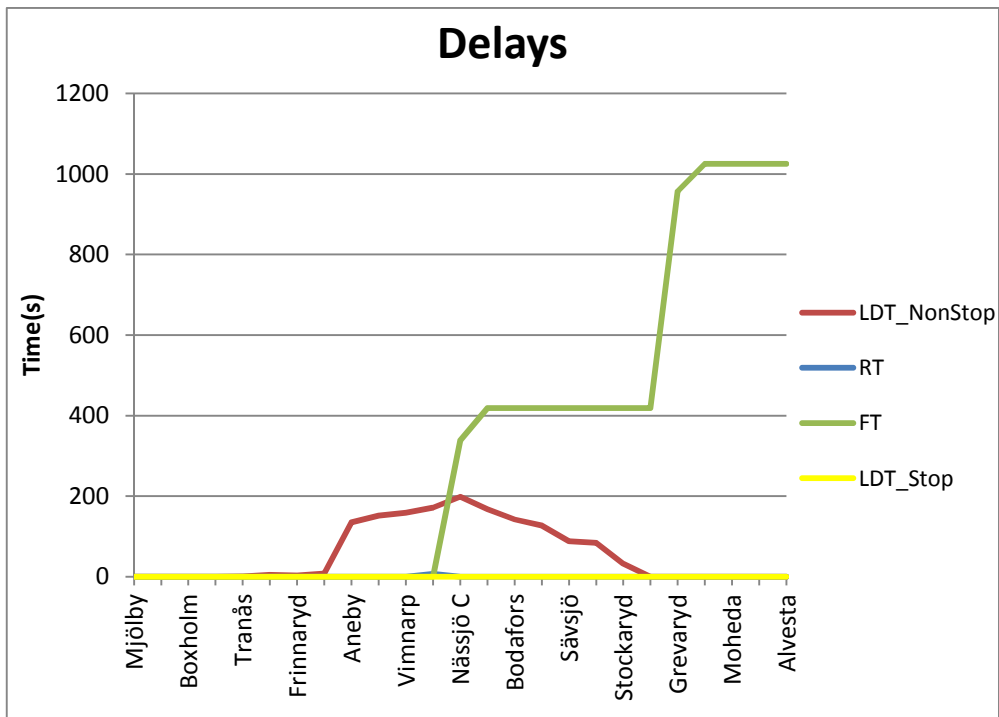


Figure 5.4 – Train delays operating on ETCS2 – scenario 2.

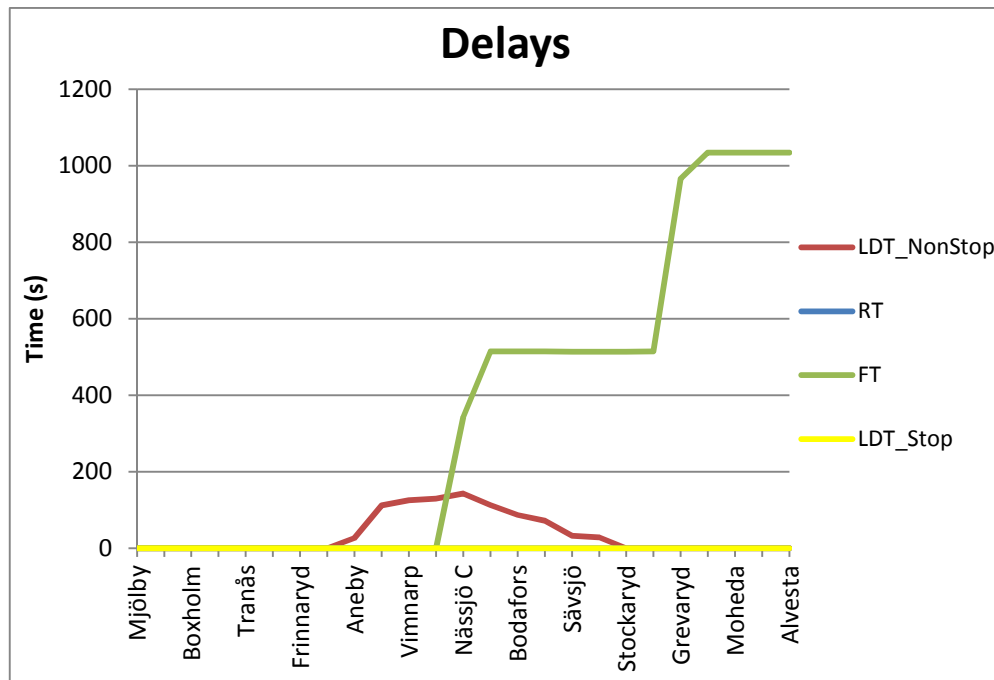


Figure 5.5 – Train delays operating on ETCS3 – scenario 2.

Results analysis of train delays registered on scenario 2

The differences between the figures of the different signalling systems operating on this scenario are more significant when compared with the differences registered in the previous simulation.

The system conventional registered the same numbers of scenario 1: the freight trains have delays of 1035 seconds, the regional trains begin to register delay at Gamlarp station (3s), reach their peak at the Grimstorp station (118s) and arrive at Alvesta station with a 45s delay. The long distance trains without programmed stops are late for the first time at the Gripenberg station (40s), reach the maximum delay at the stations of Grimstorp and Ulvstorp (311s), and arrive to Alvesta station with a 307s delay. The long distance train with programmed stops registers no delays.

In the ETCS2 operating on scenario 2, the freight trains registers a maximum delay of 1025 seconds (inferior to one registered on the conventional system); the regional trains registers a delay only at Gamlarp station (7s) and arrives at Alvesta station without any delay. The long distance trains without programmed stops are late for the first time at Tranås station (1s), reach their peak at the station Nässjö C (199s, inferior delay to the one registered on the conventional system), and come at Alvesta station on time. The long distance train with programmed stops registers no delays.

In the ETCS3, the freight trains have a maximum delay of 1035 seconds (figures registered on the conventional system) and the regional trains do not register any delays. The long distance trains NonStop are late for the first time at Aneby Station (27s), they reach their maximum at Nässjö C Station (143s, delay inferior to the one registered on the conventional systems and on ETCS2) and arrives to Alvesta station without delay. The long distance trains with programmed stops register no delays.

Scenario 3

In scenario 3, an operation with 365 cycles was executed for each system (365 days, one year), in which the train delays and punctuality were analyzed on a perturbed simulation. The punctuality is handling as a percentage of trains arriving with lateness higher than 5 minutes. Those delays and punctuality rates were executed in the first station (Mjölby), in the last station (Alvesta) and in all the stations where, according with the timetable, the train had a scheduled stop. The numbers registered are compared with the time scheduled for arrival and departure of each train, predefined in the Timetable.

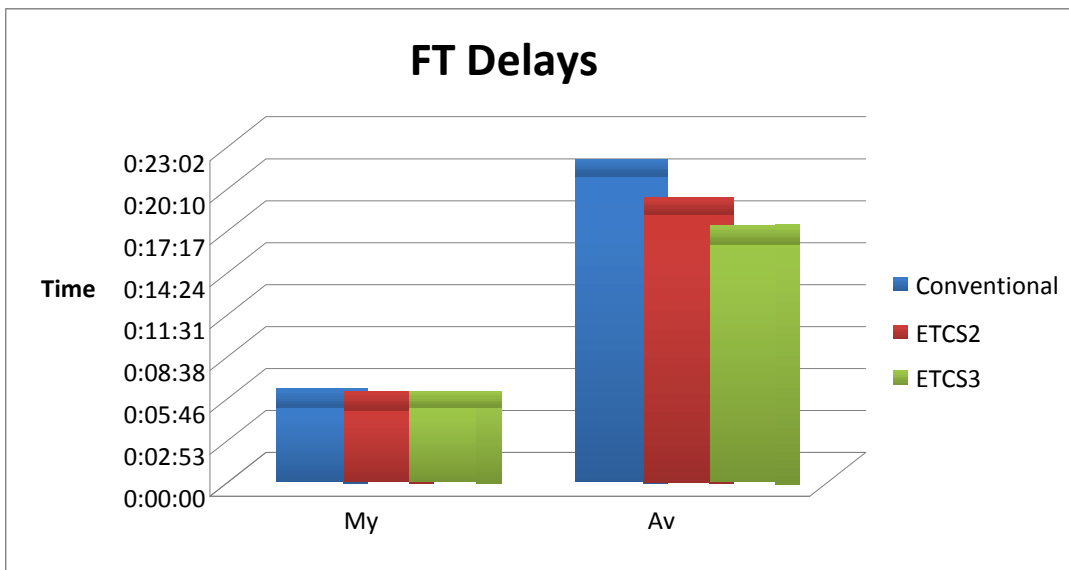


Figure 5.6 – FT average delay, operating on ATC, ETCS2 and ETCS3, with the same timetable – scenario 3.

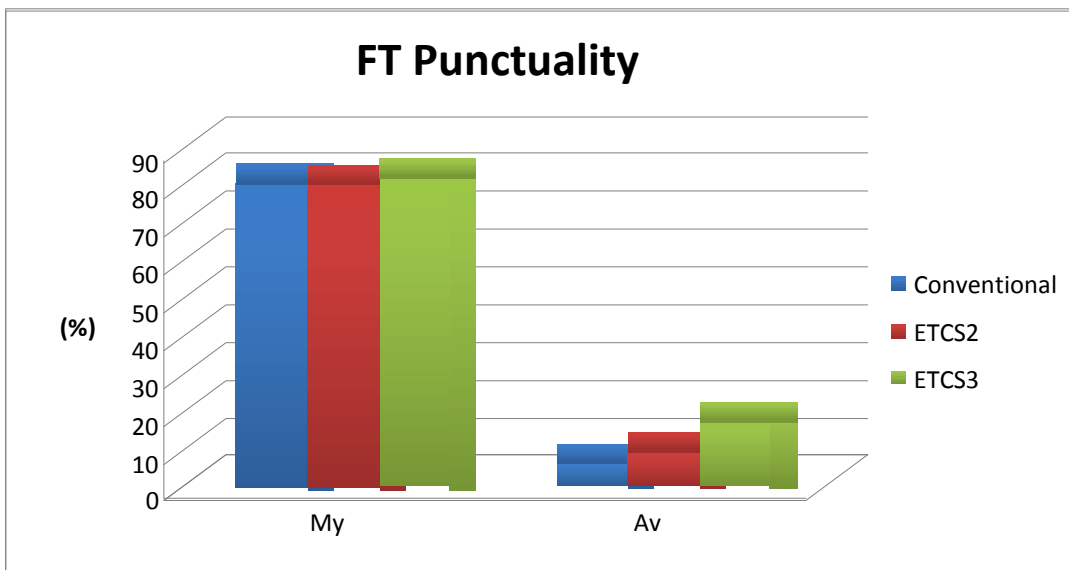


Figure 5.7 – FT punctuality, operating on ATC, ETCS2 and ETCS3, with the same timetable – scenario 3.

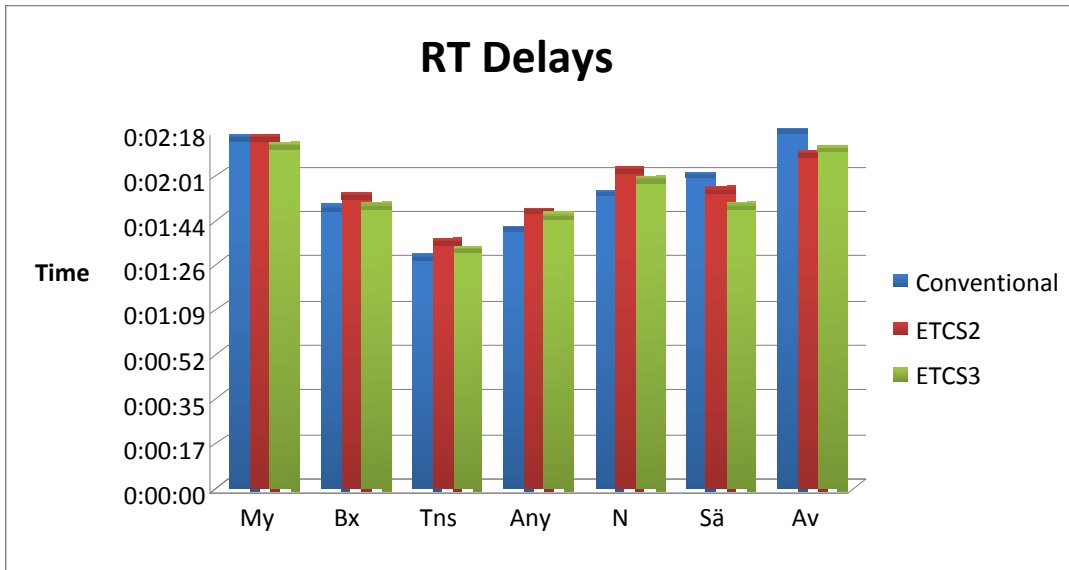


Figure 5.8 – RT average delay, operating on ATC, ETCS2 and ETCS3, with the same timetable – scenarios 3.

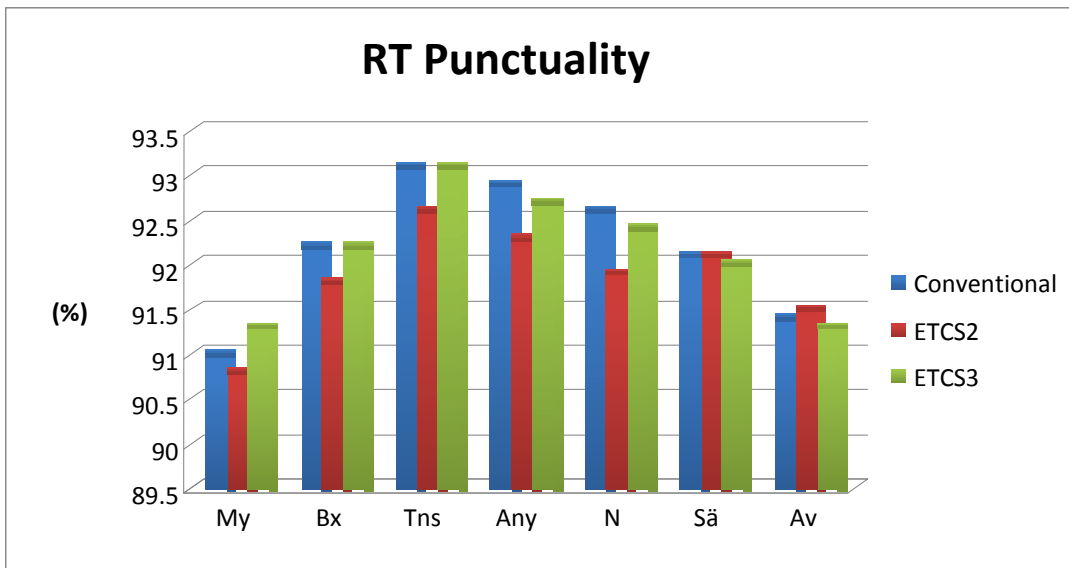


Figure 5.9 – RT punctuality, operating on ATC, ETCS2 and ETCS3, with the same timetable – scenario 3.

