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ANALYSIS OF RAILWAY SIGNALLING SYSTEMS TO INCREASE LINE AND NODE CAPACITY

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INTRODUCTION

"Europe is one of the most urbanized continents on the planet: about 75% of its population lives in urban areas" (European Enviroment Agency, 2017).

In this urban context, the car is still the widely used way of transport, while public transport manages to capture residual segments of the demand for mobility. However, in a structural framework of obvious concern and criticality for public transport, there is a component of the sector in strong expansion, that is, all rail transports. In addition, the incidence of rail transport is even more significant in large metropolitan systems where daily travel reaches its highest levels of expression.

It is known, however, that the supply of transport services is limited by the capacity of the transport system which depends on the physical size of the infrastructure, that is, the capacity of the infrastructure, the number of vehicles, the capacity of the vehicle fleet, the operating time and the traffic regime implemented.

The work, carried out in partnership with Alstom Ferroviaria s.p.a, is divided into 6 chapters.

The first chapter will have the scope to describe the railway circulation, the signalling systems, the apparatuses and the systems involved in the circulation of trains in station and in line, and the system through which it is possible to guarantee the management and the supervision of the trains.

Chapter 2 describes in depth the concept of railway capacity, defining which parameters influence it and which are the methods and the main solutions available to calculate it.

Chapter 3 is focuses on simulation models. A panoramic of the operations necessary to build, calibrate and validate the model will be provided in order to obtain a simulation that represents in the most accurate way possible the real circulation of trains.

Chapter 4 introduces a description of the Opentrack simulation software, used for the simulation of a railway net, developed by A. Nash and D. Huerlimann at the ETH IVT (Swiss Federal Institute of Technology Institute for Transport Planning and System) Zurich.

Chapter 5, the heart of the thesis, describes the simulations of circulations carried out on different real projects. First the case studies are presented specifying the purpose of each projects and then all the hypotheses (rolling stock, system response times, etc.) implemented in the Opentrack simulation software are explained. At the end all simulated scenarios are described, showing the achieved results from the performance point of view.

At least, Chapter 6 reports the conclusions of the thesis.

1. RAILWAY SIGNALLING PRINCIPLES

Railway signalling systems are complex control systems. As a result of the long railway history, there are a lot of specific national solutions based on different technologies. The key to learn how signalling systems work is to understand the fundamental control principles these systems are based on. By definition, the signaling principles are the underlying principles of a signalling based safe working system that are founded on the national standards and are independent from the requirements of a specific railway operating company and the technology used.

1.1 Basic Elements and Terms

The purpose of signalling systems is to ensure safe movements of trains on a railway infrastructure by locking movable track elements in a proper position, checking the clearance of track sections, locking out conflicting moves, and control train movements in a way to keep them safely apart. This chapter describes the trackside elements controlled by signalling systems and explains the basic terms used in the operating procedures for the safe control of movements with railway vehicles on a railway infrastructure.

1.1.1. Controlled Trackside Element

The main controlled trackside elements are: turnouts, crossing, derailers, main signals, shunting signals, axle counters and track circuits.

Turnouts

A turnout is an assembly of rails, movable points, and a frog, which create the tangential branching of tracks and allows trains or vehicles to run over one track or another (Figure 1).

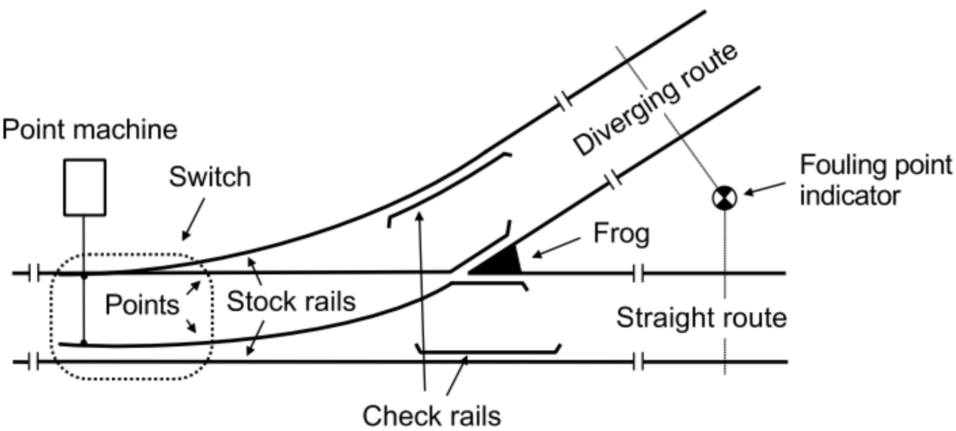


Figure 1 – Components of a turnout (Pachl, 2020).

The movability of the points is provided by using point blades made of flexible steel. The points may be operated manually or by a point machine. Point machines are either electric motor drives or electrically controlled pneumatic cylinder drives. In case of a small angle of divergence, a movable frog operated by an additional point machine could be provided. Movements on a turnout where the points face approaching traffic are called "facing point movements' whereas movements in which the frog faces approaching traffic are called 'trailing point movements" (Figure 2).

The angle of divergence is not stated in degrees but either by its tangent written as a fraction, e.g., 1: 12, or by the so-called turnout or frog number, which is the reciprocal of that fraction. So, a 1: 12 angle equals a frog number 12. The limit of occupation of the converging tracks is called 'the fouling point'. Many railways mark this limit with a trackside fouling point indicator.

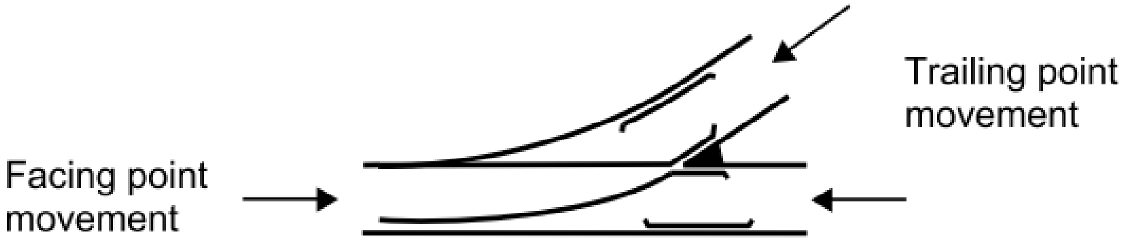


Figure 2 – Movements on points (Pachl, 2020).

In British civil engineering terms, points are also often referred to as switches. There, an entire turnout is called a 'switch and crossing', using the term 'crossing' for the frog part of the turnout. This differs from the terms in railway operation and signalling, where the term points is always used instead of switch.

Crossing

A crossing is an assembly of rails that allow two tracks to cross at grade. Like points, crossings are equipped with fouling point indicators. The inner part of a crossing is called a 'diamond'. Crossings with a large angle of intersection are designed rigidly while in case of a small angle of intersection (usually less than 1: 9), fixed diamond frogs are replaced by movable points ('switch diamond', Figure 3).

Small angle crossings may be equipped with additional points providing a slip connection to permit movements from one track to another. A crossing with a slip connection at one side is called a 'single slip', and a crossing with slip connections at both sides is called a 'double slip' (Figure 4).

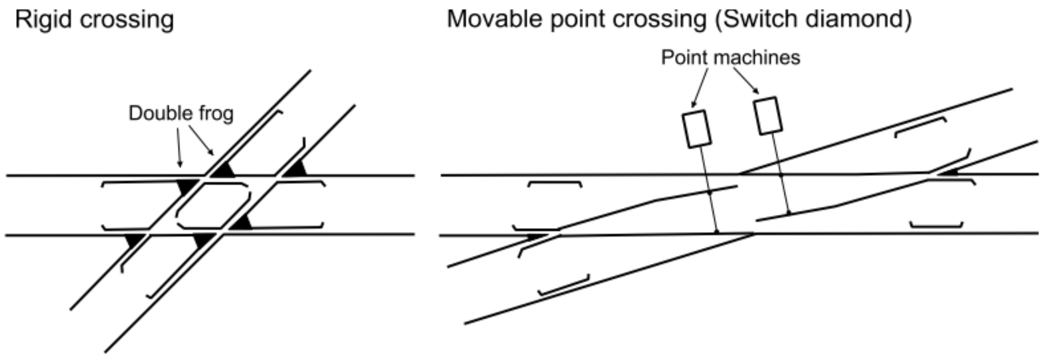


Figure 3 – Crossings (Pachl, 2020).

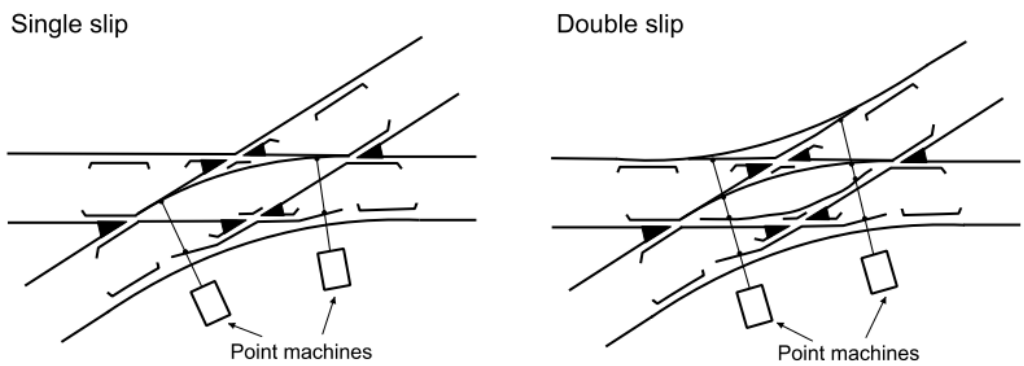


Figure 4 – Single and double slips (Pachl, 2020).

Derailers

Derailers are trackside devices that are used to protect train movements against unattended movements of vehicles on converging tracks. An unsafe movement will be derailed before it could join the protected route. In the protecting position, a derailing piece is raised over one rail. Like points, derailers can be hand or power-operated. On many railways, derailers must not be installed outside of sidings. Instead of derailers, some railways also use trap points, which have quite the same effect.

Figure 5 – A derail device installed on a siding.

Main Signals

Main signals authorize a regular train movement to enter a line section. The movement authority provided by a main signal is limited by the next main signal or a point specified in the operating rules.

Apart from lines with a low speed, a signal that authorizes a train movement requires an approach aspect at the braking distance in approach to the signal because the stopping distance is generally greater than the range of vision. The approach aspect is necessary for a safe braking when approaching a stop signal (Figure 6a). On lines where the distance between signals does not significantly exceed the braking distance, the approach aspect is usually provided by the signal in rear. On lines with very long distances between main signals, distant signals are placed at the braking distance in approach to a main signal. A distant signal can only provide an approach aspect for the signal ahead, but it cannot show a stop aspect (Figure 6b). Another common term for a distant signal used in the rulebooks of some railways is warner signal (Chandra and Aqarwal, 2008).