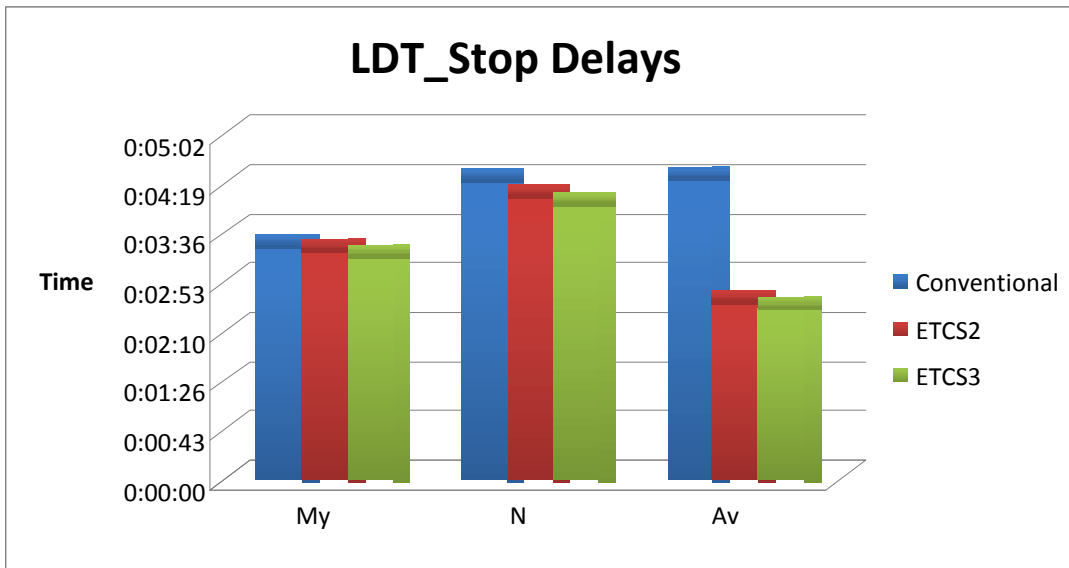


Figure 5.10 – LDT_Stop average delay, operating on a conventional system, an ETCS2 and an ETCS3, with the same timetable – scenario 3.

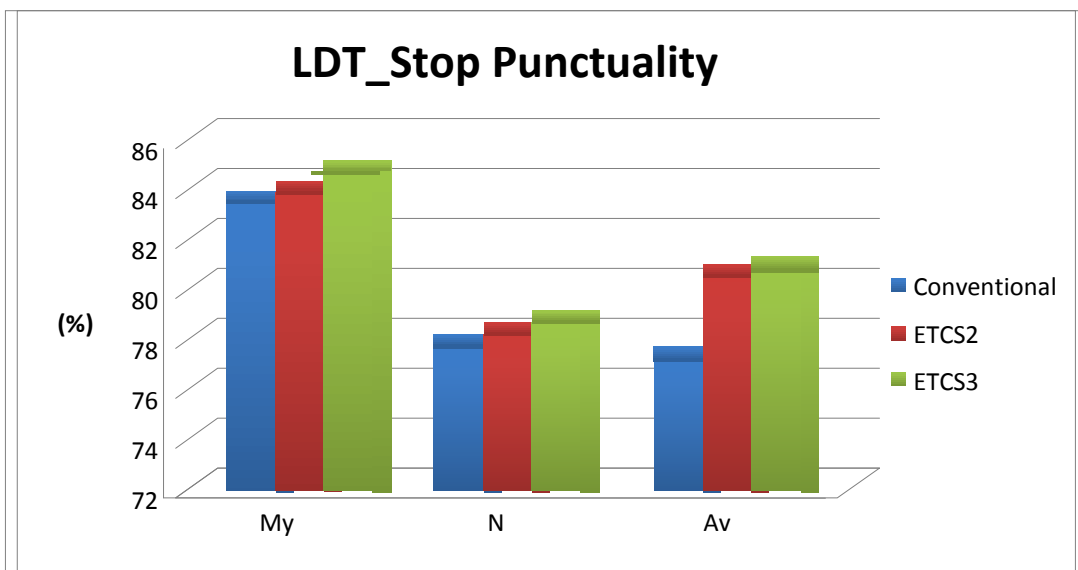


Figure 5.11 – LDT_Stop punctuality, operating on a conventional system, an ETCS2 and an ETCS3, with the same timetable – scenario 3.

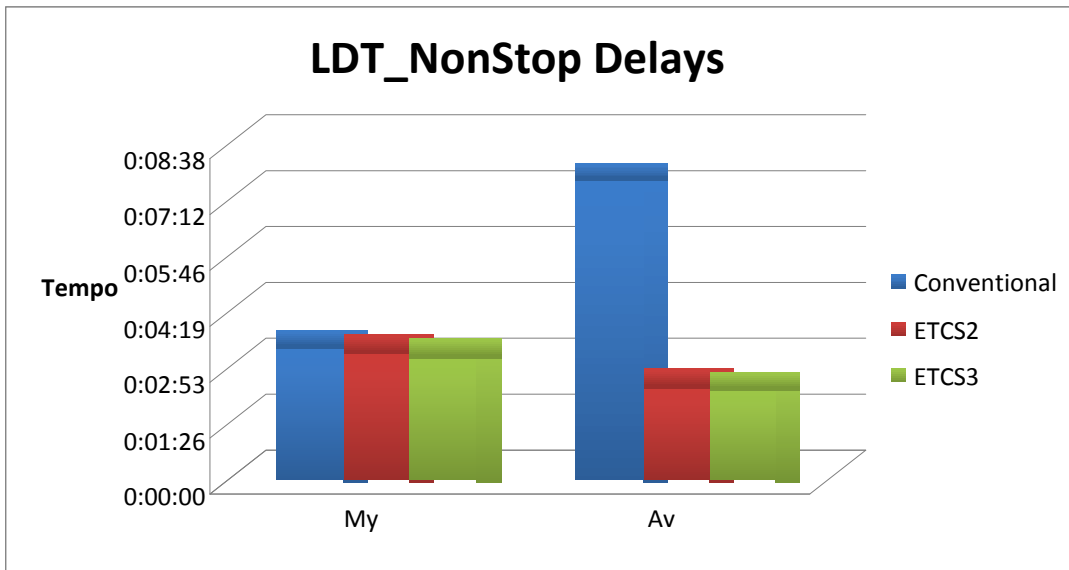


Figure 5.12 – LDT_NonStop average delay, operating on ATC, ETCS2 and ETCS3, with the same timetable – scenario 3.

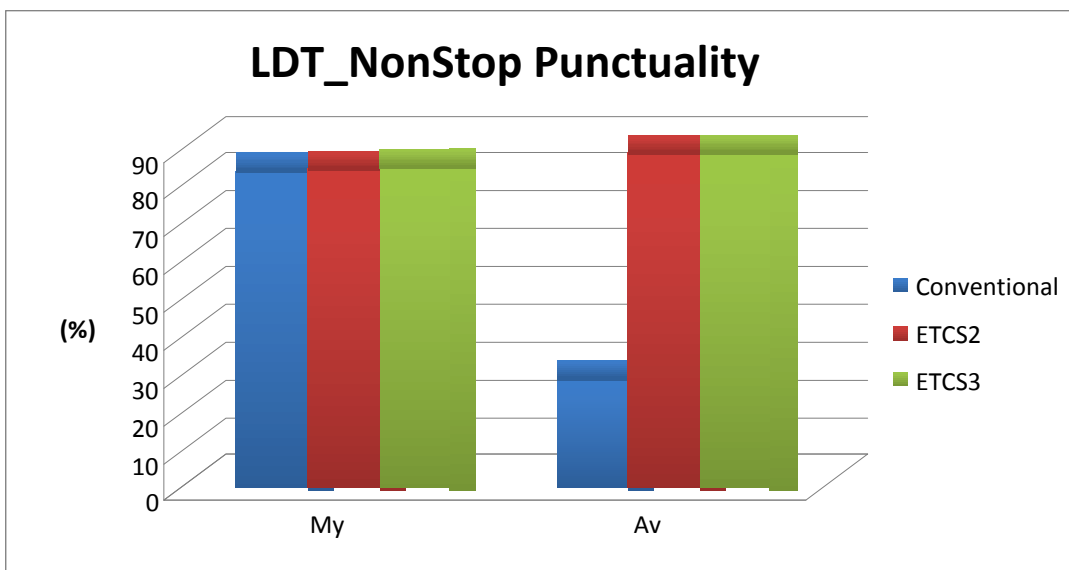


Figure 5.13 – LDT_NonStop punctuality, operating on ATC, ETCS2 and ETCS3, with the same timetable – scenario 3.

With the new schedules calculated for faster journeys with the ETCS2 and ETCS3, the results for the trains delay and punctuality on these systems and the charts comparing delay and punctuality on the conventional system, will show a disparity.

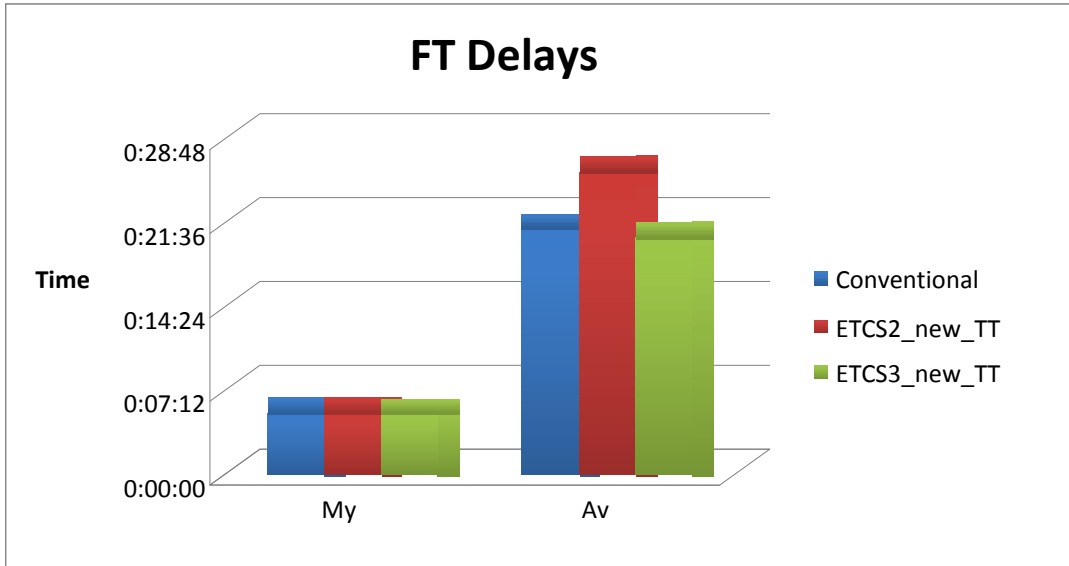


Figure 5.14 – FT average delay, operating on ATC, ETCS2 and ETCS3, with different journey durations and timetables – scenario 3.

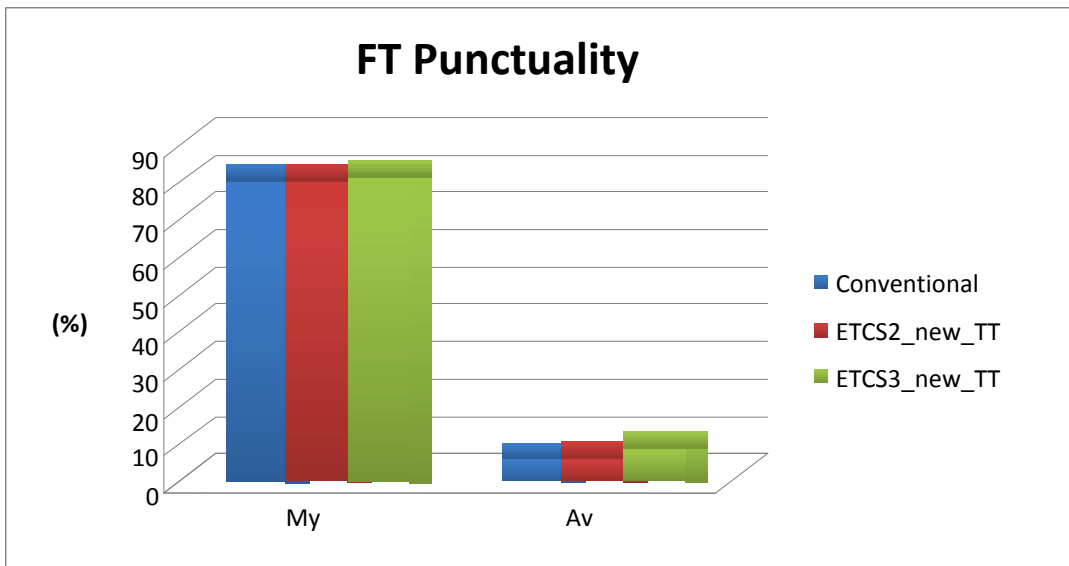


Figure 5.15 – FT punctuality operating on ATC, ETCS2 and ETCS3, with different journey durations and timetables – scenario 3.

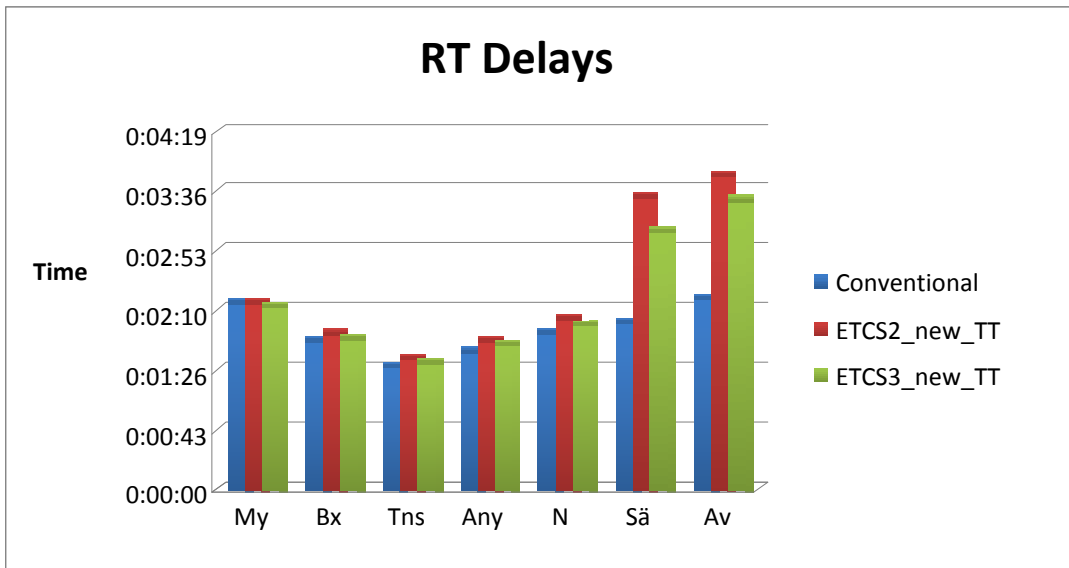


Figure 5.16 – RT average delay operating on ATC, ETCS2 and ETCS3, with different journey durations and timetables – scenario 3.

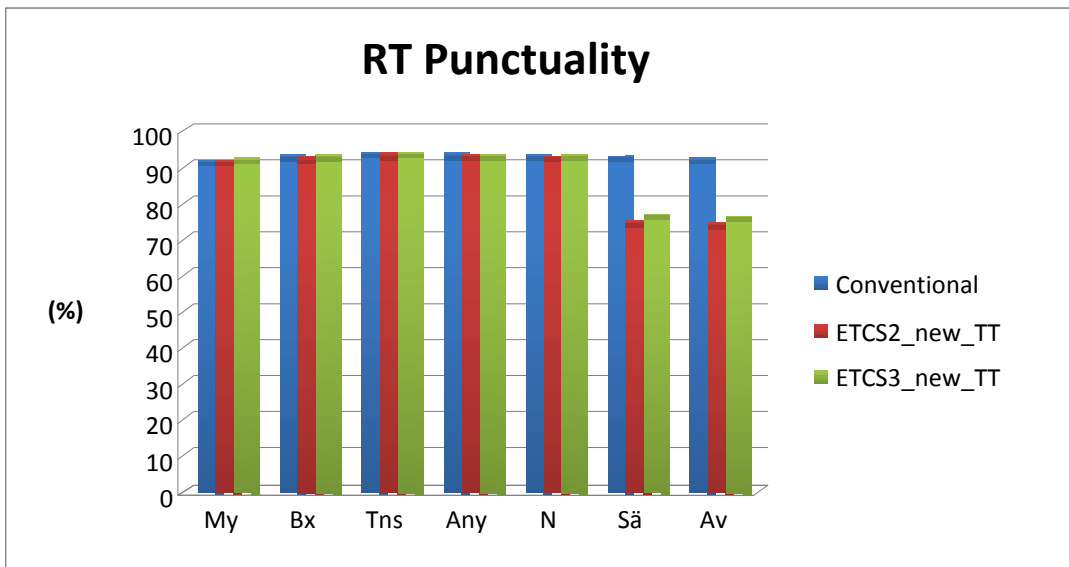


Figure 5.17 – RT punctuality operating on ATC, ETCS2 and ETCS3, with different journey durations and timetables – scenario 3.