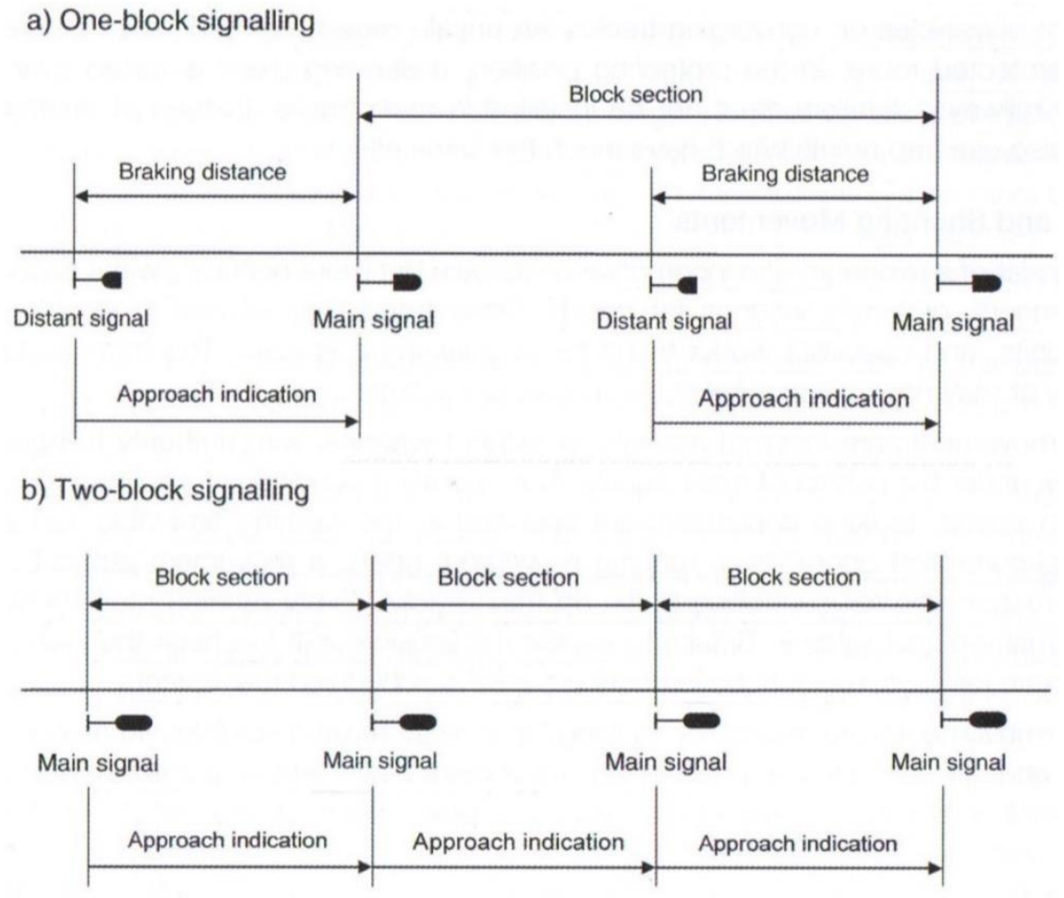


Figure 6 – Block sections limited by Main Signals (Pachl, 2014).

Shunting signals

Shunting signals are used to authorize shunting movements and to protect trains against shunting movements. On most railways, the stop aspect of a main signal also applies for shunting movements. On tracks where shunting movements may pass main signals, a shunt aspect is incorporated in the main signal, so that shunting movements may be authorized to pass main signals in stop position. For shunting signals, an approach aspect is not provided because shunting movements run at a very low speed that allows the driver to stop short of any vehicle or obstruction.

On railways that do not use the distinction between main and shunting signals, there is a signal aspect that authorizes a movement to pass a signal cautiously on sight prepared to stop short of any vehicle or obstruction. That aspect is used both for shunting purposes but also to authorize train movements to enter a section that may be occupied.

Figure 7 – Shunting signals.

Track circuits

A track circuit is an electrical circuit of which the rails of a section form a part. It usually has a source of current at one end and a detection device at the other. Sections are divided by insulated rail joints (Figure 8).

If the section is occupied by a vehicle, the axles produce a short circuit by shunting the two rails. As a result, the detection device does not receive any current and therefore it detects the section as occupied. The detection device is often implemented by a track relay, which is in a picked up position when the section is clear and dropped when the section is occupied. In modern installations, the relay is often replaced by an electronic detector. Since a track circuit is based on the closed circuit principle, any interruption of the current will lead to a safe state by making the section occupied.

The maximum working length of a track circuit is limited by the resistance between the two rails. Track circuit sections cannot be made much longer than about 2 km.

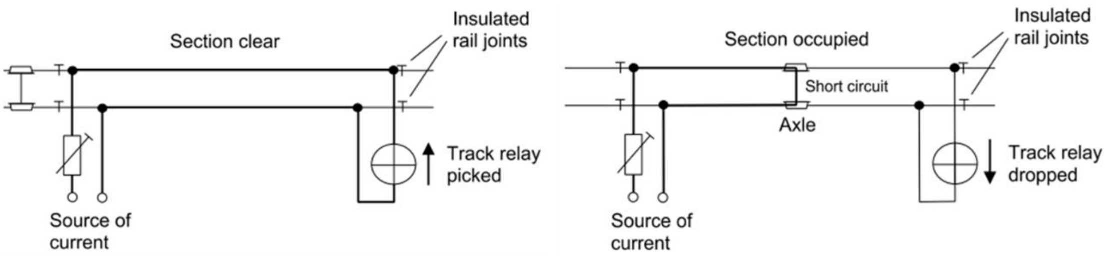


Figure 8 – Track circuit (Pachl, 2020).

Axle counters

An axle counter is a system consisting of counting points at the boundaries of a section and a counter connected to the counting points (Figure 9). The occupancy of a section is detected by comparing the number of axles that enter the section with the number of axles that leave the section. To give a clear indication, the parity of numbers is necessary. Counting points are usually made up of double contacts to detect the direction of movement. This is necessary for correct detection whether an axle is entering or leaving the section. In contrast to track circuits, the maximum working length is not limited.

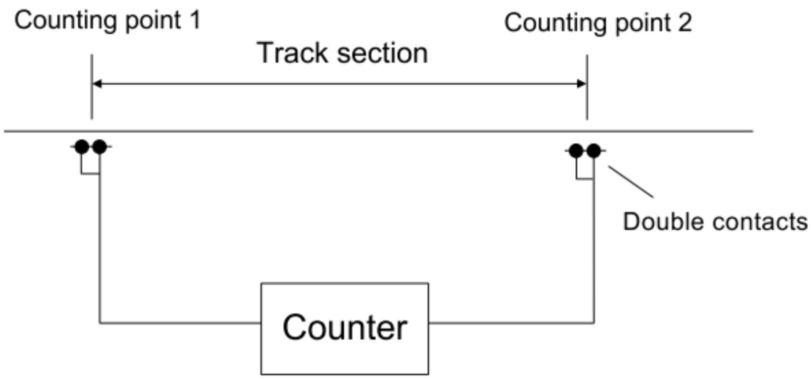


Figure 9 – Axle counter (Pachl, 2020).

1.1.2. Basic Operating Terms

Classification of Tracks

In railway operations, a track is often also referred to as a line. A route consisting of just one track is called a single line, while a route with double track operation, i.e., two parallel tracks and a specified direction for normal moves on both tracks is called a double line. For operational purposes, tracks are divided into two main classes:

- tracks that may be used for regular train movements;
- tracks that must only be used for shunting movements.

The tracks used for regular train movements are called main tracks or running lines. The lines between stations and their continuation through stations and interlocking areas belong into this category. It also includes tracks for passing and overtaking trains which are called loops on most railways (Figure

10). On signalled lines, tracks used for train movements are equipped with signalling appliances for the safe passage of trains. Along the line a train passes through, points are usually interlocked with signals that provide the movement authority. Sidings are all tracks that must only be used for shunting movements. The points of sidings are often not interlocked.

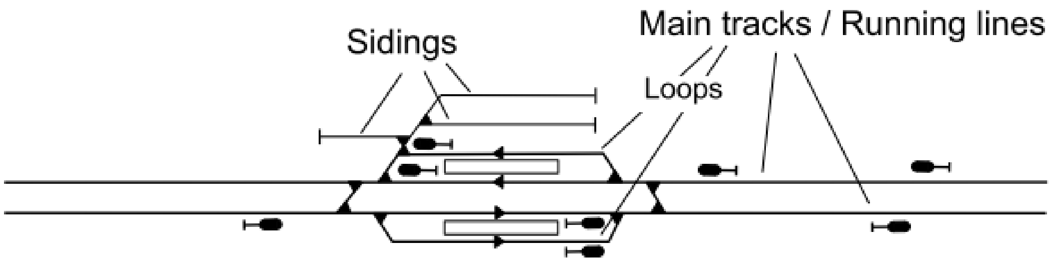


Figure 10 – Classification of tracks (Pachl, 2020).

Block Sections

A line with a fixed block system is divided into block sections for the purpose of safe train separation (Figure 6). A train must generally not enter a block section until it has been cleared by the train ahead. On lines with lineside signals, block sections are limited by signals, which govern train movements. A signal that limits a block section outside a station area is called a block signal. While the basic idea of train separation by fixed sections also applies on station tracks, many railways that separate the station areas from the open line use the term block section only outside of station areas.

Interlocking Areas

An interlocking area is a track area, where controlled signals are interlocked with points and other signals in a way that a signal can only be cleared when all points are locked in the proper position and all conflicting moves are locked out. Signals that govern routes in an interlocking area are called interlocking signals. The points and signals are controlled either by a local interlocking station or from a remote control center. Local interlocking stations are called signal boxes or signal cabins on most railways. A locally staffed interlocking station contains both the interlocking system and the user interface for the operator while modern interlocking systems are usually remote controlled from a control center.

There are two basic signal arrangements in interlocking areas: the first one are interlocking areas without consecutive interlocking signals where interlocking signal provides authority to run through the entire interlocking area into the next block section (Figure 11a). The second one are interlocking areas with consecutive interlocking signals. Such an interlocking area may contain tracks protected by controlled signals on which trains may originate, terminate, pass, and turn (Figure 11b).

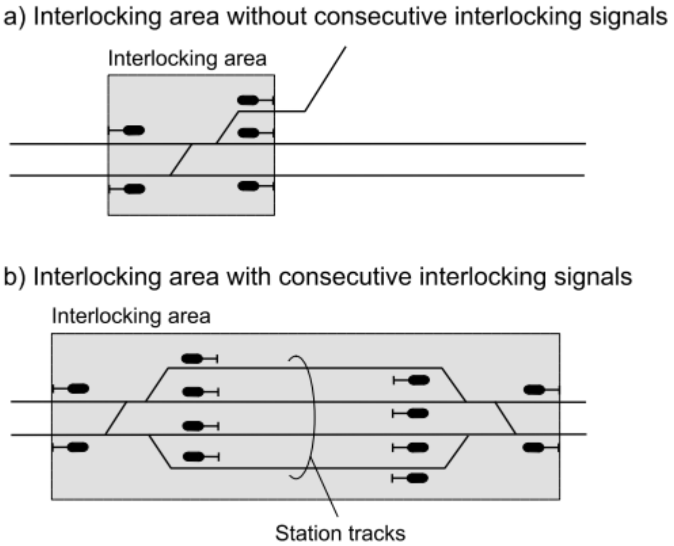


Figure 11 – Classification of tracks (Pachl, 2020).

On most railways, the interlocking signals protecting a station area from both sides are called home signals. The interlocking signals that govern train movements to leave a station track into a section of the open line are often called exit signals. Interlocking signals within the station area that are neither home nor exit signals are called intermediate interlocking signals (Figure 12). On some railways, they are also called inner home signals (when passed by arriving trains) and inner starter signals (when passed by departing trains).