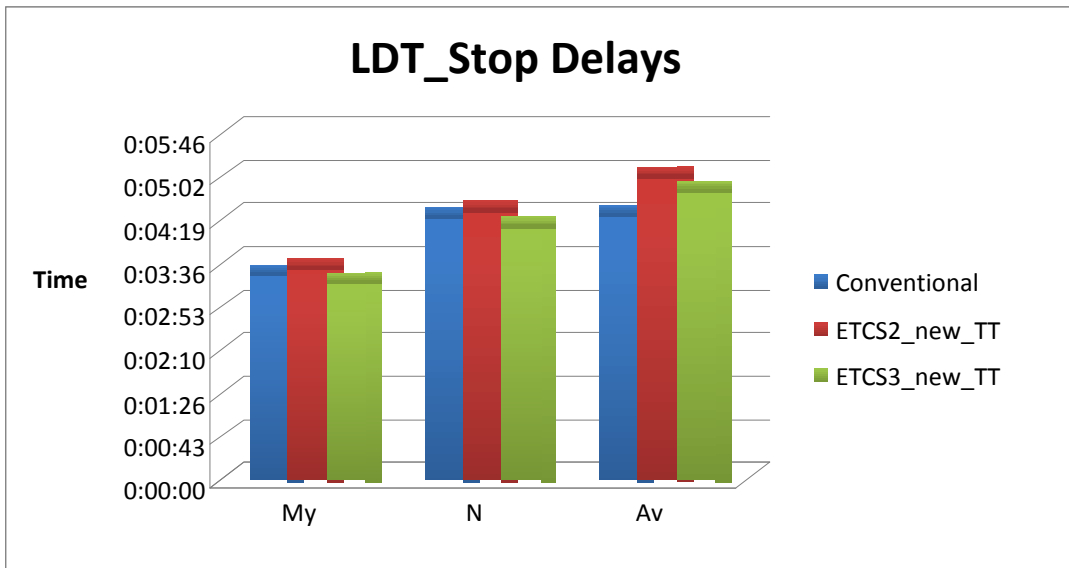


Figure 5.18 – LDT_Stop average delay operating on ATC, ETCS2 and ETCS3, with different journey durations and timetables – scenario 3.

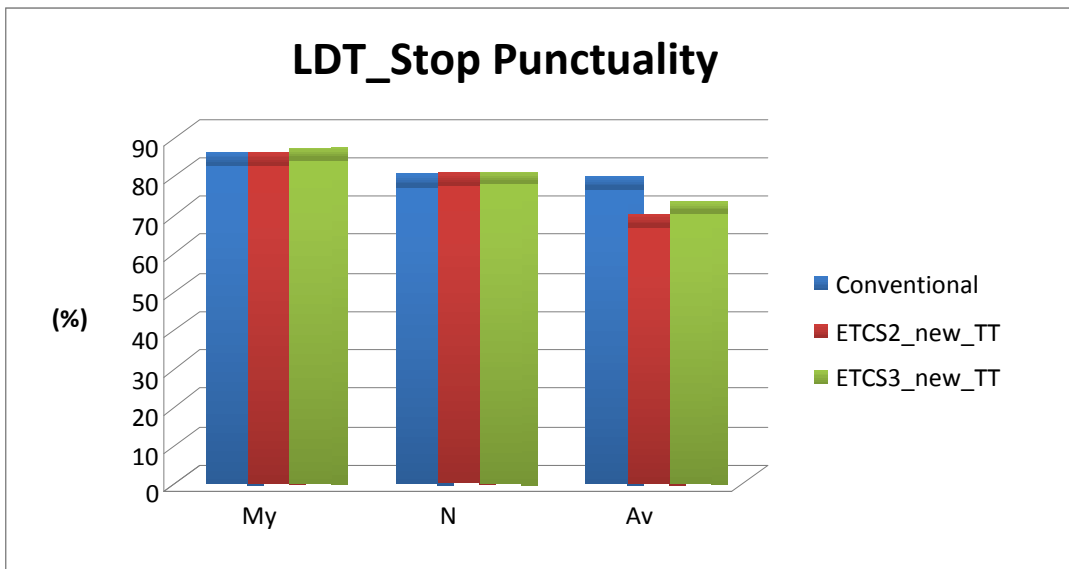


Figure 5.19 –LDT_Stop punctuality operating on ATC, an ETCS2 and an ETCS3, with different journey durations and timetables – scenario 3.

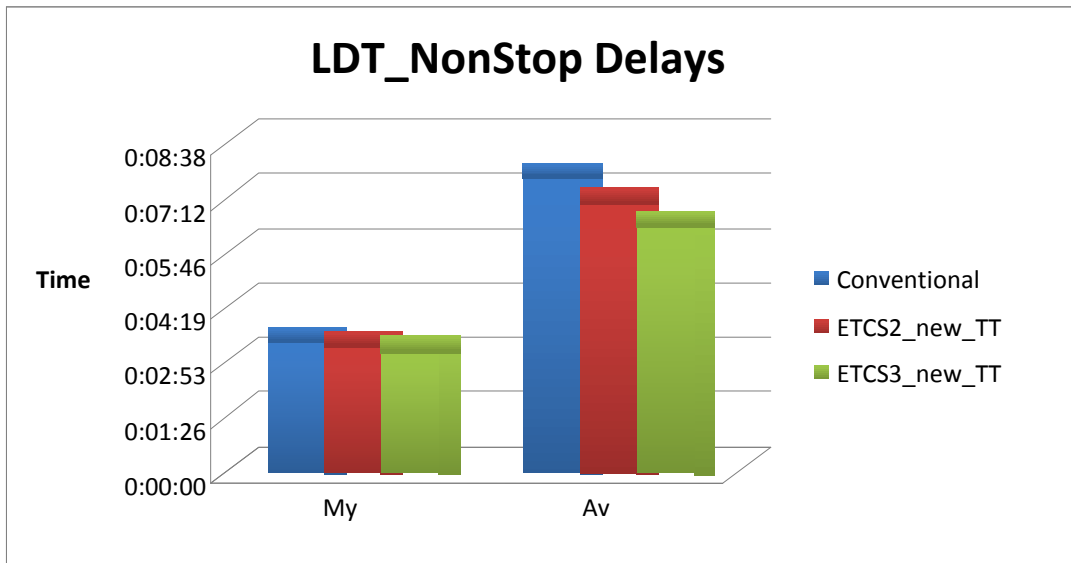


Figure 5.20– LDT_NonStop average delay operating on ATC, ETCS2 and ETCS3, with different journey durations and timetables – scenario 3.

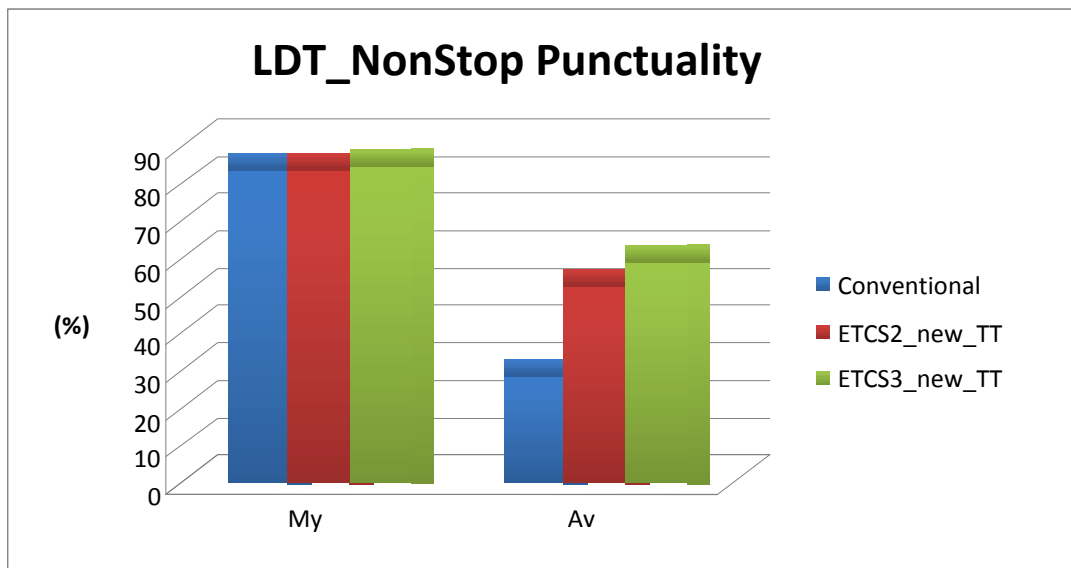


Figure 5.21 – LDT_NonStop punctuality operating on ATC, ETCS2 and ETCS3, with different journey durations and timetables – scenario 3.

Results analysis of train delays registered on scenario 3

In the outcome with the perturbed simulation for a time period of a year of the ATC, ETCS2 and ETCS3 systems, the average delay of the freight trains decreases (as shown in the figure 5.6) as a result of "transition" of the operating signalling system, from the conventional to the ETCS2 and finally to the ETCS3. Regarding the punctuality, as shown in graphic 5.7, it increases with the "transition". In the last station, Alvesta, can attest some disparity on the punctuality rates in all different systems: ATC (6,2%), ETCS2 (9,1%) and ETCS3 (17,3%).

On the other hand, the regional trains register an average delay and punctuality very similar on all the three systems (figures 5.8 and 5.9). But even with very close figures, the best punctuality records at the Alvesta station were produced in the ETCS2 (91,5%), followed by the ATC (91,4%) and finally the ETCS3 (91,3%).

The average delay and punctuality numbers from the LDT_Stop are similar in the ETCS2 and ETCS3 (figure 5.10), being the last system the one with the best results: 80,8% punctuality rate at the Alvesta Station against the 80,5% punctuality rate of the ETCS2. The ATC is the system with the worst results (figure 5.11), showing an average punctuality of 77,2% at the last station.

The train with the shortest journey duration, the LDT_NonStop, obtains similar results regarding the average delay rate in the ETCS2 and the ETCS3 (figure 5.12), being the last system the one with the best results, with a substantial difference if compared with the ATC. The ETCS3 has a punctuality rate of 88,7% at the Alvesta station against 88,6% punctuality rate of the ETCS2, shows once again the best figures. The conventional system obtains quite low results, (figure 5.13) with only 29,0% punctuality rate in the last stop.

When the journey durations are cut down, the train schedules are updated. Therefore, the results are slightly different.

After the schedule update, the freight trains obtained different average delay rates on the ETCS2 and on the ETCS3. Although the new figures registered by the ETCS3 continue to be an improvement when compared the registered values from the ATC (figure 5.14), they came short when compared to the ETCS2 values. Regarding the punctuality rate at Alvesta Station, nothing changes in the results hierarchy, with just slightly different numbers: ATC (6,2%), ETCS2 (6,6%) and ETCS3 (9,4%), as shown in figure 5.15.

The regional trains, with the new timetable, registered different average delay and punctuality in all three signalling systems (graphic 5.16). The ATC registered the best results, followed (with some distance) by the ETCS3 and finally the ETCS2. The best punctuality rate at Alvesta Station was achieved on the conventional system (91,4%), followed by ETCS3 (75,6%) and finally the ETCS2 (73,5%), as shown in graphic 5.17.

The average delay rate of the LDT_Stop is similar in all three systems (figure 5.18), but the system with the best figures is the ATC, followed by the ETCS3 and finally the ETCS2. Concerning the punctuality rate, it's the same scenario: 77,2% on the conventional system, 70,6% on ETCS3 and 67,4% on ETCS2, (figure 5.19).

The train with higher priority on the track, the LDT_NonStop, obtains the best average delay rate in the ETCS3, followed by the ETCS2 - although with some distance - and finally, with bigger numbers, the conventional system (figure 5.20). The punctuality rate of this type of train in the ETCS3 is of 59,5%, of 52,8% in the ETCS2 and with much lower numbers, the ATC with 29,0%, (figure 5.21).

The results of this scenario makes one conclude that the ETCS3 obtains the best results in the average delay and in the punctuality rates of all vehicles when arriving to the Alvesta Station. The ETCS2 obtains slightly worst figures but even so quite better than the ATC results.

With the timetable update scenario, due to the shorter journey durations of the Long Distance Trains on the ETCS3 and ETCS2 when compared with the ATC (LDT_Stop: minus 8'23''; LDT_NonStop: minus 8'54''), the best results are once again in the ETCS3. However, with the Freight Trains and LDT_NonStop the time gap is not as evident after the time change. On the other hand, the Regional Trains and the LDT_Stop show the best results on the conventional system, which did not suffer any schedule alteration.

This line is not a high-speed dedicated track. Quite the contrary, it is one where also circulate other types of trains. Therefore and in spite of the journey duration of the LDT is shorter on the ETCS3 and ETCS2 when compared with the ATC, it's probably better to do not to reduce it in such acute way, so it don't disturb the other trains operation.

5.2.2. JOURNEY DURATIONS

After analyzing the scenarios 4 and 5, where the LDT and RT are operated, the following results were obtained:

Long Distance Train

LDT	Journey duration
Dedicated_track_ETCS3	0:41:29
Dedicated_track_ETCS2	0:41:28
ETCS3	0:55:34
ETCS2	0:55:34
Conventional	1:03:35

Table 5.1 – LDT journeys duration - scenarios 4 and 5.

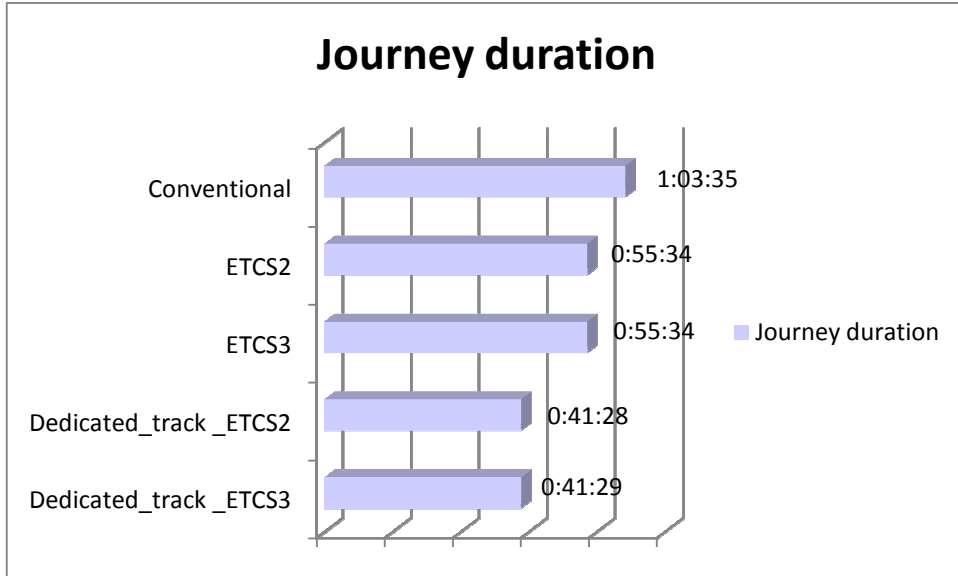


Figure 5.22 – LDT journeys duration - scenarios 4 and 5.