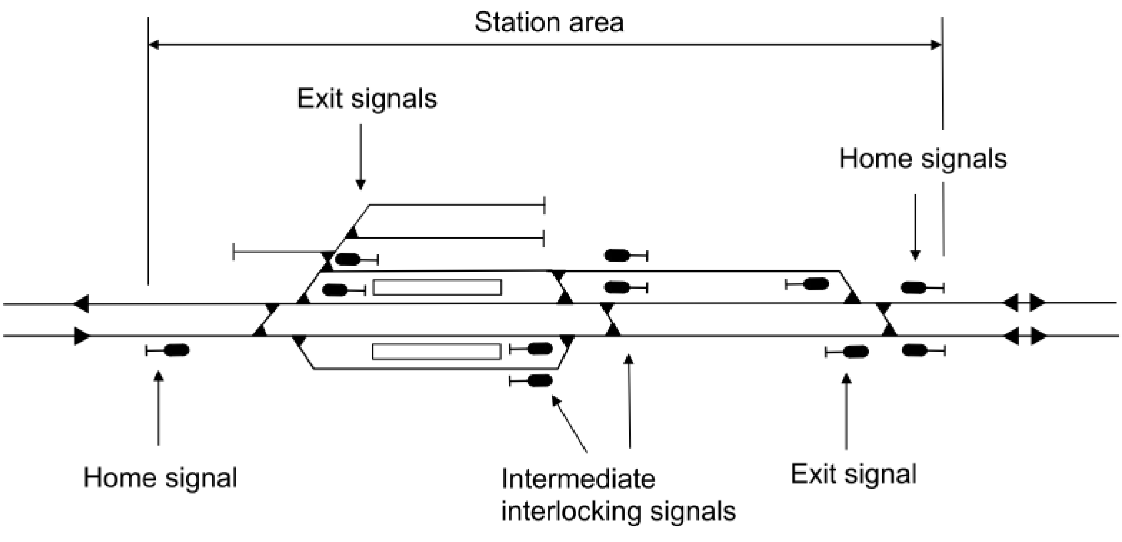


Figure 12 – Station area with intermediate interlocking signals (Pachl, 2020).

Movements with Railway Vehicles

On most railways, the normal train movements are separated from the so-called shunting movements. Train movements, also known as "running movements", are movements of locomotives or self-propelled vehicles, alone or coupled to one or more vehicles, with authority to occupy a section of line under operating conditions specified in the operating rules. Every train displays rear-end markers (tail lights or marker boards) to enable the lineside staff to check the train completeness (Figure 13).

Figure 13 – Rear-end markers (RFI, 2016).

All regular movements running along the line from station to station are train movements.

The authorization of a train movement has two elements:

- A valid timetable as the authority to run through the network along a predefined route by specified operating conditions (timetable authority);
- A movement authority for every single section of track in the path of the train.

The movement authority to enter a section of track is issued by the operator who is in charge of controlling train movements on that section of track. In this way, a train is always under external guidance of a train control operator. The authority for train movements is given by:

- A proceed indication of a main signal;
- A proceed indication of a cab signal display;
- A call-on signal permitting a train to pass a signal displaying a stop aspect under special conditions;
- A written or verbal instruction permitting a train to pass a signal displaying a stop aspect under special conditions;
- A written or verbal authority on non signal-controlled lines.

Shunting movements are movements for making up trains, moving vehicles from one track to another, and similar purposes. Shunting movements are accomplished without a timetable under simplified conditions at a very low speed that allows the driver to stop short of any vehicle or obstruction.

The authority of shunting movements is given by:

- A proceed indication of a shunting signal, which may be combined with a main signal to authorize a shunting move to pass the main signal in stop position;
- Verbal permission.

Double Track Operations

For double track operation, there is usually a specified direction of traffic for each track. While right track operation dominates slightly worldwide, there is a significant number of countries where left track operation is the standard form (i.e Italy, France, Belgium). On lines not equipped with a bidirectional signalling system for two-way working, all regular train movements have to be made with the normal direction of traffic. On such lines, movements against the normal direction (also called "wrong line moves" or "reverse movements") have to be authorized by special instructions under staff responsibility. On lines that are equipped with a signalling system for two-way working, movements against the normal direction can be authorized by clearing a main signal.

Many railways do not install intermediate block signals for reverse movements because on most lines, reverse movements are not carried out frequently. For temporary single track working is case of a track closure, the direction on the remaining track will change after almost every train. So, intermediate block signals would have no effect on capacity. Intermediate block signals for movements against the normal direction do only make sense on sections, where parallel moves on both lines are carried out on a regular basis.

Figure 14 shows typical examples of signal arrangements for double track operation. On many railways, a normal direction of traffic is only in effect outside of station areas.

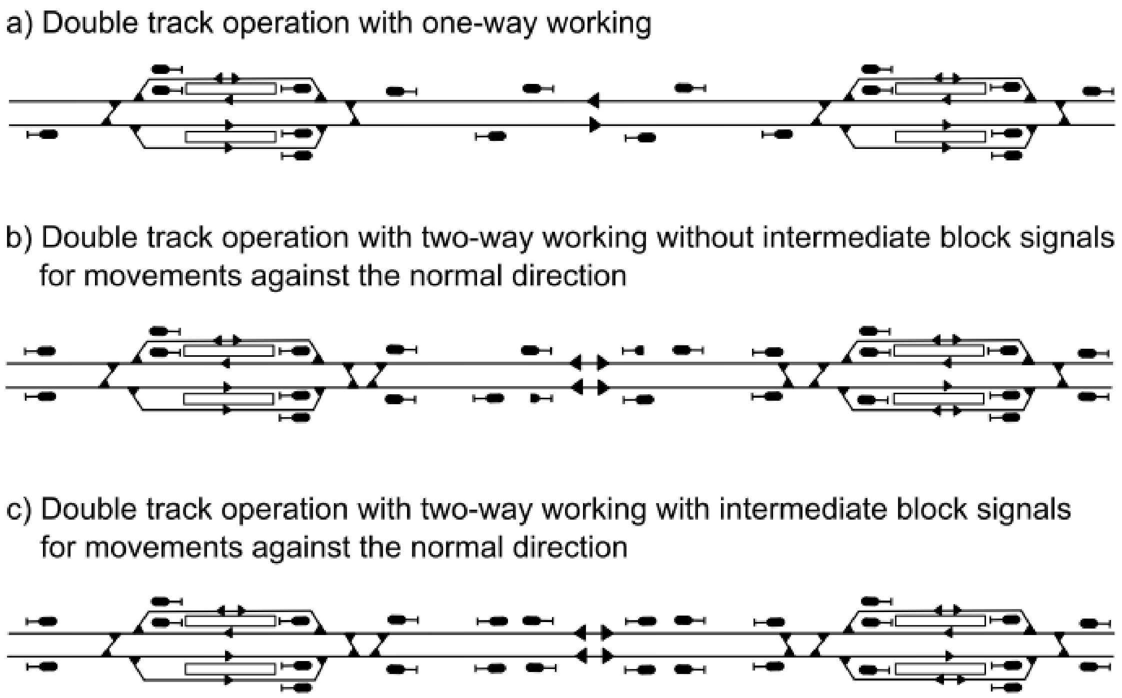


Figure 14 – Signal arrangements for double track operations (Pachl, 2020).

1.2 Spacing Trains

In a steel wheel on steel rail system, the static friction coefficient is on average eight times less than in road traffic. As a result, the maximum braking force that can be transmitted between wheel and rail for a given weight is also eight times less. That leads to braking distances for railway vehicles that may exceed the viewing range of the driver significantly. Thus, train separation cannot simply be based on the viewing range but has to be controlled by trackside technology.

This chapter describes the theory behind the train separation, analyzing in detail the train and block control principles and how the different systems work.

1.2.1. Theory of Train Separation

There are three basic theoretical principles of train separation:

- Relative braking distance;
- Absolute braking distance;
- Fixed block distance.

Relative Braking Distance

In relative braking distance mode, the distance between two following trains equals the difference of the braking distances of the trains plus an additional safety margin. For the headway ("head-to-head") distance between two trains following each other, the length of the first train has to be added (Figure 15a). The braking distances of both trains have either to be calculated with braking curves based on the same deceleration rate, or by applying the rule that in case of a better braking performance of the second train, a minimum safety margin must always be kept between the two trains.

While relative braking distance leads to a maximum of line capacity, there are two essential problems. When points are to be moved between two trains, the second train cannot follow at relative braking distance but must be kept at full braking distance in approach to the points until the points are safely locked in the new position. As a result, the line capacity is limited by the point zones where successive trains may take different routes. Another problem is that in case of an accident of the first train, the second train has no chance to stop and is going to collide with the first train. For these problems, this principle has not yet applied for train separation but is used by some freight railways for processing the coupling and uncoupling of helper locomotives on the move.

Absolute Braking Distance

Absolute braking distance leads to a distance between two following trains that equals the braking distance of the second train plus an additional safety margin. For the minimum headway, the length of the first train has to be added (Figure 15b).

Train separation by absolute braking distance is often seen as the best-suited principle of train separation. The only problem that has so far prevented the introduction of this principle outside of mass transit systems is the lack of a usable technology for onboard checking of train completeness (train integrity) of freight trains, which is needed for safe location of the train's rear end. However, with the further development of radio-based operating technologies, train separation by absolute braking distance may be widely introduced in the near future. The absolute braking distance mode is also generally known as 'moving block'.

Fixed Block Distance

In a fixed block system, the line is divided into consecutive block sections. A block section may be exclusively occupied by only one train at a time. The distance between two following trains equals the braking distance of the second train plus the length of the block section plus an additional safety margin. Thus, the headway distance equals the headway of absolute braking distance plus the length of the block section (Figure 15c). While the minimum headway of a fixed block system exceeds the minimum headway of a moving block system, the capacity limiting effect of the block sections is often overrated.

In train control with lineside signals, the block sections are limited by signals. Nowadays, running in fixed block distance is the most common principle of train separation worldwide.

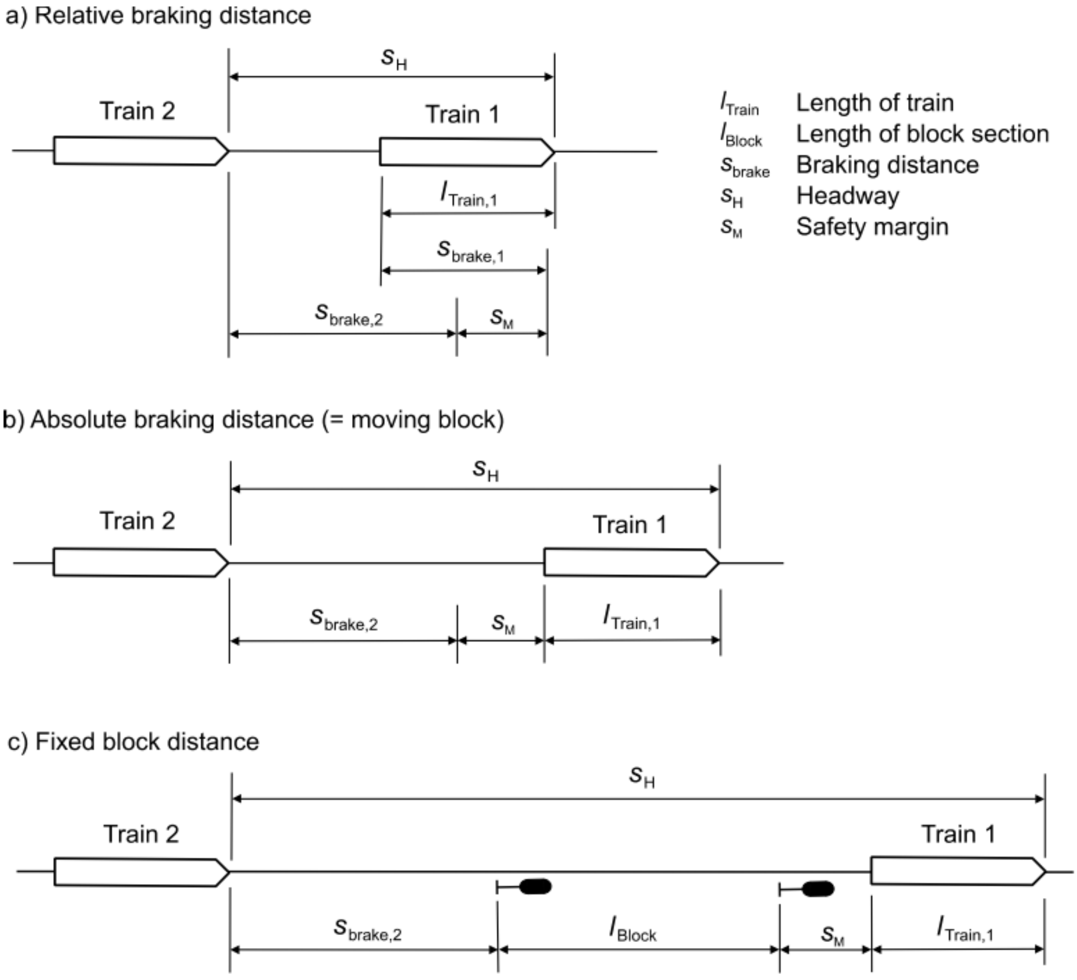


Figure 15 – Principles of train separation (Pachl, 2020).

1.2.2. Train Control Principles

The principle used for safe train separation depends on the following criteria:

- How movement authority is transmitted from track to train;
- How the track is released behind a train.

If movement authority is only transmitted at discrete points, e. g. at lineside signals, this will necessarily lead to a fixed block system. Each movement authority has to cover the entire section up to the next point at which further authority may be received. On lines where trains are governed continuously by a cab signal system, this restriction does not exist. However, continuous transmission of movement authority is not yet a sufficient criterion to abolish fixed block sections. In addition, the train has to release the track not in fixed intervals but continuously. This requires a permanent train-borne checking of train completeness. Since for traditional railway systems, a sufficient solution for that problem has not yet been found, train separation at a fixed block distance is still the standard principle for safe train spacing on most railways worldwide.

Before explaining the different principles of train separation, another essential feature has to be mentioned. The braking distance of a train does not mainly depend on the weight of the train but on the percentage of the weight that is used to transmit braking force between wheel and rail. Trains with the same braking ratio have generally the same braking distance. For safe train separation, a train must always have a clear track ahead at least as long as the braking distance. Thus, from the viewpoint of capacity, it makes sense to assemble vehicles into trains. All vehicles that form a train do need just one common braking distance for the entire consist. This will significantly reduce the capacity consumption that is produced by the long braking distances. This is why running whole trains instead of single vehicles is one of the very basic characteristics of a railway system.

1.2.2.1 Train Control by Lineside Signals

Guiding Trains in Fixed Block Operation

While, with the introduction of radio-based train control system, railways move more and more toward cab signalling, lineside signals are still the dominating form of train control. They are even used in many new installations. Since lineside signals can only transmit movement authorities at fixed intervals, train control by lineside signals always leads to a fixed block operation. For this, the line is divided into block sections limited by signals. To clear a signal for a train that is to enter a block section, the following conditions must have been fulfilled (Figure 16):

- The train ahead must have cleared the block section;
- The train ahead must have cleared the overlap beyond the next signal (only on lines where block overlaps are used);
- The train ahead must be protected by a stop signal.

On lines with bidirectional operation, the train must also be protected against opposing movements.

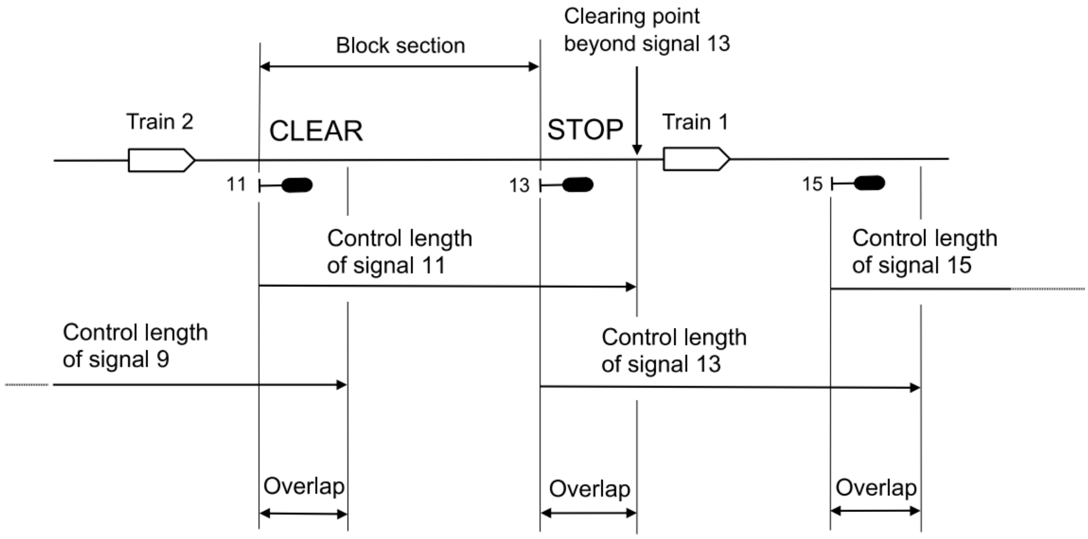


Figure 16 – Control length of signals on a fixed block line (Pachl, 2020).

The control length of a signal is the length of track beyond a signal that must be safe and clear to enable that signal to be cleared. When overlaps are used, the control length exceeds the length of the block section and overlaps with the control length of the next signal. The main purpose of the overlap is to provide additional safety in case a train overruns a stop signal by a short distance due to bad brake handling. A signal must not be cleared until the full control length is clear. Thus, the clearing point beyond a signal equals the end of the control length of the signal in rear. Some railways do not use overlaps and in that case, the control length of a signal equals the block length.

Lineside Signal Indications

Lineside signals provide information both for safe train separation but also for guiding trains through point zones. Concerning the classification of signal aspects, these systems can be divided in two basic principles of signalling:

- Speed signalling;
- Route signalling.

In a speed signalling system, the signals indicate the speed not to be exceeded by a train while in route signalling, the facing point signals indicate the route over which the train is being sent. In route signalling, the driver must know the speed limit of every route the train may run over. While systems follow the speed signalling principle, route signalling is also still quite common, in particular on railways with roots in the British system.

In some systems, the speed or route information is part of the block signal aspect e.g., by using combinations of different lights. Other systems, in particular modern European installations, use supplementary speed or route indicators (Figure 17). In such systems, the block signal itself gives only information about the occupation of the following block sections. So, the block signal aspects can be designed in a very simple form.

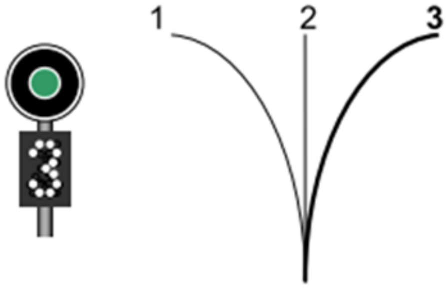


Figure 17 – Italian speed signal (left) and route signal (right) (RFI, 2016).

For train separation, most railways use three basic indications, usually displayed by a red, yellow, and green aspect. That's why, such a system is also known as three-aspect signalling (Figure 18).

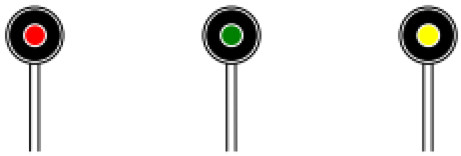


Figure 18 – Italian line signals (RFI, 2016).

Since different names are used for these indications in the rulebooks of individual railways, the generic terms as stated in Table 1 are used here.

Stop	Train must stop at the signal
Expect stop	Train may proceed with caution prepared to stop at the signal ahead
Clear	Train may proceed

Table 1 – Basic signal indications (Pachl, 2020).

Regarding the principle of providing the approach indication there are two kinds of signalling (Figure 19):

- One-block signalling;
- Multiple-block signalling.

In one-block signalling (Figure 19 a), the indication of a main signal depends only on the state of the block section beyond the signal. A main signal cannot provide any approach information for the next signal. So, every main signal must have a distant signal whose only purpose it is to provide the required approach indication. The distant signal is placed at the braking distance in approach to the main signal. On lines with short block sections that do not significantly exceed the braking distance, the distant signal is placed at the main signal in rear. In such systems, the head of a main signal and the head of the distant signal for the next main signal are often mounted one above the other on the same mast.

In multiple-block signalling, the indication of a main signal depends on the state of two or more following block sections. Very common is two-block signalling in which the approach indication is given by the aspect of the rear main signal without need for separate distant signals (Figure 19 b). Since two-block signalling uses the same three basic signal aspects as one-block signalling, both principles fall into the category of “three-aspect signalling”.

Multiple-block signalling renders a very efficient signalling but requires block sections not much longer than the stopping distance. On lines with very long block sections, multiple-block signalling is not useful because approach indication given too early will reduce the capacity of the line by increasing the signal headway of following trains. Many modern signal systems may be alternatively used with one-block or multiple-block signalling depending on the actual block length.

Some railways even use three-block signalling in which a main signal provides information on three block sections ahead by using an advance approach indication (Figure 19 c). For this, a fourth signal aspect is used telling the driver to be prepared to stop at the second signal ahead. That is, why such a system is called four-aspect signalling. By three-block signalling, the braking distance may exceed the block length enabling signals to be placed at shorter intervals to improve capacity. On railways that use speed signalling, the same effect can be achieved by progressive speed signalling (Figure 20).

In progressive speed signalling, a train approaching a stop signal is progressively slowed down by speed indications. So, the maximum speed at which the train may pass the last signal in approach to a stop signal will ensure a safe braking within the short block section. Although more than three signal aspects are used (mostly four aspects but in some installations even more), it is only a two-block signalling system because an approach information is only given for the signal ahead.

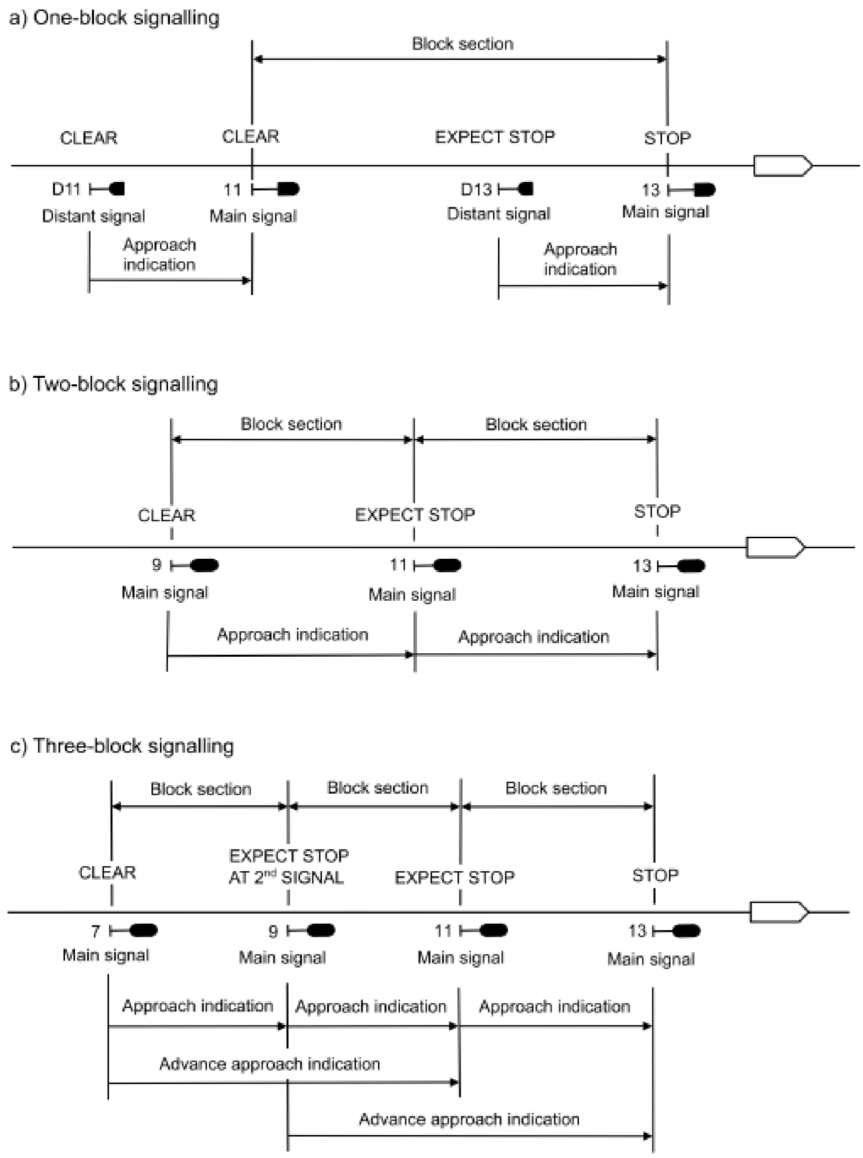


Figure 19 – Different Principles in the Application of the Approach Indication (Pachl, 2020).