The regional train registered the shortest journey duration on the ETCS2 with dedicated track, with a difference of only 4 seconds to the ETCS3 with dedicated track. Comparing the shortest journey duration – ETCS2 with dedicated track - with the longest - conventional line with ATC – one verifies that it exist a nine minutes difference. The journey durations with intermediate numbers occurred on the ETCS2 and ETCS3 with present-day track, with a gap of 00:04:54 and of 00:04:49 respectively.

Regional Train

RT	Journey duration
Dedicated_track_ETCS3	1:11:46
Dedicated_track_ETCS2	1:11:42
ETCS3	1:16:53
ETCS2	1:16:48
Conventional	1:20:42

Table 5.2 – RT journey duration - scenarios 4 and 5.

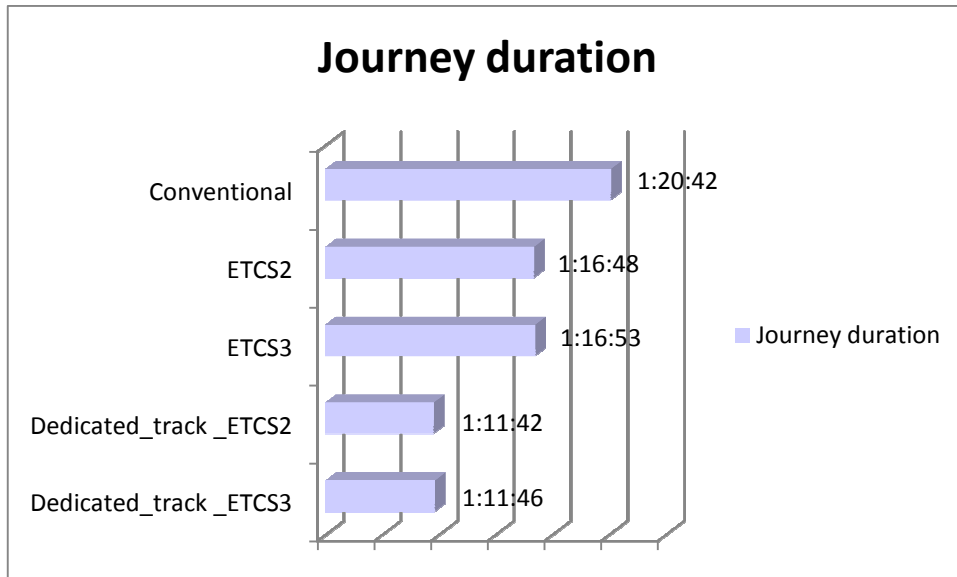


Figure 5.23 – RT journey duration - scenarios 4 and 5.

The regional train registered the shortest journey duration on the ETCS2 with dedicated track, with a difference of only 4 seconds to the ETCS3 with dedicated track. Comparing the shortest journey duration – ETCS2 with dedicated track - with the longest - conventional line with ATC – one verifies that it exist a nine minutes difference. The journey durations with intermediate numbers occurred on the ETCS2 and ETCS3 with present-day track, with a gap of 00:04:54 and of 00:04:49 respectively.

Results analysis of the journey durations

When analyzing the journey durations of both trains (LDT and RT), we can attest that the speed difference in a dedicated track results in a shorter travelling period in both systems (ETCS2 and ETCS3) when compared with the ATC. This difference is more accentuated in the LDT because this vehicle reaches higher speeds than the RT and its timetable have less scheduled stops.

In the ETCS2 and the ETCS3 on the present-day track, the difference of the journey duration is not so accentuated when compared with the ATC, but due to the higher speed of these two systems, they register relevant differences.

5.2.3. MINIMUM HEADWAY

The results of the scenarios 4 and 5 were the following ones:

LDT

LDT	Headway
Dedicated_track_ETCS3	0:04:49
Dedicated_track_ETCS2	0:05:06
ETCS3	0:03:03
ETCS2	0:03:24
Conventional	0:03:15

Table 5.3 – LDT minimum headway - scenarios 4 and 5.

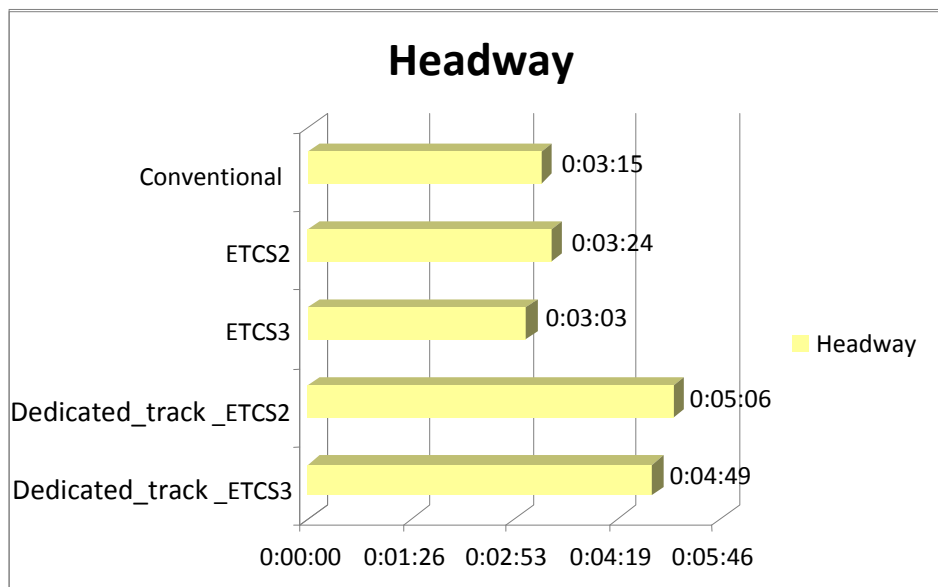


Figure 5.24 – LDT minimum headway - scenarios 4 and 5.

The lowest record of minimum headway for LDT was in the actual track with the ETCS3 (00:03:03), followed close by the conventional system also in the present-day line (00:03:15) and ETCS2 (00:03:24). The worst result was accomplished on a dedicated-track with the ETCS2 (00:05:06), followed by the ETCS3 (00:04:49) on a dedicated track.

RT

RT	Headway
Dedicated_track_ETCS3	0:03:44
Dedicated_track_ETCS2	0:04:17
ETCS3	0:02:45
ETCS2	0:05:16
Conventional	0:05:00

Table 5.4 – RT minimum headway - scenarios 4 and 5.

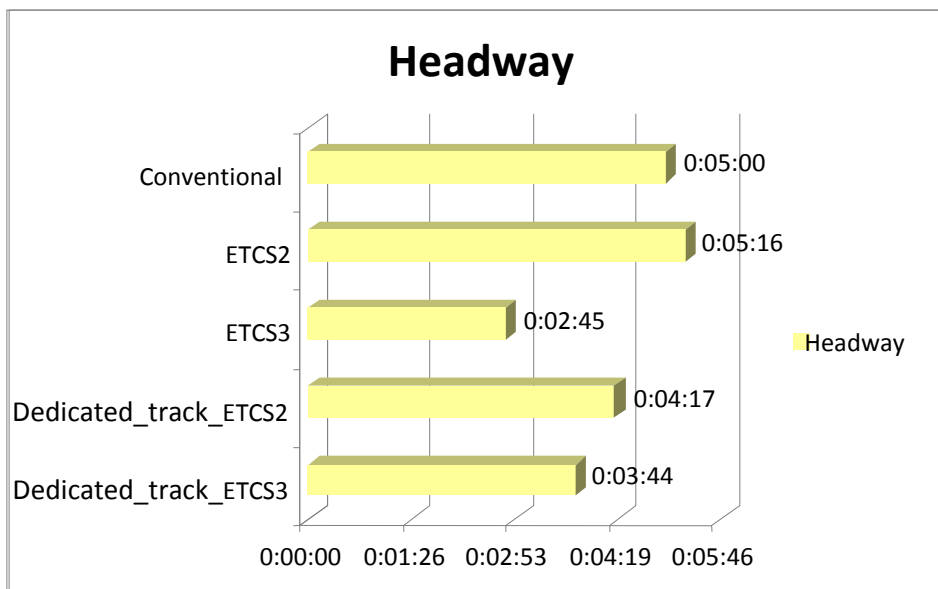


Figure 5.25 – RT minimum headway - scenarios 4 and 5.

Regarding the regional train, the best result was also registered in the actual line with the ETCS3 (00:02:45), followed at a great distance by the ETCS3 on a dedicated track (00:03:44). The third place, also registered on a dedicated track, was accomplished by the ETCS2 (00:04:17). With the worst numbers and very distant from the best headway, is the simulation of the actual line operating on ETCS2 (00:05:16) and on ATC (00:05:00).

Results analysis of the minimum headway

Analysing the results, it can be attested that the best numbers of minimum headway were both accomplished by the LDT and the RT operating in Moving Block System, in the present-day line on a ETCS.

One can also verify that the two worst results of the LDT are produced on a dedicated track (ETCS2 and ETCS3). This is explained by the combination of the highest speed achieved by the LDT and the small number of programmed stops; although the ETCS3 operates in Moving Block (and consequently has a slightly better result than ETCS2), the trains that succeed the first vehicle have higher braking curves and bigger distance gaps between themselves, when comparing with other systems operating on a lower speed.

As for the regional train, due to the high number of programmed stops executed during the operation, the system with the best results of minimum headway is the ETCS3 (Moving Block), not only on the actual track but also in a dedicated track. This operating system responds better to the different braking curves between trains, even in higher speeds, achieving a minor distance gap between vehicles.

5.2.5. MAXIMUM NUMBER OF TRAINS

Concerning to the maximum number of trains operating in a hour, without the precedent train interfere with the operation of the succeeding train, the results of the scenarios 4 and 5 were the following ones:

LDT

LDT	Trains per hour
Dedicated_track_ETCS3	13
Dedicated_track_ETCS2	12
ETCS3	20
ETCS2	18
Conventional	19

Table 5.5 – Long Distance Trains per hour - scenarios 4 and 5.

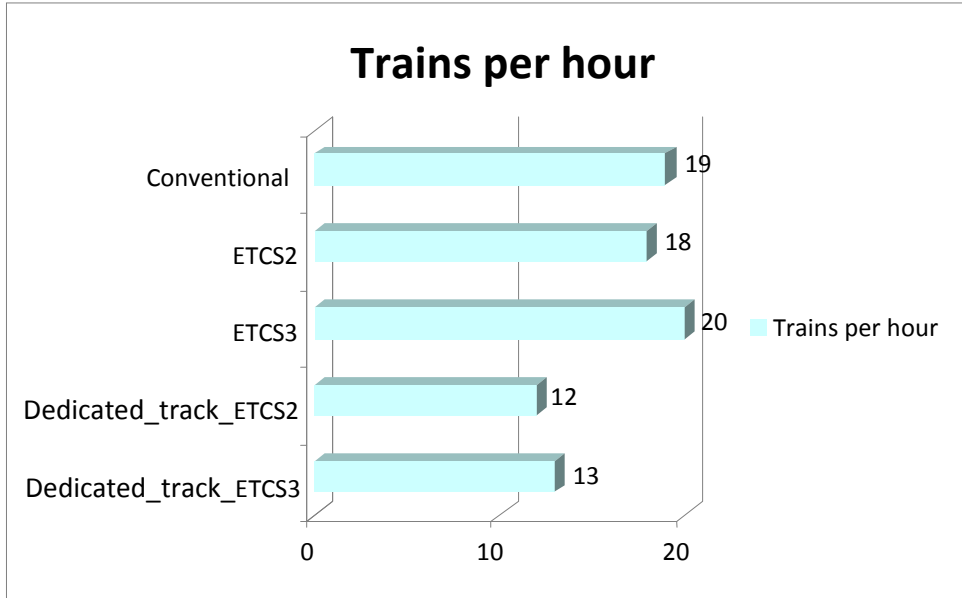


Figure 5.26 – Long Distance Trains per hour - scenarios 4 and 5.

The largest number of LDT operating in a hour was accomplished in the ETCS3 on the present-day line. The second best result, with close numbers, were the conventional system and the ETCS2 operating on the same line, with 19 and 18 trains respectively. In the dedicated tracks, very distant figures were registered: the ETCS3 with 13 trains and the ETCS2 with 12 vehicles.

RT

RT	Trains per hour
Dedicated_track_ETCS3	17
Dedicated_track_ETCS2	15
ETCS3	22
ETCS2	12
Conventional	13

Table 5.6 – Regional trains per hour – scenarios 4 and 5.

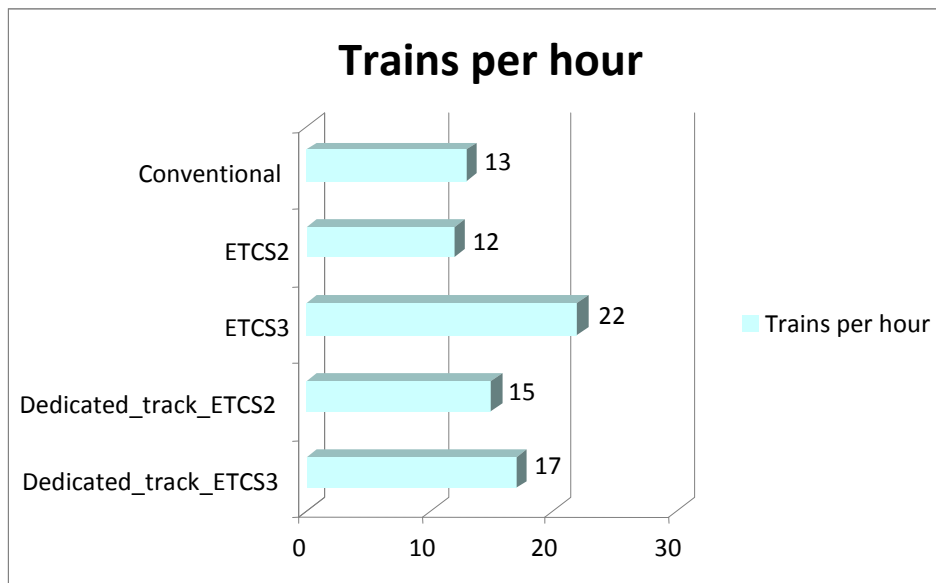


Figure 5.27 – Regional trains per hour – scenarios 4 and 5.

With the RT was possible to operate more vehicles during one hour in the ETCS3 on the actual line and the closest registered figure was also achieved in the ETCS3 but in a dedicated track. After them, with the third best result, is the ETCS2 on a dedicated track, operating 15 trains during one hour. Finally and very apart from the numbers of the others systems, are the ATC and the ETCS2 with the results of 13 trains and 12 trains respectively.

Results analysis of the number of trains per hour

The maximum number of trains to circulate during one hour is directly related with the track's minimum headway with the different systems in study. Therefore, one can attest that the system that allows operating the largest number of long distance trains during the period of one hour is the ETCS3 on the present-day track. It's also corroborated that, due to the speed increase on the dedicated track, the potential number of vehicles operating during one hour is quite inferior when compared with the same systems to operate in the actual line.

Regarding the maximum number of regional trains operating during one hour, once again it is confirmed that the ETCS3, both in the actual and in the dedicated track, is the system that obtains the best results, very apart from other systems figures.

5.3. MAINTENANCE COSTS

When choosing a signalling system, apart from the technical conditions, it is imperative to consider the implementation costs and, no less important, the costs originated from the system use during its life cycle.

Because this study takes place in an already operating line, it is important to analyse the costs of its functioning. Let us analyse the system's maintenance costs in the study.