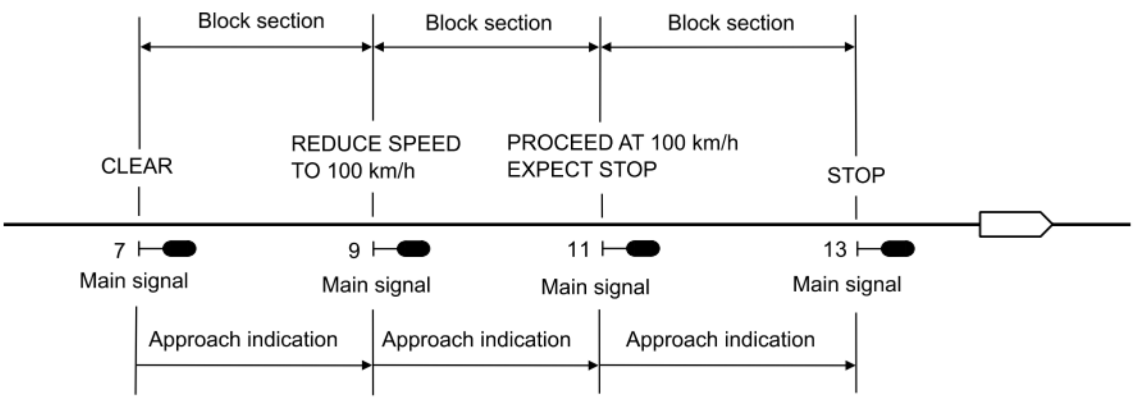


Figure 20 – Progressive speed signalling (Pachl, 2020).

The Blocking Time Model

For the non-delayed passage of trains, a signal must be cleared before an approaching train is forced into a brake application by the aspect of the signal in rear. The minimum headway between two following trains depends on the so-called "blocking time" (Pachl, 2020, 2014).

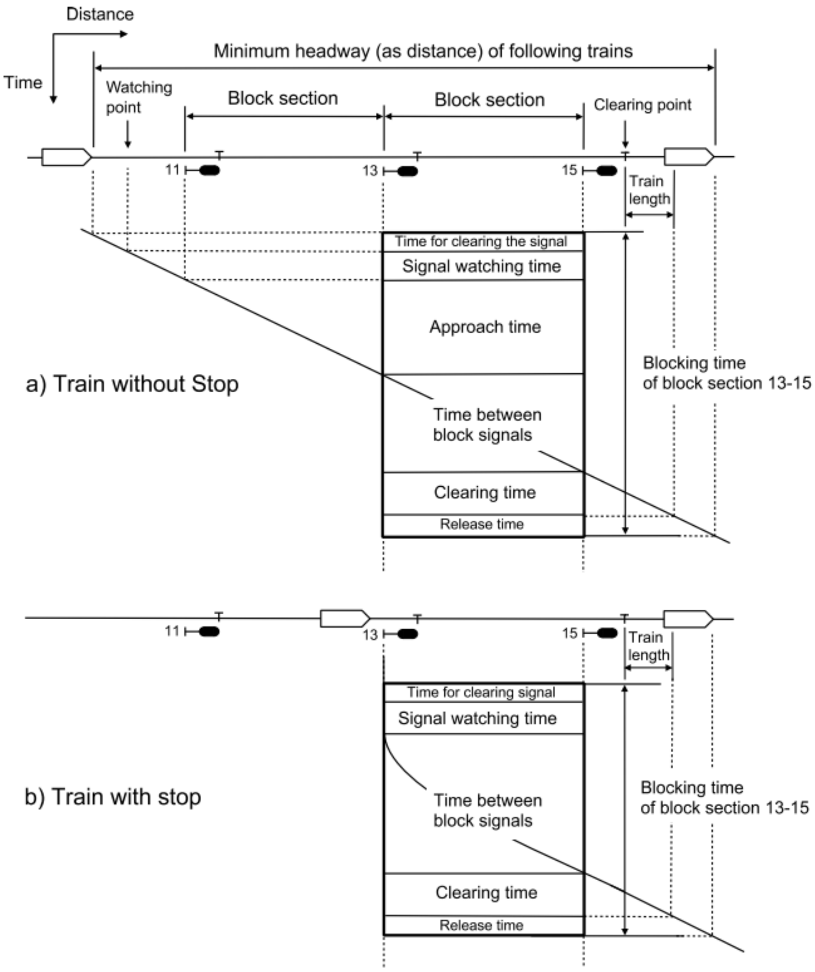


Figure 21 – Blocking time of a block section (Pachl, 2020).

The blocking time is the time interval in which a section of track (usually a block section) is allocated exclusively to a train and therefore blocked to other trains. The blocking time lasts from the latest possible time movement authority to enter the section has to be issued by clearing a signal without delaying the train up to the time at which movement authority to another train to enter the same section can be issued. So, the blocking time describes the time window that has to be kept clear for the non-delayed passage of a train through a track section. While it is explained here for a lineside signalling system, the idea behind the blocking time model is universal and can also be applied to cab signalling systems and to automatic train operations; it even works for moving block systems.

The blocking time of a track section is usually much longer than the time the train occupies that section. In train control with lineside signals, for a train without a scheduled stop, the blocking time of a block section consists of the following time intervals (Figure 21):

- The time for clearing the signal;
- The signal watching time i.e. a certain reaction time by which the signal must be cleared ahead of the train to prevent the driver from applying the brakes;
- The approach time between the signal that provides the approach indication and the signal at the entrance of the block section;
- The time between the block signals;
- The clearing time to completely clear the block section and, if required, the overlap;
- The release time to "unlock" the block section.

The approach time equals the time the signal has to be cleared ahead of a train to prevent this train from passing an aspect at the signal in rear that will force the train into a brake application. It does not apply if the train has a scheduled stop at the signal at the entrance of the block section. In such a case, the signal watching time applies at that signal. There, it is the reaction time of the driver to get the train into motion after the signal has been cleared.

Drawing the blocking times of all block sections a train passes into a time-over-distance diagram leads to the so-called "blocking time stairway" (Figure 22). The blocking time stairway represents perfectly the operational use of a line by a train. Computer-generated blocking time stairways are a typical feature of advanced scheduling systems to establish conflict-free train paths.

By means of the blocking time stairways, it is possible to determine the minimum headway between two trains. The blocking times directly establish the signal headway as the minimum time interval between two following trains in each block section. The line headway is the minimum headway between two trains not only considering one block section but the whole blocking time stairways of the line (Figure 23). In this case, the blocking time stairways of two following trains touch each other without any tolerance in at least one block section (the 'critical block section').

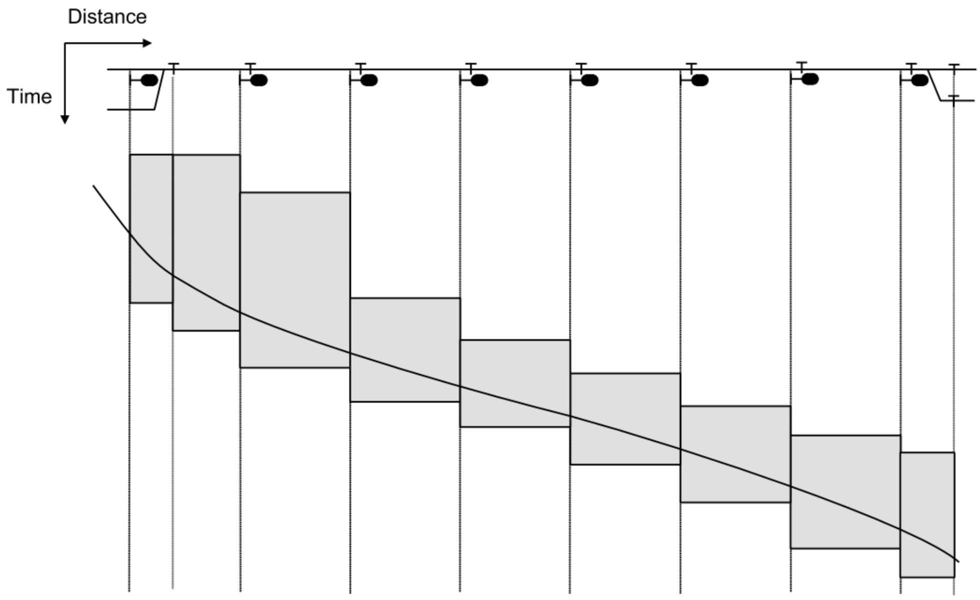


Figure 22 – Blocking time stairway (Pachl, 2020).

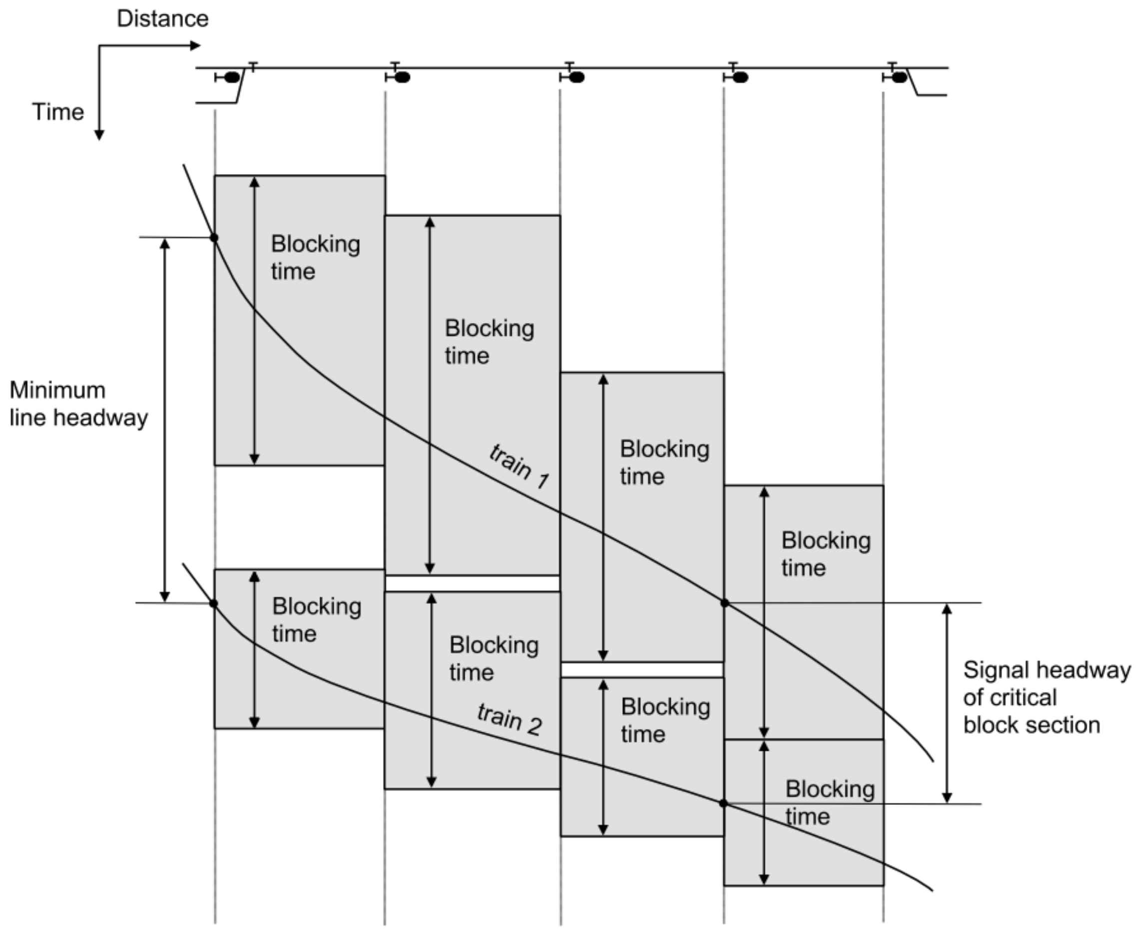


Figure 23 – Signal headway and line headway (Pachl, 2020).