In the maintenance costs analysis, it was considered the already existing track equipments in the line Mjölby - Alvesta (track circuits, signals and balises). The points maintenance cost was not taken in consideration, because it is an expense inherent to all of the systems in study.

The data used for this comparison were supplied by Lars Lagestam, Head of Section, *Interlocking systems, Trafik/Teknik/Signal och teleteknik/Signalställverk* of the Trafikverket, the Swedish National Traffic Administration. I thank him for his valuable help.

The track equipments of the branch line Mjölby – Alvesta in the current system (ATC), have the following costs:

Track circuits		Annual cost
Batteries maintenance		2,645,000.00 kr
Maintenance /relay adjusting		
Joint replacement		
Joint maintenance		
Failures repairmen		
Signals		Annual cost
Maintenance		1,450,000.00 kr
Light bulbs replacement		
Failures repairmen		
Balises (with cable)		Annual cost
Maintenance		362,000.00 kr
Failures repairmen		
Fixed balises (no cable)		Annual cost
Maintenance		262,000.00 kr
Failures repairmen		

Table 5.7 – Track equipments maintenance costs for the line Mjölby–Alvesta (ATC).

It is clear that every year around 4.719.000 SEK are expended and considering the system's life cycle (30 years), 141.570.000 SEK are used in the maintenance of the signalling equipments.

Conventional	Maintenance costs
4,719,000 kr	Year
141,570,000 kr	Life cycle (30 years)

Table 5.8 – Maintenance costs calculation for the line Mjölby–Alvesta (ATC).

In a European Train Control System Level 2, it is important to consider that neither the use of rail signals nor balises (with cable) are necessary. Consequently, the maintenance costs would be reduced to 2.907.000 SEK per year and to 87.210.000 SEK during the system life cycle.

ETCS2	Maintenance costs
2,907,000 kr	Year
87,210,000 kr	Life cycle (30 years)

Table 5.9 – Maintenance costs calculation for the line Mjölby–Alvesta (ETCS2).

On the other hand, in an ETCS3 one must take in consideration that, apart from absence of need from rail signals and balises with cable, track circuits are dispensable. Therefore, in this system, the reduction costs are in order of 262.000 SEK per year and 7.860.000 SEK during the system life cycle.

ETCS3	Maintenance costs
262,000 kr	Year
7,860,000 kr	Life cycle (30 years)

Table 5.10 – Maintenance costs calculation for the line Mjölby–Alvesta (ETCS3).

Comparing the maintenance costs of the different signalling systems, one can attest that between the conventional system and the ETCS2 one could save around 1.812.000 SEK of costs per year and about 54.360.000 SEK in thirty year period.

Conventional – ETCS2	
1,812,000 kr	Year
54,360,000 kr	Life cycle (30 years)

Table 5.11 – Maintenance costs differentiation between the ATC and the ETCS2.

Comparing the maintenance costs between the ATC and the ETCS3, one can attest that could save around 4.475.000 SEK of costs per year and about 133.710.000 SEK in thirty year period.

Conventional – ETCS3	
4,475,000 kr	Year
133,710,000 kr	Life cycle (30 years)

Table 5.12 – Maintenance costs differentiation between the ATC and ETCS3.

Comparing the maintenance costs between the ETCS2 and ETCS3 could be saved 2.645.000 SEK per year and of 79.350.000 SEK in thirty years.

ETCS2 - ETCS3	
2,645,000 kr	Year
79,350,000 kr	Life cycle (30 years)

Table 5.13 – Maintenance costs differentiation between ETCS2 and ETCS3.

6

CONCLUSION AND DISCUSSION

6.1. CONCLUSION AND DISCUSSION

This paper aimed to analyse with some insight the impact of a rail signalling system alteration in an already existent line, Mjölby - Alvesta. It was therefore necessary to study an extensive documentation and accomplish a case of study.

The obtained results from diverse simulations in the case study, helps to answer the objectives in the present work and to understand that the replacement of the ATC for the ETCS level 2 and ETCS level 3 (even with the same speed limit) will reduce the train delays (smaller delay on the ETCS3). With the increase of speed in the track, only possible after the implementation of the ETCS level 2 and ETCS level 3, the delay differences between the different signalling systems are even more evident.

When the line is operated on a very busy daily timetable and some operation perturbations are added up to simulation for a period of one year, it is attested once again that the best performances in the average delays and punctuality rates are carried out by the ETCS level 2 and by the ETCS level 3.

The ETCS level 2 and the ETCS level 3, by increasing the speed limit on the line, reduces the journey duration when compared with the conventional system.

Regarding the line's capacity, headway and number of vehicles operating at the same time, the ETCS level 3 stands out from the other two systems, because it allows a shorter headway and consequently, permits the circulation of a larger number of trains at the same time in the track.

As regards the maintenance costs of signalling systems, when comparing the contrast of expenses per year of the ATC with the ETCS level 2, the conclusions are quite clear: the ETCS level 2 has a quite smaller sum. But the ETCS level 3 figure is even smaller when compared with those two systems. The analysis of the maintenance costs of the three systems life cycle (30 years) supports the conclusion that the investment in the maintenance of the conventional system is quite higher when compared with the ETCS level 2 figures, but it is monumental relatively to the ETCS3 numbers.

However, were not considered in this study implementation costs related to the implementation of the different systems.

In relation to the ETCS level 2, but especially to the ETCS level 3, one can also affirm that both systems have lower equipment failure rates, which means less flaws and perturbations in the rail track

operation. This is proportional to the reduced maintenance costs because the number of existing track equipments will be very inferior when balanced against the conventional system.

In conclusion, with the rail signalling ETCS level 2 and ETCS level 3 - especially due to the last system's greater results- one can increase the allowed maximum speed in the track and improve the line's interoperability and safety in the rail transport. But one can find more advantages in adopting these systems: the train delays are reduced, with or without line perturbations; the punctuality rate of the circulating trains is elevated; a higher number of vehicles operating the line at the same time are doable; improved headway; lower maintenance costs and fewer track equipments failures.

The importance of this study results can be demonstrated after the observation of the assemblage of investments occurring in Sweden at this time.

The *Trafikverket*, the Swedish Transport Administration, is executing at this time several projects as for example the Botniabanan High Speed Line project (ERTMS level 2) estimated in 13,2 billions of Swedish crowns (SEK), which goal is to increase the safety in the people's transport, open new journey opportunities for passengers and promoting regional development, by reducing journey durations and by promoting a less pollutant transport. [83, 84]

The Stockholm City Line project, with an investment estimated in 16,8 billion of SEK, will enable the double the traffic capacity approaching the city centre and increase the punctuality rate. [85]

The Hallandsås project, estimated in 10,5 billions of SEK, has as development aim the improving of line's capacity from four trains per hour to 24 trains per hour and to work as a fundamental link of long distance passengers traffic (Copenhagen-Malmö, Gothenburg, Oslo).[86, 87]

The CITYTUNNEL project (Malmö), with an investment around 8,565 billion of SEK, expects to increase the line's capacity in more than 40% and to reduce the journey durations. [88]

6.2. FUTURE DEVELOPMENTS

During the assembling of the present work, relevant aspects of the rail signalling systems were analyzed. Nevertheless, the information compiled resulting from all of the consulted documents and the case study, recommends that the investigation should be continued, completing and improving the collected data.

Therefore, the following matters should be studied in towards to deepen its comprehension:

- Analysis of the implementation costs of the new systems to be deployed (ETCS level 2 and ETCS level 3);
- Analysis and comparison of LCC (Life Cycle Cost) of the different signalling systems that are a part of this study.
- Analysis and comparison of the RAM (Reliability, Availability and Maintainability) of the different signalling systems that are a part of this study.
- Study of the costs and implementation of the rail signalling ETCS level 2 and ETCS level 3 on a rail line built from scratch and compared it with the conventional system.

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ANNEX

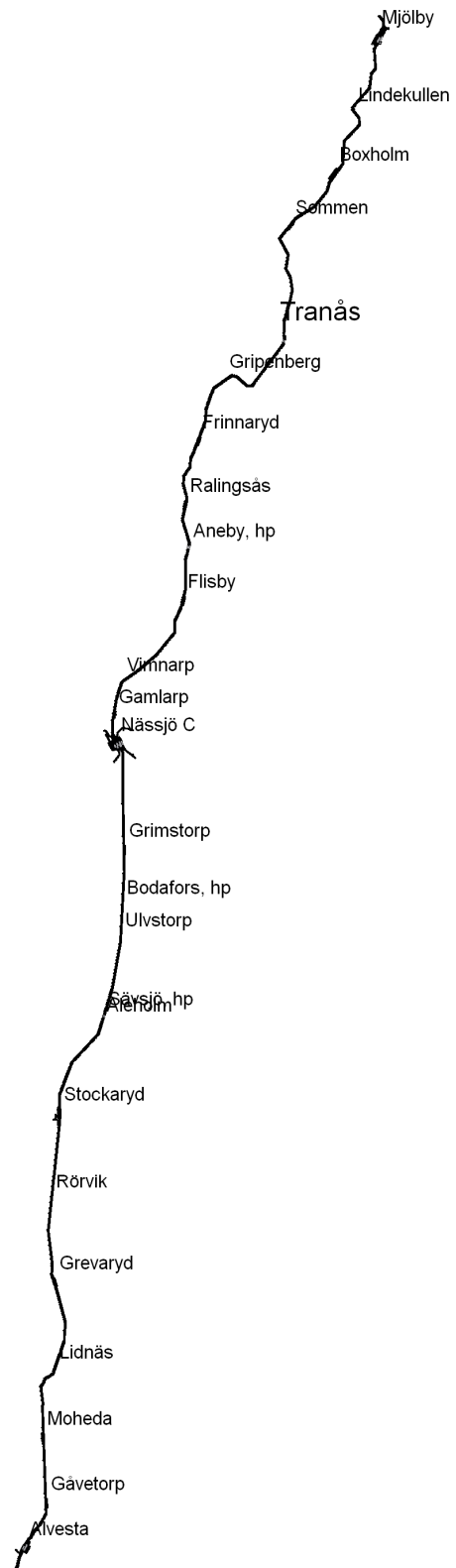


Figure 7.0 – line Mjölby – Alvesta.

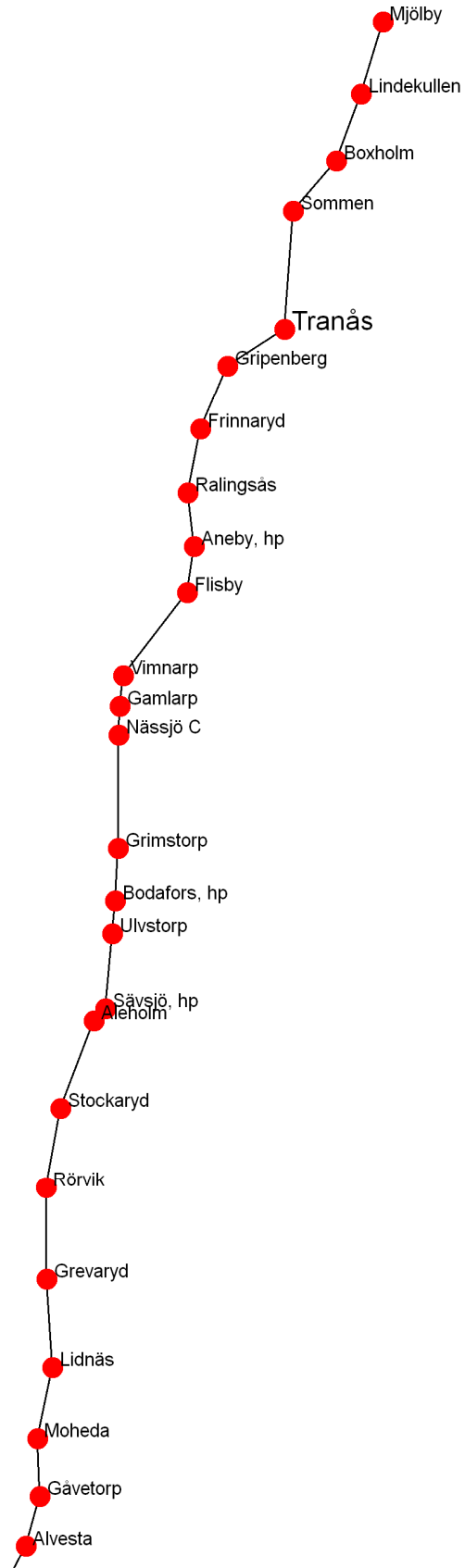


Figure 7.1 – line Mjölby – Alvesta.

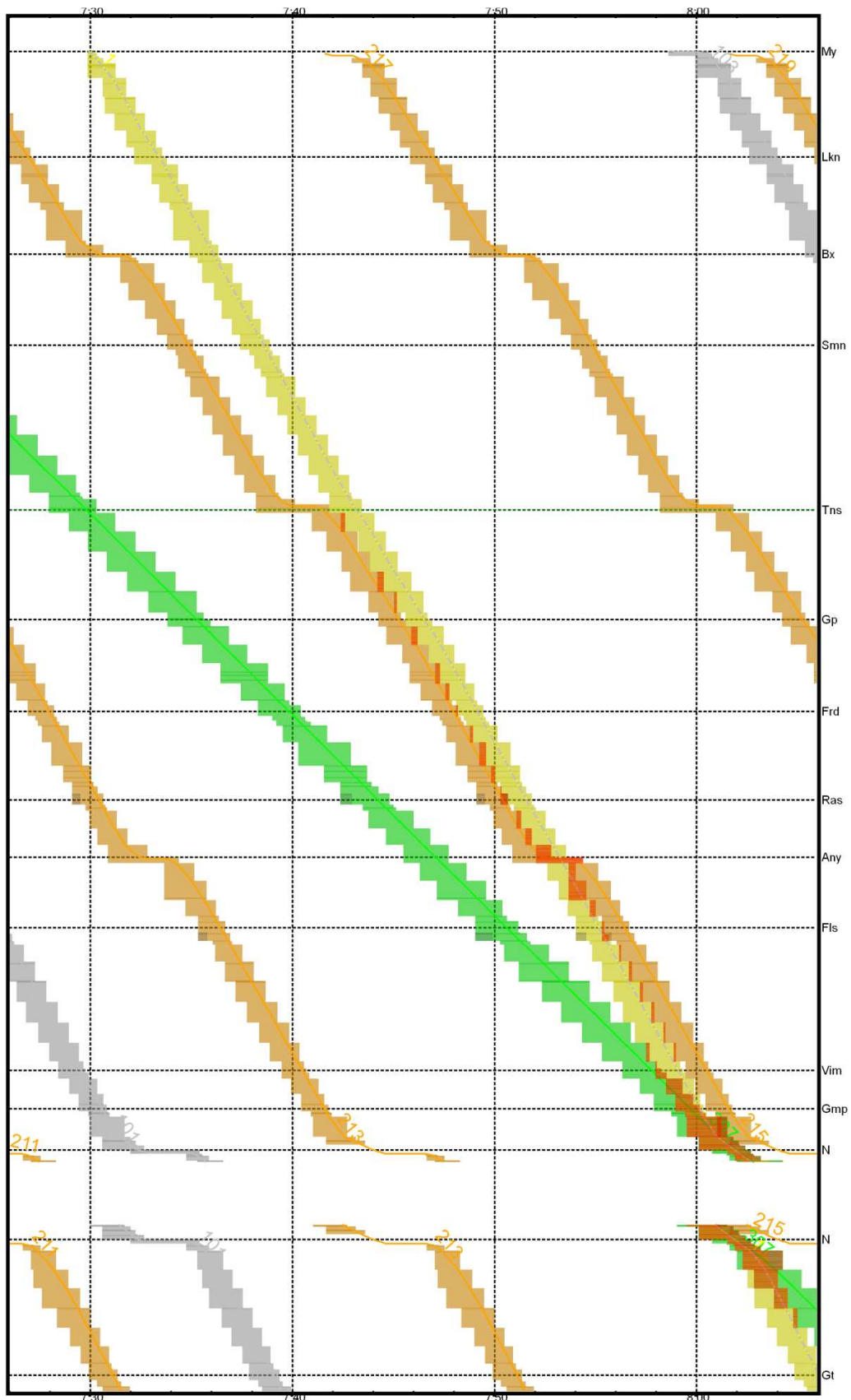


Figure 7.2 – Diagram with fixed block duration (ATC and ETCS2) in the Mjölby – Alvesta.

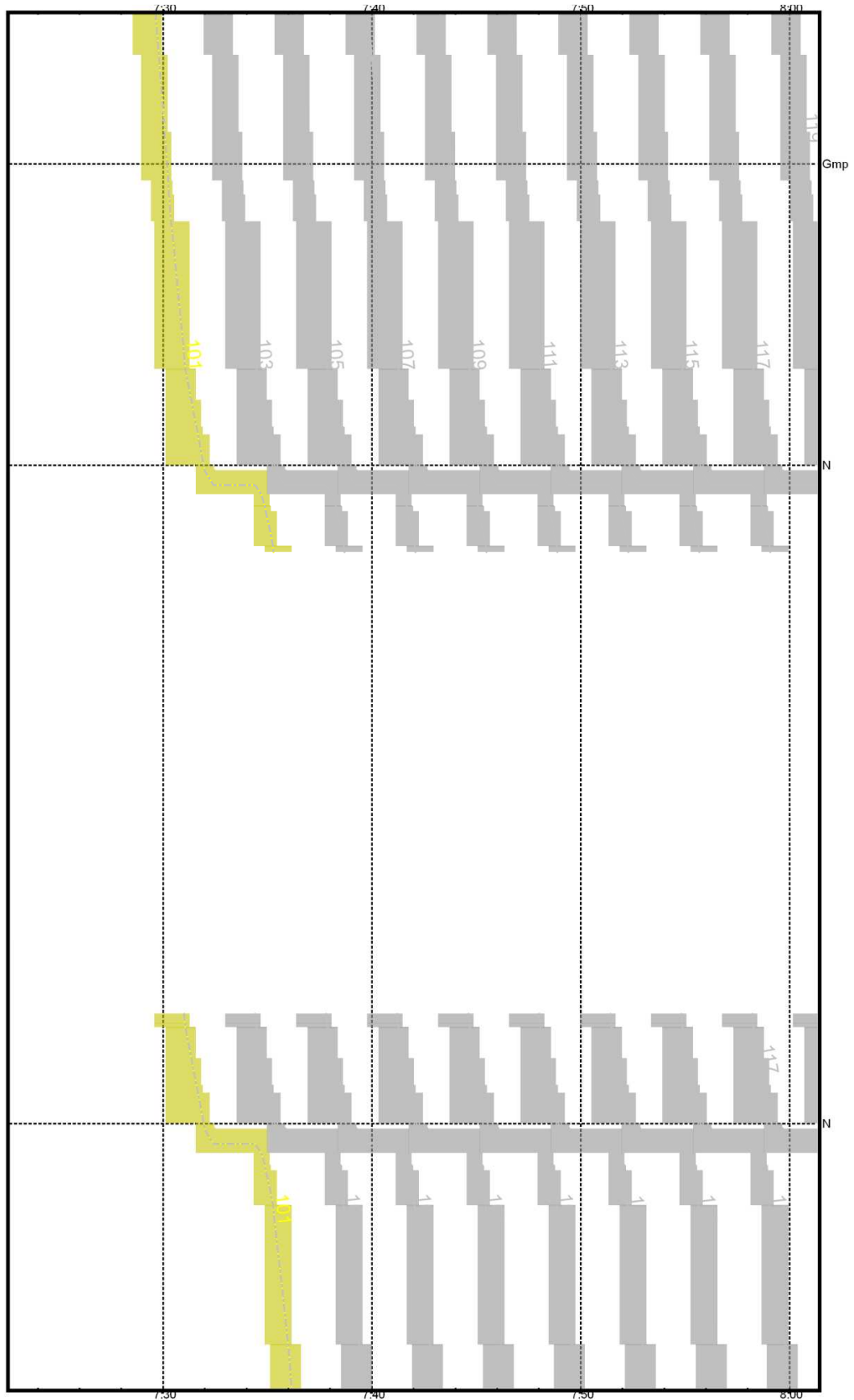


Figure 7.3 – Fixed block headway on the rail line and section (ATC and ETCS2) in Mjölby – Alvesta.

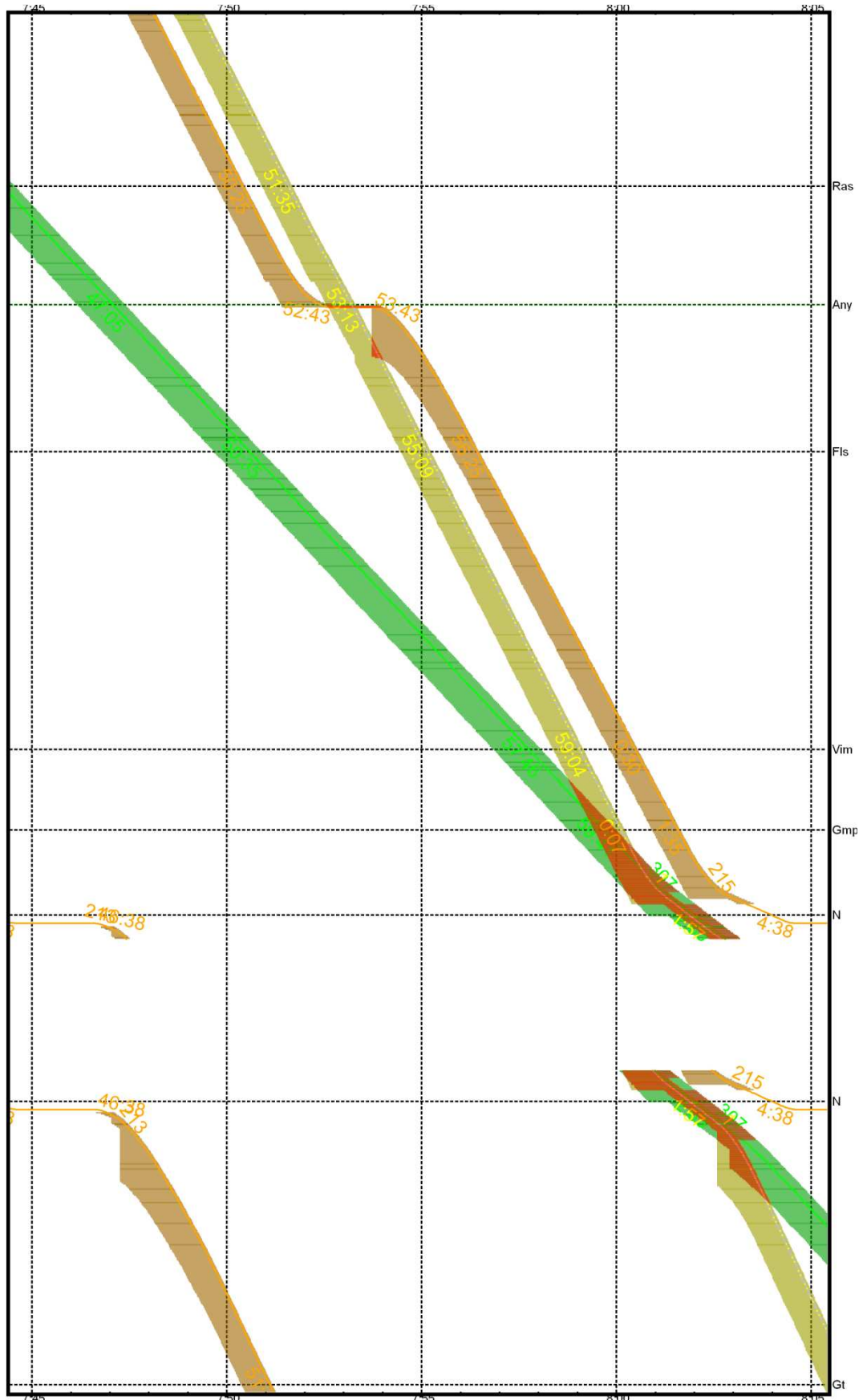


Figure 7.4 – Diagram with moving block duration (ETCS3) in the Mjölby – Alvesta.

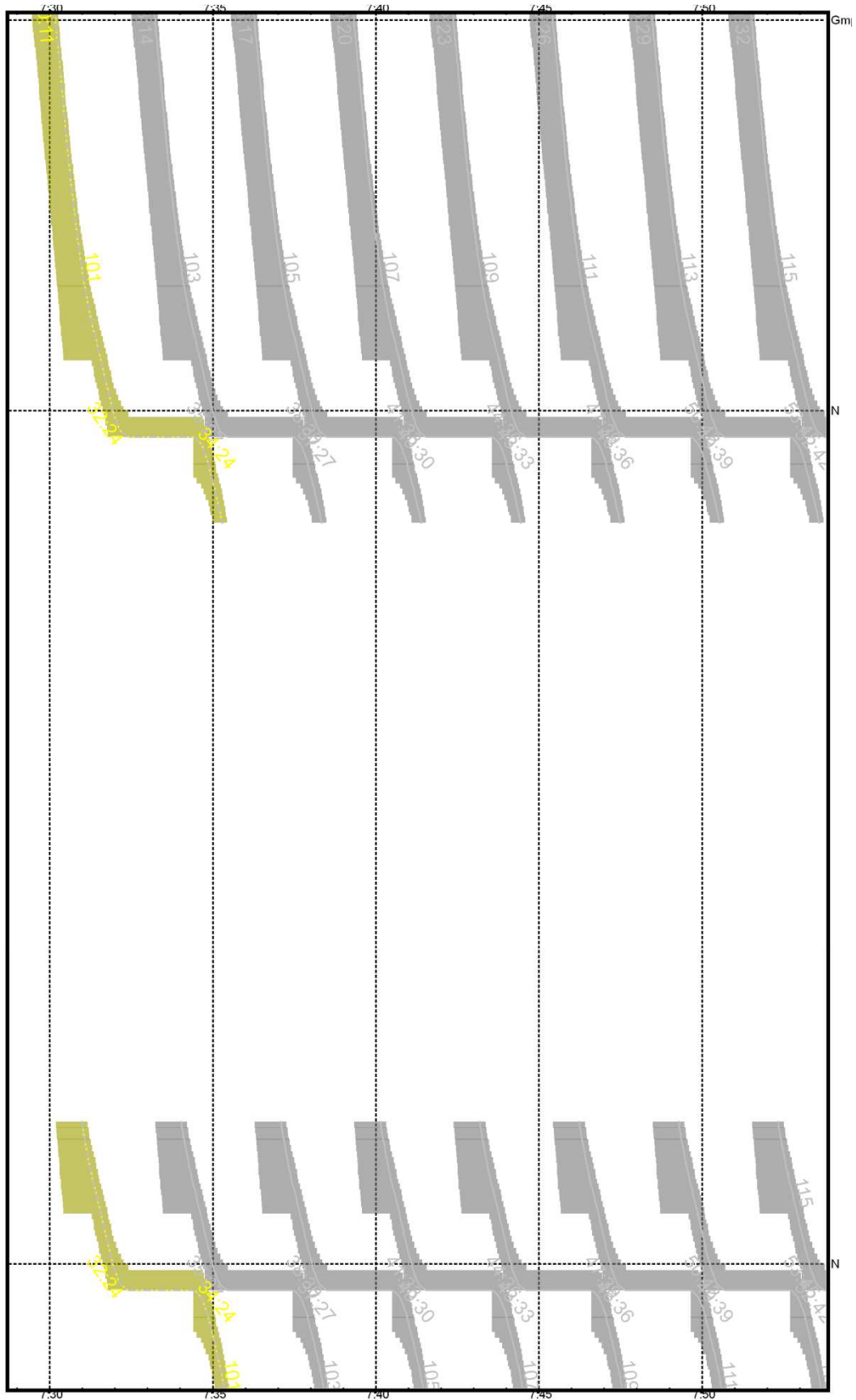


Figure 7.5 – Fixed block headway on the rail line and section (ETCS3) in Mjölby – Alvesta.