On lines with mixed traffic, the minimum line headway depends significantly on the speed differences between trains. On lines where all trains run at quite the same speed (typical on mass transit railways), the critical block sections are usually the block sections in which the blocking time includes the dwell time of platform stops (station sections, Figure 24). On such lines, signals should be placed in a way that keeps the blocking time of the station sections as short as possible.

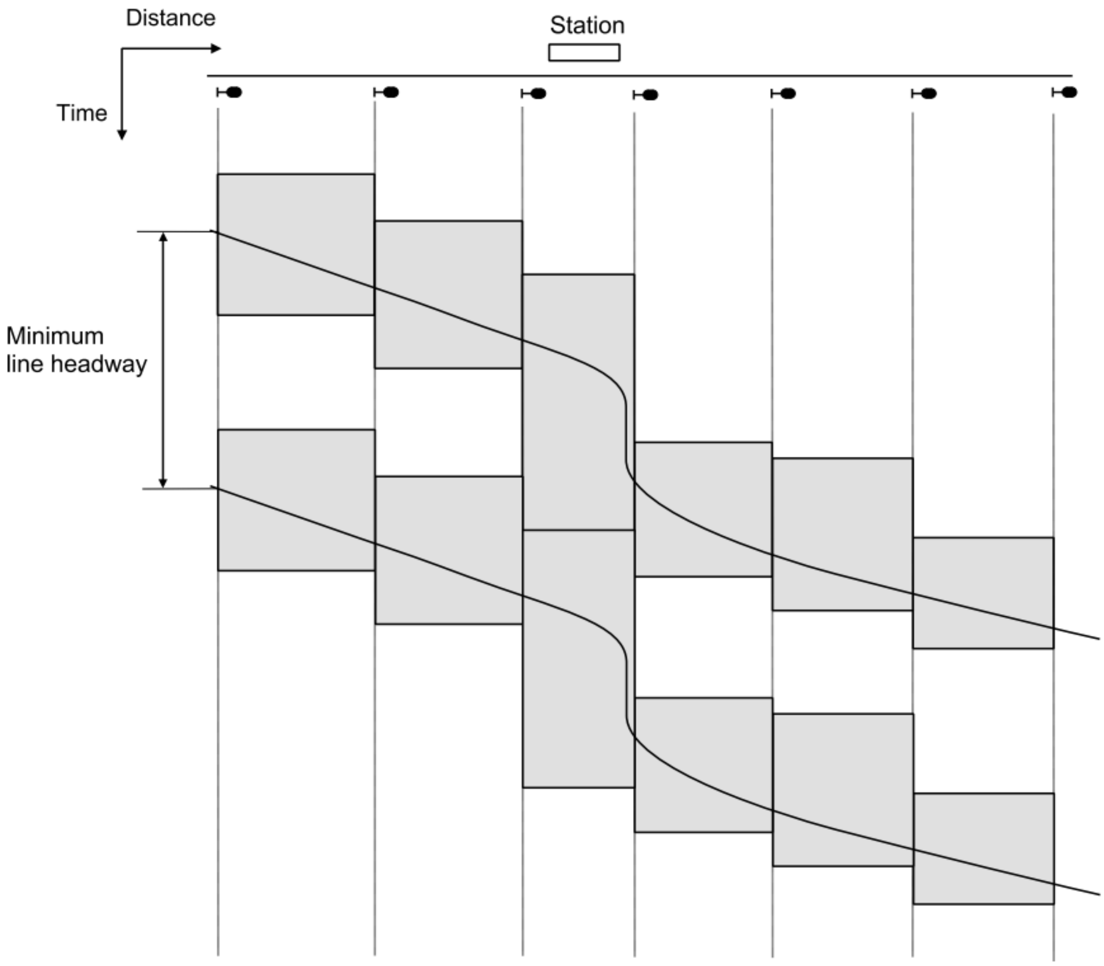


Figure 24 – Blocking time stairways on a mass transit railway (Pachl, 2020).

1.2.2.2 Train Control by Cab Signalling

In cab signalling, the movement authority is directly displayed on the driver's desk (Figure 25). On most railways that use cab signalling, it is combined with a continuous Automatic Train Protection (ATP) system that provides the control data for the cab signals. While cab signalling allows the infrastructure operator to remove lineside signals completely, cab signalling may also be used as an overlay system on lines equipped with lineside signals, so trains may be controlled either by cab signals or lineside signals. To avoid confusion for the driver, most railways established the rule that on such lines, cab signal indications are always superior to lineside signals.

On some railways, there are still older cab signal systems in use that work only as auxiliary systems. On such lines, trains are still governed by lineside signals, but the cab signal indications support the driver in watching the lineside aspects.

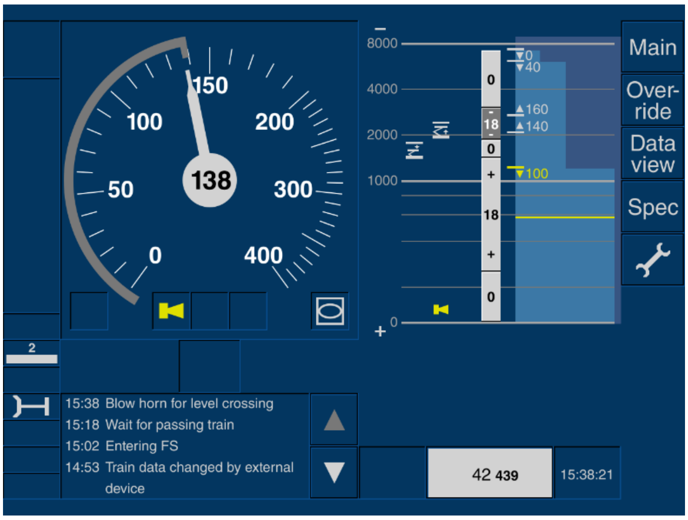


Figure 25 – The ETCS driver machine interface.

Cab signalling with fixed block sections

The main reason for having fixed block sections on lines with cab signalling is the need for checking of train completeness by track clear detection technology. As an approved technology, it is used on many lines with exclusive passenger operations. On cab signaling lines without lineside signals, most railways use block marker boards to mark the block limits for degraded mode operations.

Sometimes, block sections are also used on cab signal-controlled lines with exclusive passenger operations where train completeness is checked on board without track clear detection technology. That principle is called virtual block, because the block sections exist only virtually in the control system without any field installations along the line. The reason for having virtual block sections instead of moving block is to reduce the amount of data transmission by radio. In contrast to a moving block system where the continuous upgrade of the movement authority requires data transmission at very short intervals, the movement authority of a virtual block system is only upgraded after the train ahead has cleared a block section. This significantly reduces the data traffic from track to train. If capacity needs to be improved, the block lengths can easily be reduced in the control system without changing anything in the field.

The main difference of cab signalling with fixed block sections from a fixed block system with lineside signals is the independence from the approach distance of the lineside signal system, which is the distance between the signal at the entrance of the block section and the signal in rear that provides the approach indication. The approach time is no longer the running time between these two signals but the running time within the real braking distance based on the supervision curves of the cab signal system. Also, due to the absence of lineside signals, a signal watching time to spot a signal aspect at a specific location is no longer needed. The other elements of the blocking time do not differ from a system with lineside signals (Figure 26).

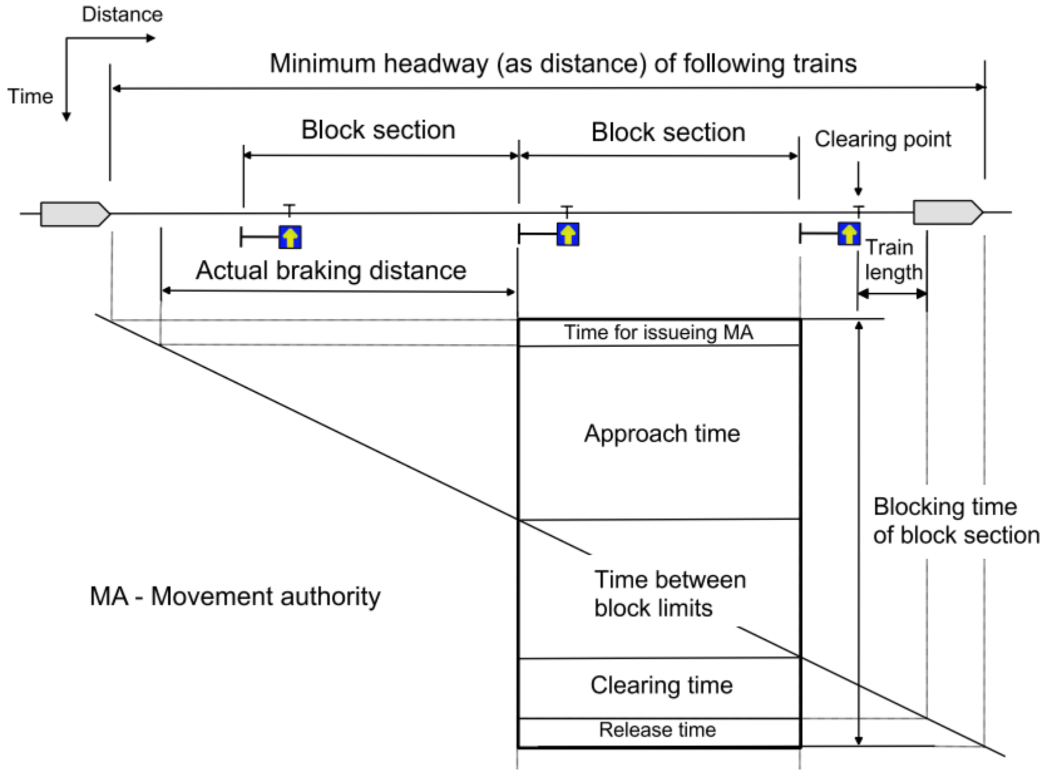


Figure 26 – Blocking time of a block section on a cab signaling line (Pachl, 2020).

Cab Signalling with Moving Block

Moving block is based on absolute braking distance. Since the fixed block sections are eliminated, the line is cleared continuously behind the rear end of a moving train. Beside a continuous detection of the train location and train completeness, it also requires a continuous upgrade of the movement authority. Figure 27 demonstrates the effect on the minimum headway compared with a fixed block cab signaling system.

Today, moving block is only used in some transit systems. One reason why the interest of standard railways in moving block is rather limited is that the potential improvement of line capacity by the introduction of moving block is often overrated. On a moving block line, the length of the block sections is reduced to zero. That means that the running time within the block sections will be eliminated in the blocking time diagram. All other components of the blocking time can also be found in moving block. On most lines, the total of these other components is much greater than the part of the blocking time that can be eliminated by moving block. That is why, compared with fixed block operation with short block sections, moving block will just lead to a moderate improvement of capacity. On lines with mixed traffic of trains running at different speeds, the possible improvement is almost negligible compared to a system with short block sections. Same is true for single lines with bidirectional operation. That is, why many railways prefer the principle of virtual block in new developments of radio-based cab signalling systems.