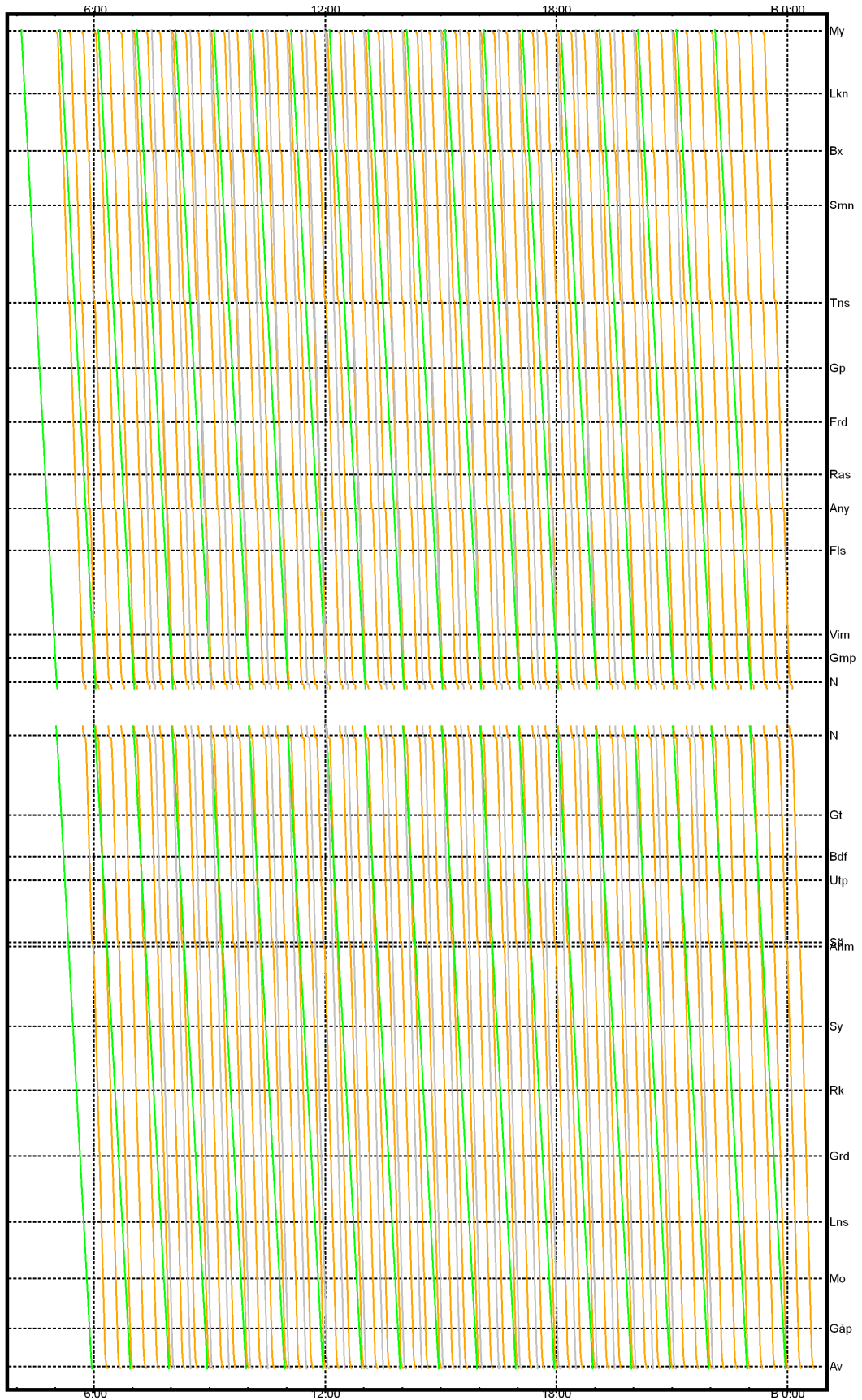


Figure 7.6 – Timetable 1

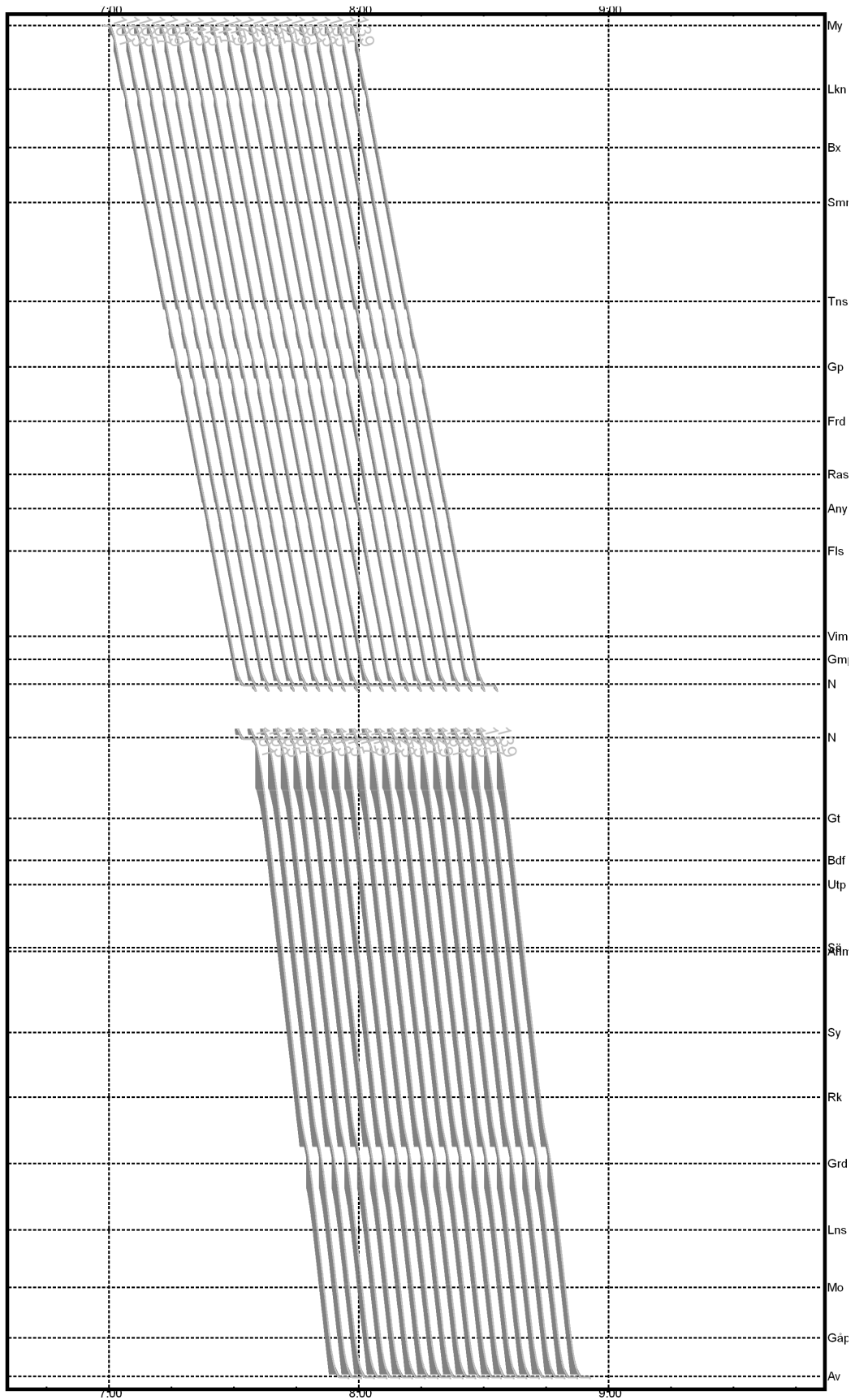


Figure 7.7 – Timetable 2.

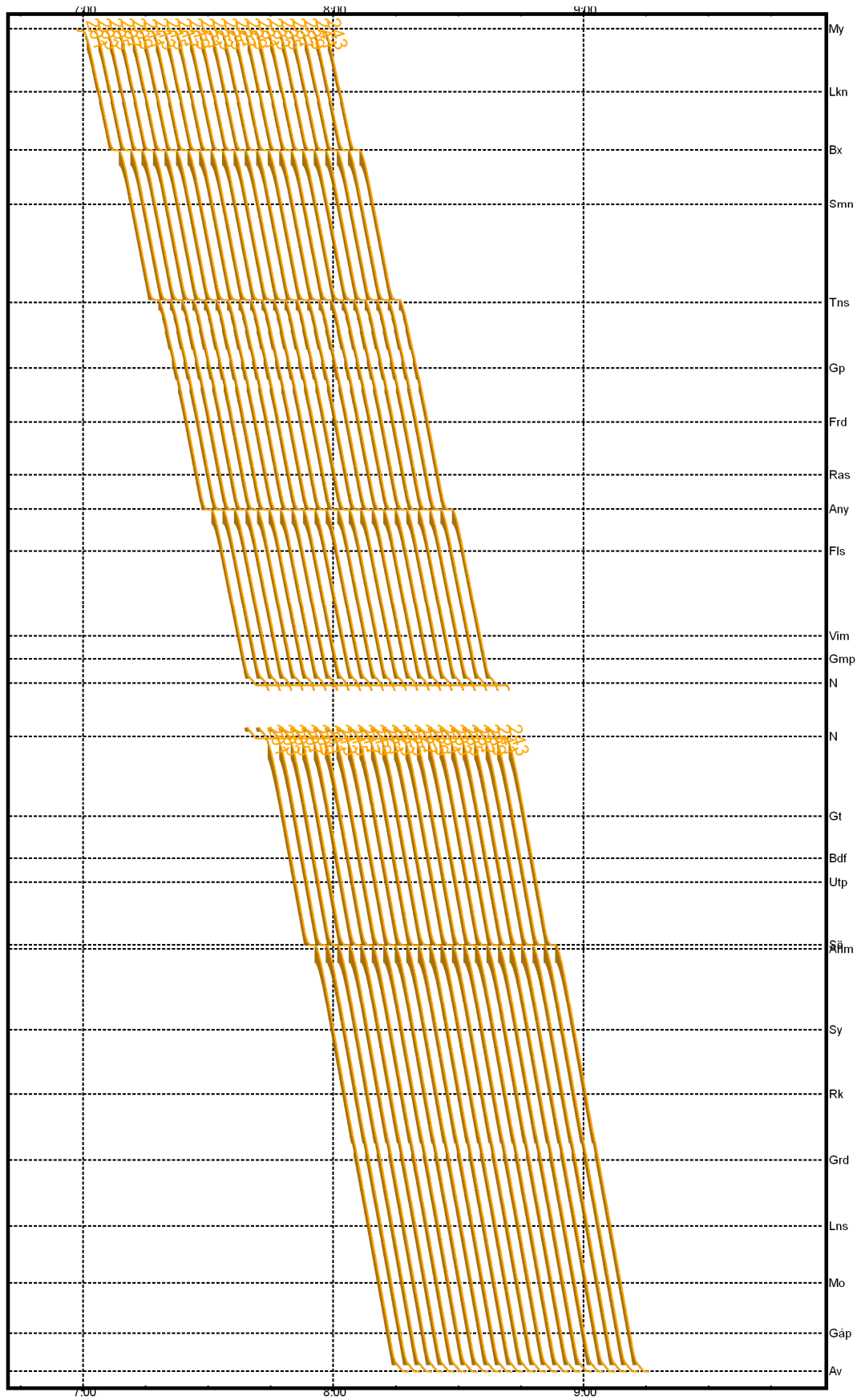


Figure 7.8 – Timetable 3.

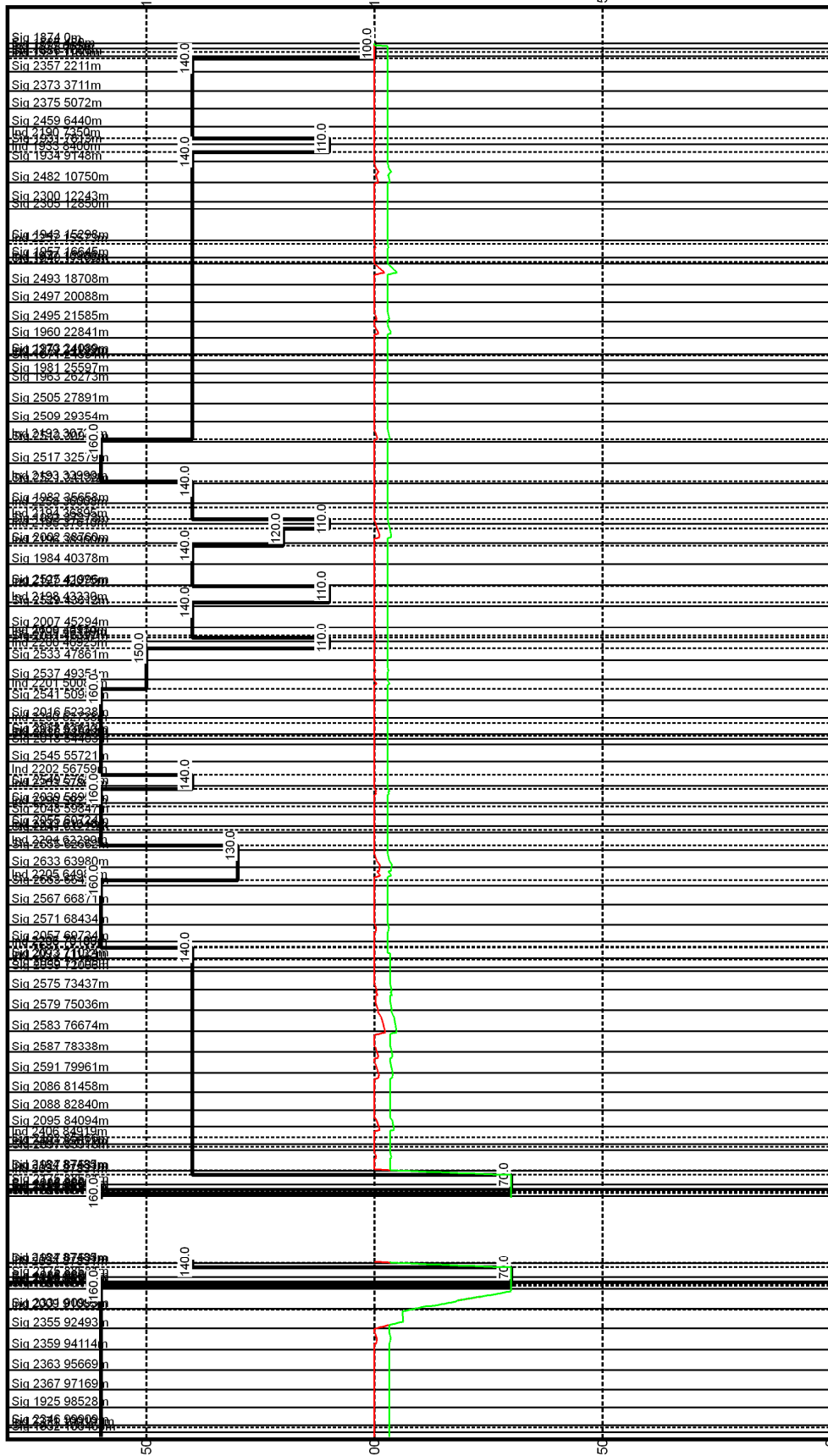


Figure 7.9 – FT speed chart in Mjölby – Alvesta with a speed limit of 200 Km/h.

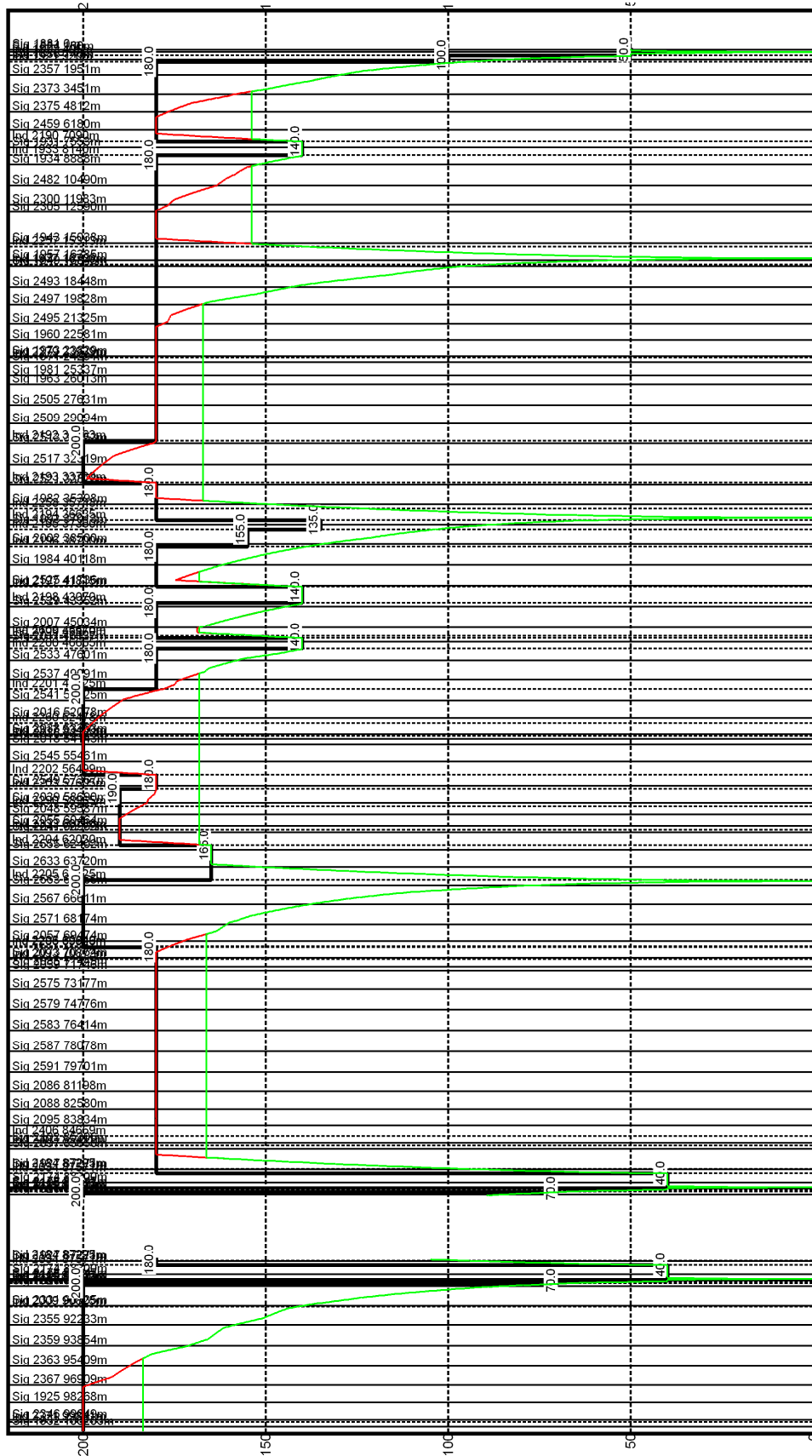


Figure 7.10 – RT speed chart in Mjölby – Alvesta with a speed limit of 200 Km/h.

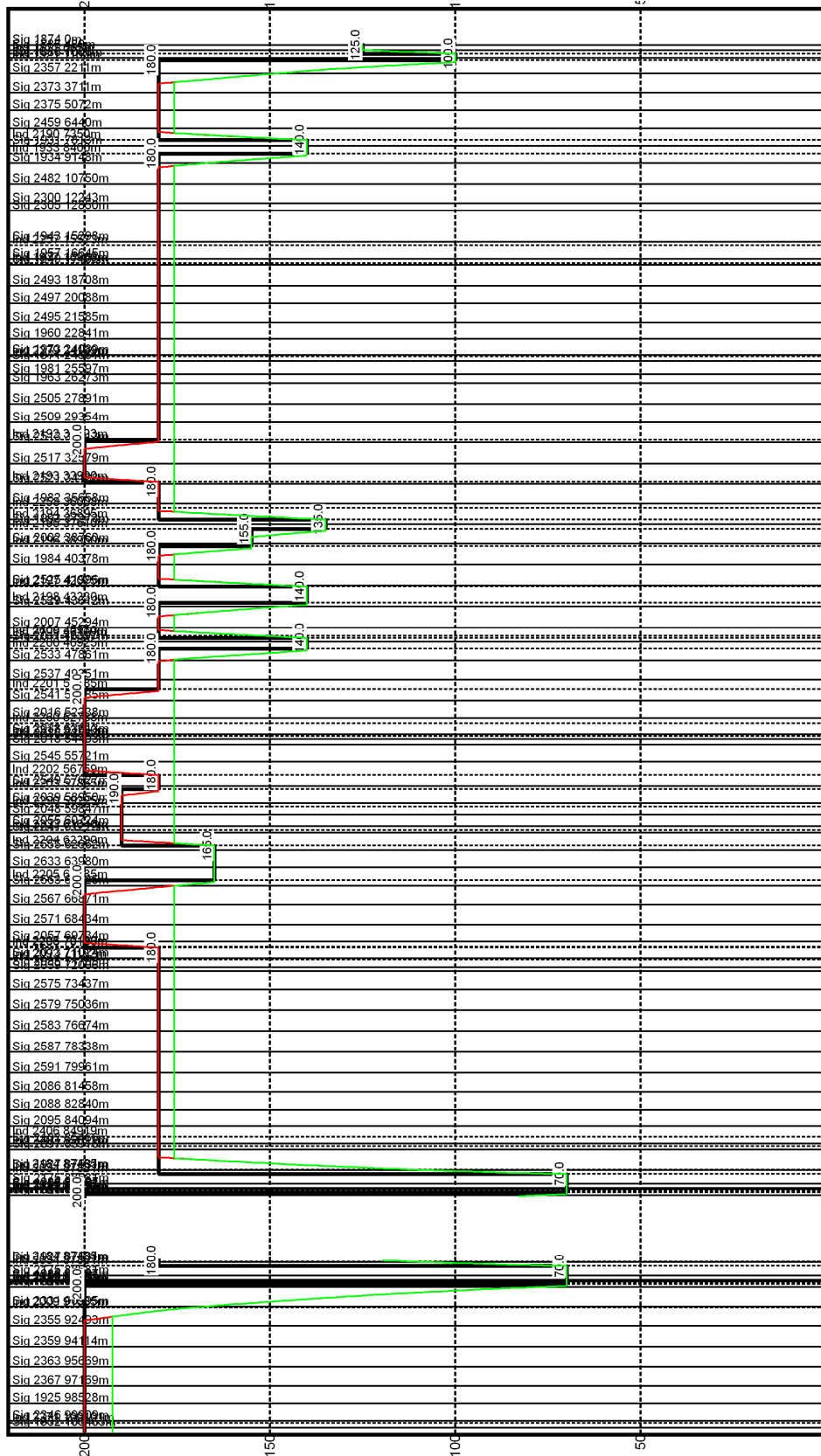
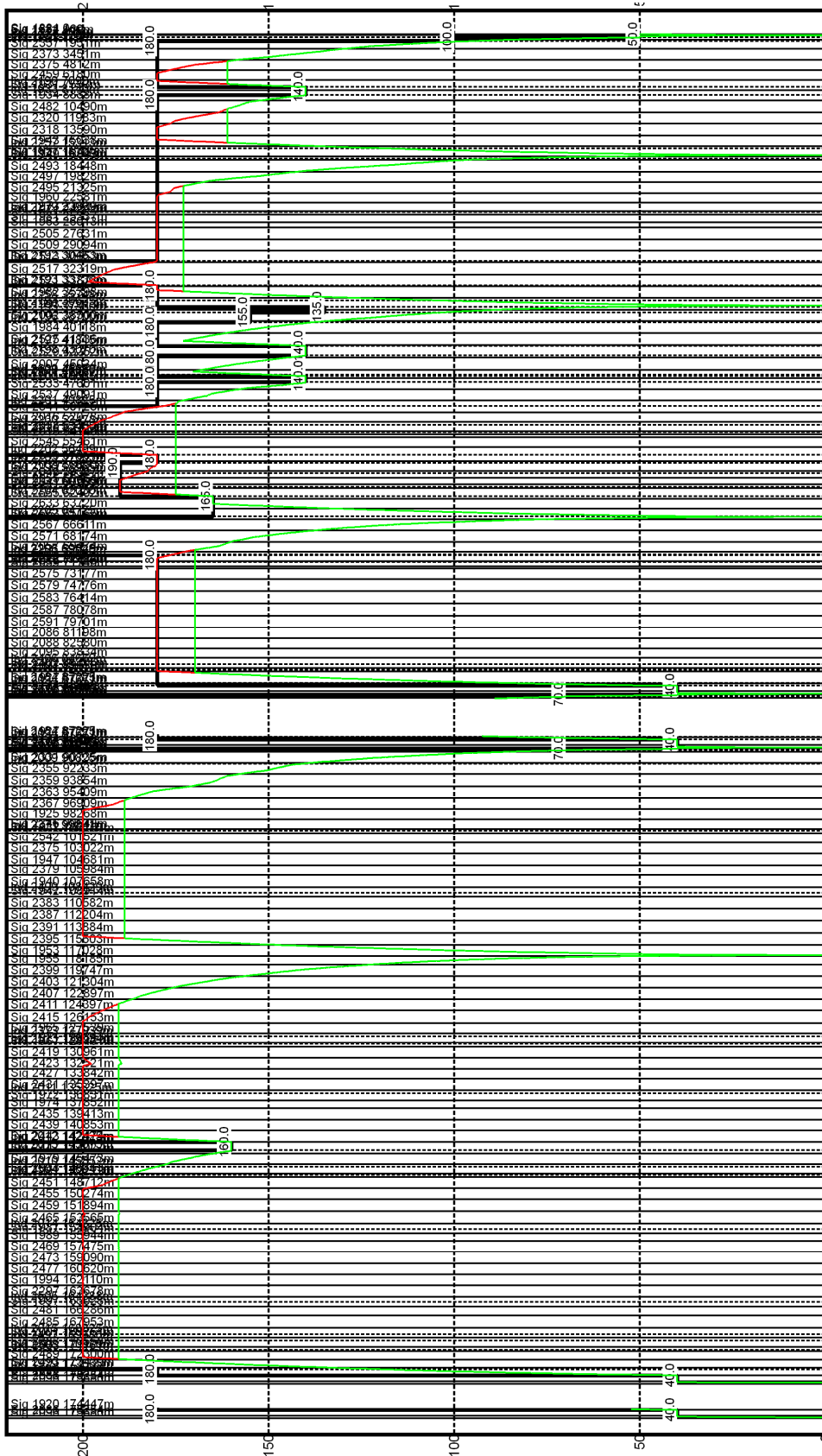


Figure 7.11 – LDT speed chart in Mjölby – Alvesta with a speed limit of 200 Km/h.



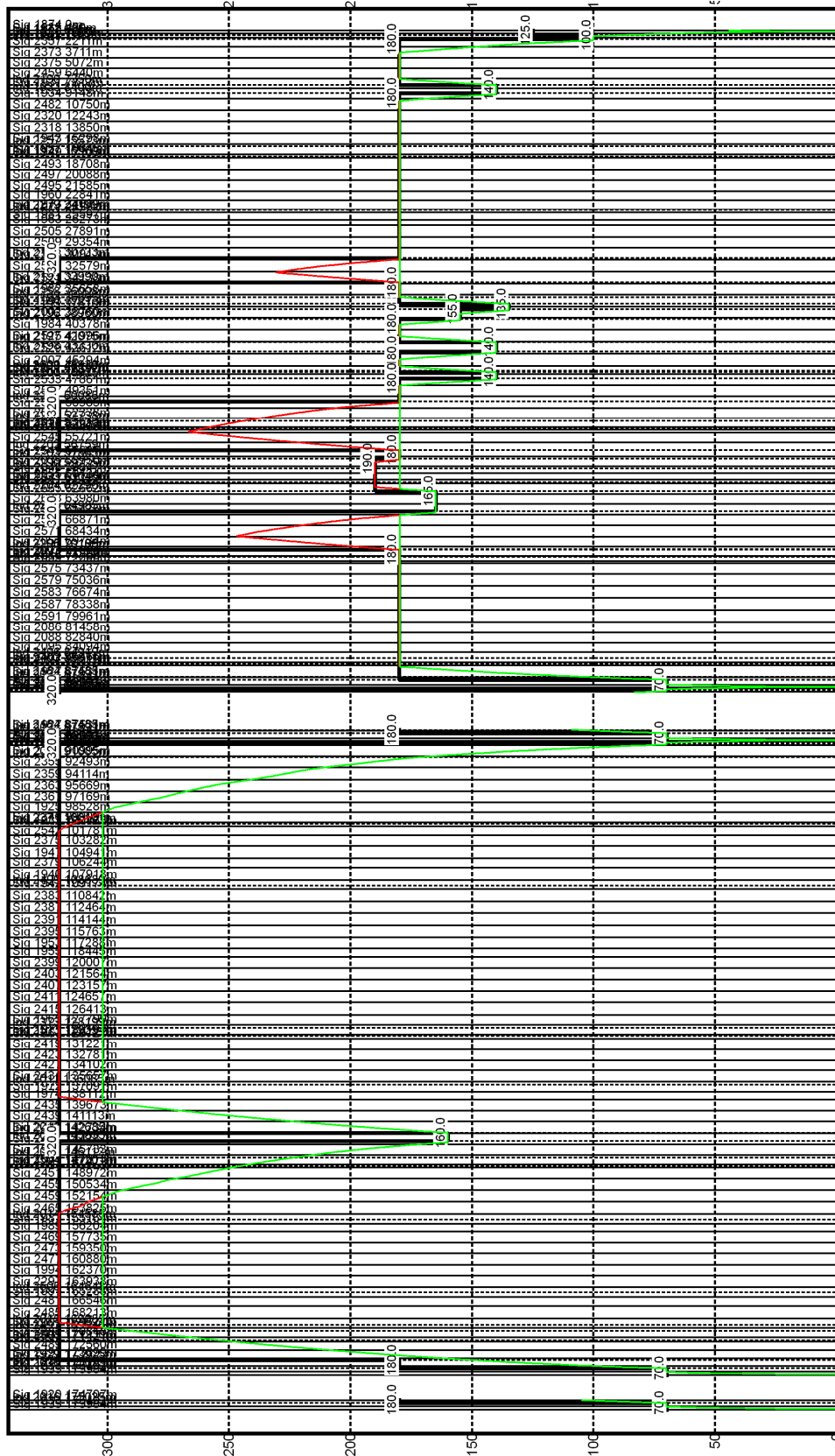


Figure 7.13 – LDT speed chart in Mjölby – Alvesta (with a speed limit of 320 Km/h – the current limit is 200 km/h).

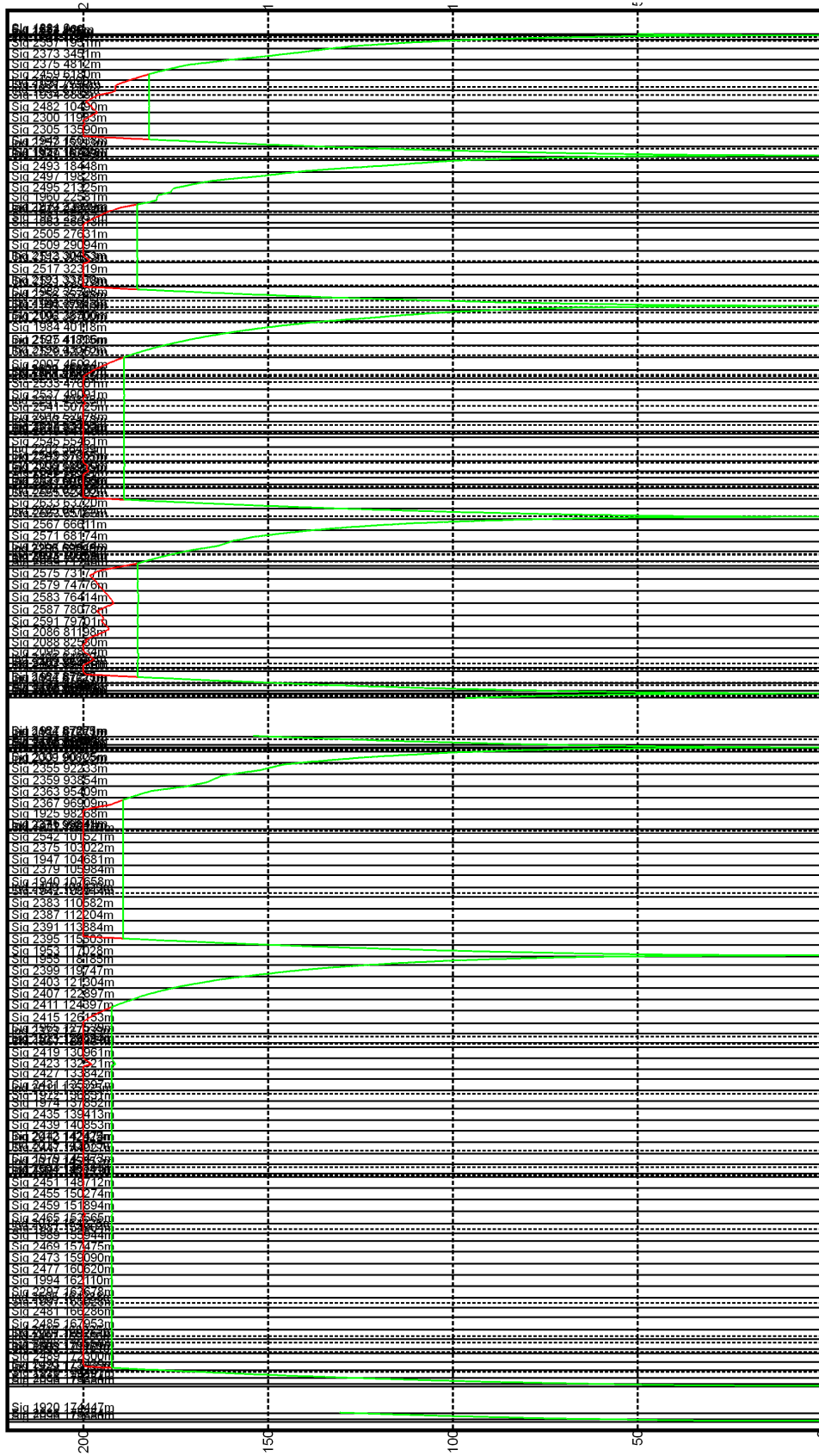


Figure 7.14 – RT speed chart in Mjölby – Alvesta (with a speed limit of 320 Km/h along the line).