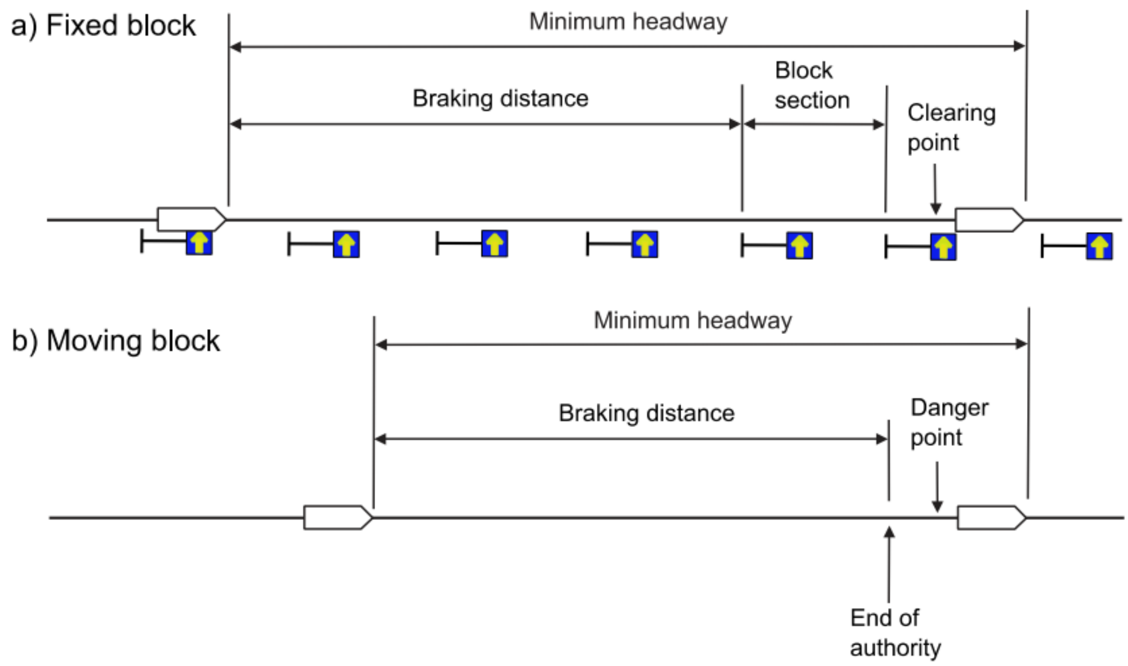


Figure 27 – Headway in cab signalling with fixed block and moving block (Pachl, 2020).

1.2.3. Block Control Principles

To ensure safe train separation, the control procedures must ensure that the movement authority to enter a section of line must not be issued unless two basic conditions are in effect:

- The line is clear up to the desired authority limit and the rear end of the last train ahead is safely protected by that limit;
- All opposing moves on the same stretch of line are safely locked out.

While these basic safety requirements are valid both in fixed block and moving block systems, the solutions to meet these requirements differ.

1.3.2.1 Block Control by verbal Communication

On branch lines operated at a low speed and a very low traffic density, train movements may be protected just by operating rules under staff responsibility. This is based on verbal communication by radio or telephone. For this, two principles exist:

- Dispatcher-controlled operation;
- Train control by local operators.

Today, most lines of that kind have some kind of dispatcher control. The dispatcher is an operator responsible for train control on a longer stretch of line. The dispatcher communicates with the train crews by radio. Points are manually operated by the train crews. Train crews report the arrival at stations or specific locations to the dispatcher who keeps track of all movements either by manually recording these messages on a paper train sheet or by entering them into a computer system. Movement authorities issued by the dispatcher are also transmitted verbally by radio and recorded manually.

1.3.2.2 Block systems for Fixed Block Operation

In mainline operations, the fixed block criteria are enforced by block systems that provide positive locking of signals in stop position as long it is not safe for a train to enter the block section these signals protect. Since block systems are only used to enforce fixed block operation on line sections between station areas, they are often referred to as line block systems (Theeg and Vlasenko, 2019; UIC, 2012). On station tracks between successive interlocking signals, fixed block operation is not enforced by a block system but by the interlocking system when setting routes from signal to signal. That is, why on many railways, station tracks between successive interlocking signals are not referred to as block sections.

Block Working Principles

To protect a train that has entered a block section against following trains, the signal at the entrance of the section is locked in stop position. The signal can be either a lineside signal or just a section limit (usually marked by block marker board) where a train must not proceed without cab signal indication. If converging lines lead into the same section, the block locking is in effect for all signals leading into that block section. After the train has completely left the block section including the overlap (if overlaps are required) and is protected by a stop signal, the block section is released. Now, a signal at the entrance of the block section can be cleared for a following train (Figure 28).

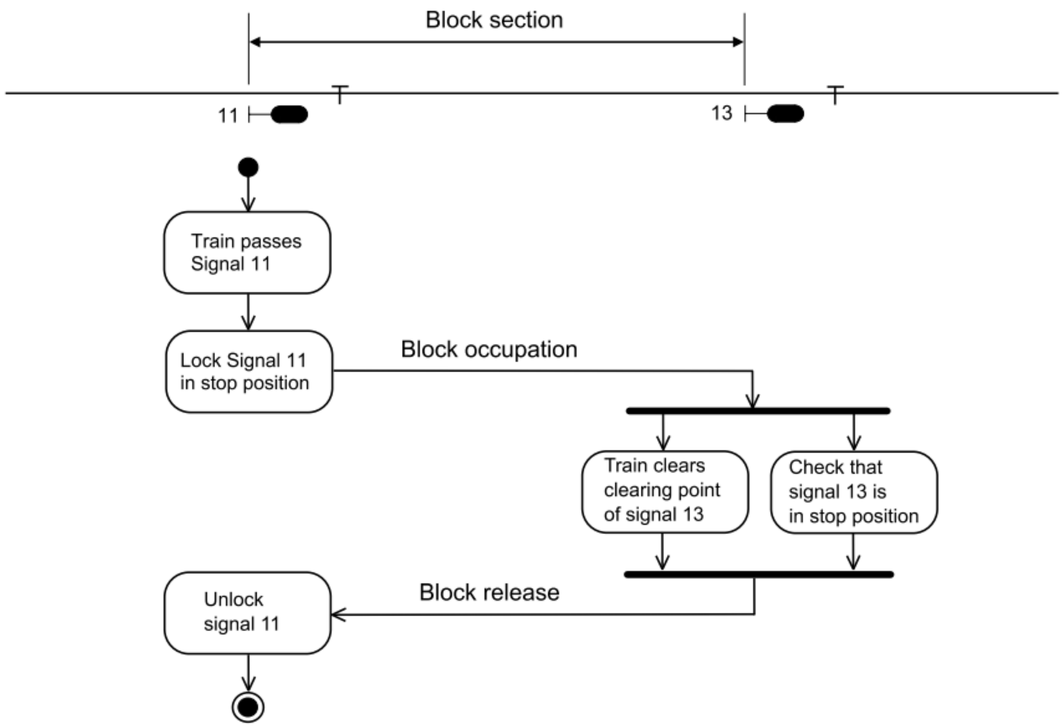


Figure 28 – Block protection of following movements (Pachl, 2020).

Manual Block Systems

In a manual block system, the block sections are not yet equipped with continuous track clear detection. The signals protecting the block sections are manually controlled by local operators. The stations are equipped with electric block instruments connected by a block line. After a train has entered a block section, the operator at the entrance of the section would restore the signal and operate a block instrument to lock the signal in stop position.

Today, most manual block systems work as so called semi-automatic block systems, which uses relay circuits instead of block instruments. In a semi-automatic block system, the block locking after a train has entered the block section is applied automatically. However, after the train has left the section, it has to be released manually by an operator. In modern control centers, semi-automatic block systems are often used at the interface to lines still equipped with old technology.

Automatic Block Systems

In an automatic block system, block sections are equipped with automatic track clear detection to enable the signals to work automatically. An automatic signal will only clear if the entire control length up to the clearing point beyond the next signal is clear and a train ahead is protected by a stop signal. To release a block section, a train must not only have cleared the section and the overlap but must also have restored the next signal. This condition confirms that the train has safely passed the exit side of the block section. So, the safe block working does not only depend on the track clear detection but is overlaid by the block cycle of Figure 28.

This improves the safety of automatic block systems based on track circuits. If the occupation of the block section disappeared due to a malfunction of the track circuit while the train has not yet left the section (e.g., if some dirt has gotten on the rails), the block section will not release. It will also not release if the train has left the section but failed to restore the signal at the exit side of the section to stop position due to a malfunction of the next track circuit. For automatic block systems working with axle counters, that safety procedure is automatically enforced, since the track occupation could never disappear without having the train passed through the counting point. Passing through the counting point will also safely restore the signal to stop.

Concerning the control principle, automatic block systems can be divided into two classes (Figure 29):

- Decentralised automatic block systems;
- Centralised automatic block systems.

In a decentralised automatic block system, the control devices are located in field cabinets directly at the block signals. These block signal cabinets exchange block control information either by an electric block line or through coded track circuits. After a train has left a block section, the signal at the entrance of that section is immediately cleared.

In a centralised automatic block system, the block control is part of the centralised control system that also controls the interlocking areas. Instead of exchanging block control information, centralised block sections are treated similar like routes in an interlocking system.

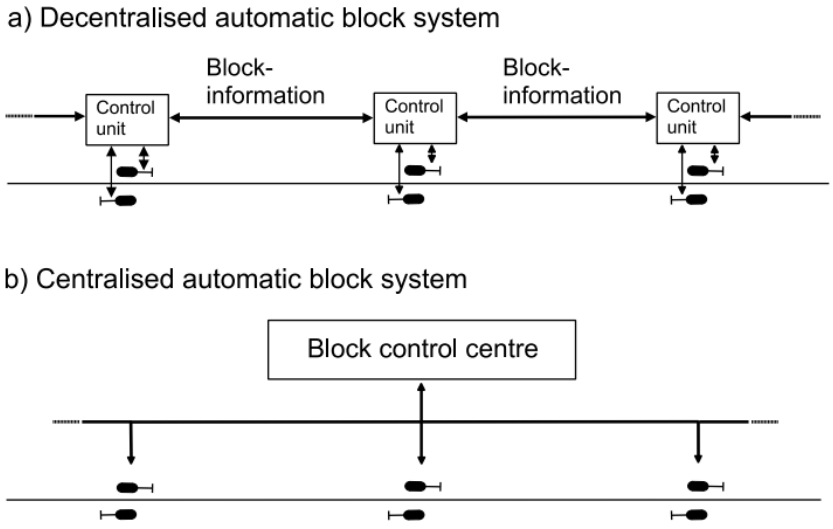


Figure 29 – Decentralized and centralised automatic block system (Pachl, 2020).

1.3.2.3 Block Control in Moving Block Operations

Moving block systems need an accurate on-board train location system that transmits the current location at very short intervals to a radio block center. With every reported location, the train must also confirm train completeness. By these data, the radio block center calculates the danger point to protect the rear end of the train.

Between that danger point and the authority limit of a following train, there is a supplementary safety distance that is an equivalent to the block overlap in a traditional fixed block system. It is the minimum safety distance kept between the two trains if the second train stops behind the first train. If points are going to be moved between two trains following each other in moving block, an additional time window for moving the points is needed. That time windows is to be calculated by the radio block center when upgrading the movement authority for the second train.

The radio block center will always safely prevent frontal crashes by locking out overlapping opposing movement authorities. On line sections outside of station areas where trains cannot reverse, an additional direction control is needed that works similar as the direction locking in a fixed block system. A train must not enter such section as long any opposing movement is travelling through that section or has authority to enter that section from the next location where the train sequence may be changed.

1.3 Automatic Train Control

A railway train is an ideal system for automation. It uses a fixed guidance system, its acceleration and braking can be predicted, its position detected, its direction confirmed and its timing regulated. All this, makes automation of train control a relatively simple task. However, there are limitations:

- Train formations that can vary need to be individually registered into the system;
- Variations to railhead conditions need to be factored into the system;
- Not all existing railways are ideal for automation and may need significant upgrades.

Nevertheless, automation has considerable benefits for safety and performance and can offer better throughput of trains of up to 8% just by the elimination of manual driving variability.

The automation of train movements was gradually developed from the need to enforce signal commands so that drivers could not allow trains to pass beyond their limit of movement authority (LMA).

Automatic Train Control is divided in three sub-system (Figure 30):

- ATP (Automatic Train Protection);
- ATO (Automatic Train Operation);
- ATS (Automatic Train Supervision).

ATC has been adopted around the world to describe the architecture of the automatically operated railway (Connor, 2019).

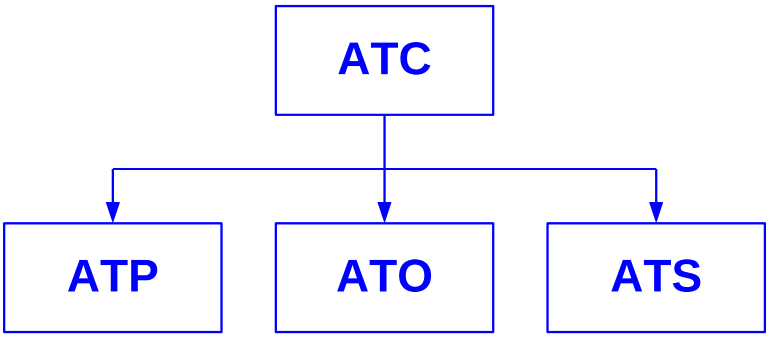


Figure 30 – ATC sub-system (Murolo, 2019)

1.3.1. The ATC Package

The first part of the package of an ATC system is Automatic Train Protection (ATP), where the train is given a Limit of Movement Authority (LMA). This is based on the train's current speed, its braking capability and the distance it can go before it must stop. On a manually driven train, the driver manages this through a combination of route and stock knowledge and the visual information received from wayside signals. On the automated train, the data for the LMA is transmitted from the track to the train where the on-board computer registers the current speed and calculates the target speed that the train must reach and by when. This is electronically plotted in the form of a braking curve. If the train is allowed to exceed the profile of the curve, the brakes will automatically apply to bring the train to a stand (or at least to within the permitted speed).

The second part of an ATC system is Automatic Train Operation (ATO). This is the driving part of the operation. Looking at a manually driven train, we will see that the driver initiates the starting of the train, allows its acceleration to the permitted speed, slows it where necessary for speed restrictions and stops at designated stations in the correct location. The ATO system will carry out these parts of the operation with the exception that the driver normally initiates the train start.

Lastly, ATS system performs supervisory roles such as assignment of routes, dispatch of trains, and maintaining or adjusting schedule. The data received by the ATP control unit is usually limited to indicating that a train is in the block or the speed limit currently imposed in the block. This data is sent to the ATS computer where it is compared with the timetable to determine if the train is running according to schedule or is late or early. To adjust the train's timing, the ATS can send commands to the ATO spots located along the track.

There are lots of variations of ATC around the world, but all contain the basic principle that ATP provides safety and is the basis upon which the train is allowed to run. ATO provides controls to replace the driver, while ATS checks the running times and adjusts train running accordingly (Connor, 2019).

1.4 Automatic Train Protection

Automatic Train Protection (ATP) systems transmit information on movement authorities and speed limits from the line to the train to initiate an automatic brake application if the train violates the valid limits. In train control with lineside signals, an ATP system works in addition to the lineside signals and with the main purpose of preventing trains from violating stop signals. On cab signalling lines, the ATP system provides the guiding information for the cab signal indication.

1.4.1. Classification of ATP Systems

Concerning the form of data transmission between track and train, there is a general distinction between intermittent and continuous ATP systems. In an intermittent ATP system, the data is transmitted to the train at discrete points along the track. Data transmission points are provided at signals and sometimes at selected intermediate locations between signals.

Intermittent ATP systems are mainly an add-on to lineside signals with the main purpose to prevent trains from overrunning stop signals. When approaching a stop signal, the train will get a first data transmission at the beginning of the braking distance. That data transmission initiates a braking curve supervision forcing the train to slow down to a speed at which the train can be brought to a stop within the overlap distance. When violating the stop signal at that speed, the train will come to a stop before the danger point. When passing the signal after it has been cleared, the data point at the signal will up- grade the supervised speed in the on-board unit. To avoid a negative impact on capacity by forcing trains to approach a cleared signal at a slow speed until the speed limit will be upgraded by the data point at the signal, additional data points may be provided on the approach of the signal. When passing such an infill data point after the signal has been cleared, the speed limit will be upgraded immediately.

Continuous ATP systems transmit control data continuously from track to train. This enables the ATP system not only to protect but also to guide the train. The control data transmitted to the train is used for the cab signal indication. Lineside signals are no longer needed but may be provided for degraded mode operations. For data transmission, the following principles are used:

- Data transmission by coded track circuits (pulse or frequency code);
- Data transmission using a cable loop track antenna;
- Radio-based data transmission in combination with transponders for the purpose of train location.

Today, a big number of different national ATP systems exists. Also, there are still railways that do either not yet have any ATP systems or just very simple ones. Today, there are three big international ATP project to replace older systems for better interoperability and to be used in all new installation:

- The European Train Control System (ETCS);
- The Chinese Train Control System (CTCS);
- The North American Positive Train Control System (PTC).

Existing installations of older ATP systems are gradually replaced by systems covered by these projects (Figure 31).

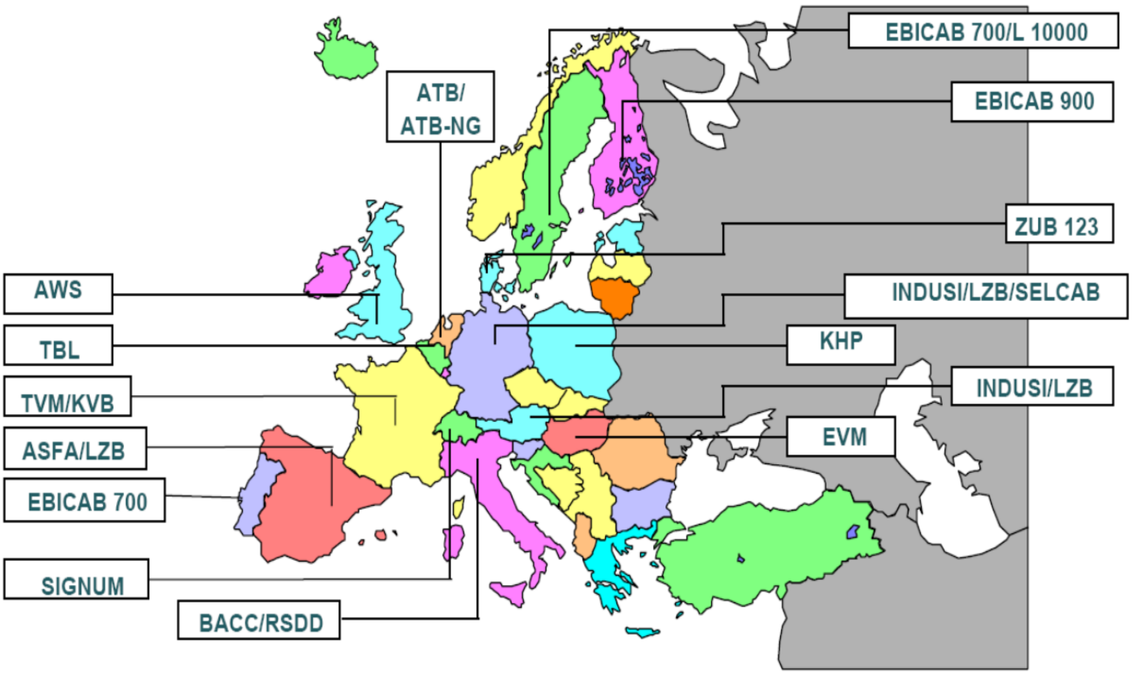


Figure 31 – Legacy ATP system throughout Europe (EC, 2006).

1.4.2. European Train Control System (ETCS)

For the European railway system, one of the big challenges is to improve interoperability. One of the key points to be solved in cross-border operation is the interoperability of ATP systems. While on European mainlines, ATP is a standard feature, the variety of existing ATP systems is enormous (Bailey, 1995). With a very few exceptions, ATP systems change at any national border. Today, the only solution for cross-border operation is either to change locomotives at national borders or to use expensive multi-equipped locomotives. To overcome this situation, the ETCS project was launched.

1.4.2.1 ETCS and ERTMS

ETCS stands for European Train Control System and is a layer (i.e., a sub-project) of the European Rail Traffic Management System (ERTMS). Today, the ERTMS just consists of the ETCS and the digital radio system GSM-R. While ETCS represents the train control part of ERTMS, the GSM-R provides the wireless communication system needed for the higher ETCS levels. GSM-R is not only needed for the ETCS but has also replaced the older radio systems for general voice and data communication in railway operations. It is based on the public GSM standard but provides some specific features needed in train control. Since GSM is already an outdated mobile communication standard, it will be replaced in the next years by the FRMCS (Future Rail Mobile Communication System), which is based on 5G radio technology.

The idea of ETCS is to gradually replace the existing ATP systems by an advanced train control system. In that system, train control information can be transmitted by transponders (so-called Eurobalises), short loop antennas (so-called Euroloops), or by digital radio.

1.4.2.2 ETCS Levels

Based on the different communication technologies, several levels have been specified for the trackside equipment (Stanley, 2011; UNIFE, 2017a). By these levels, the ETCS can be adapted to different operating needs. In all these levels, the same on-board equipment is used.

ETCS Level 1

In Level 1, ETCS works as an advanced intermittent ATP system. Train control information is transmitted by controlled transponders, which get their information from the traditional signalling system via a lineside electronic unit (Figure 32).

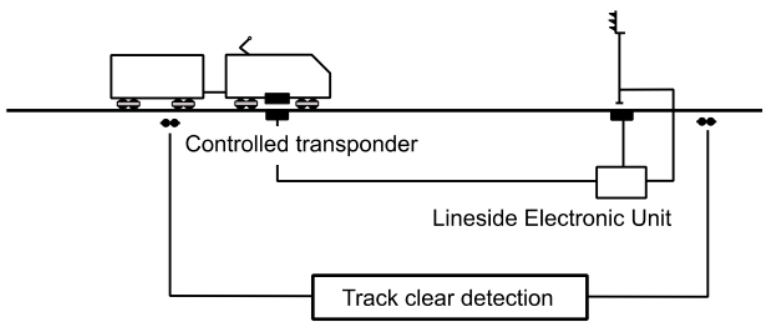


Figure 32 – ETCS level 1 (Pachl, 2020).

When approaching a stop signal, a transponder at the beginning of the braking distance will transmit data to calculate the brake supervision curve in the on-board unit. The train will have to follow this curve until having reached a so-called release speed. At this speed, the signal can be passed. If the driver passes a stop signal at release speed, the train will get an emergency brake intervention and brought to a safe stop within the overlap. If the signal has been cleared in the meantime, the transponder at the signal will upgrade the on-board unit to the speed permitted in the section beyond the signal.

To improve capacity, a train approaching a stop signal may be released from the braking curve supervision after the signal has been cleared by transmitting infill information. As shown in Figure 33, infill information may be provided by additional transponders (spot infill), a loop antenna (loop infill), or by digital radio (radio infill).

ETCS level 1 can be operated either in full supervision or in limited supervision mode. In full supervision, the train speed is permanently supervised by the ETCS. If loop or radio infill information is provided at all points that may limit a movement authority, trains can be governed by cab signals without need for lineside signals. Without such infill information, lineside signals of some kind are still needed. After a train has stopped at a signal, the authority to proceed cannot be transmitted by the ETCS.

In limited supervision, the ETCS emulates the functionality of a traditional intermittent ATP system. In this mode, trains are always governed by lineside signals while the ETCS supervision works in the background.

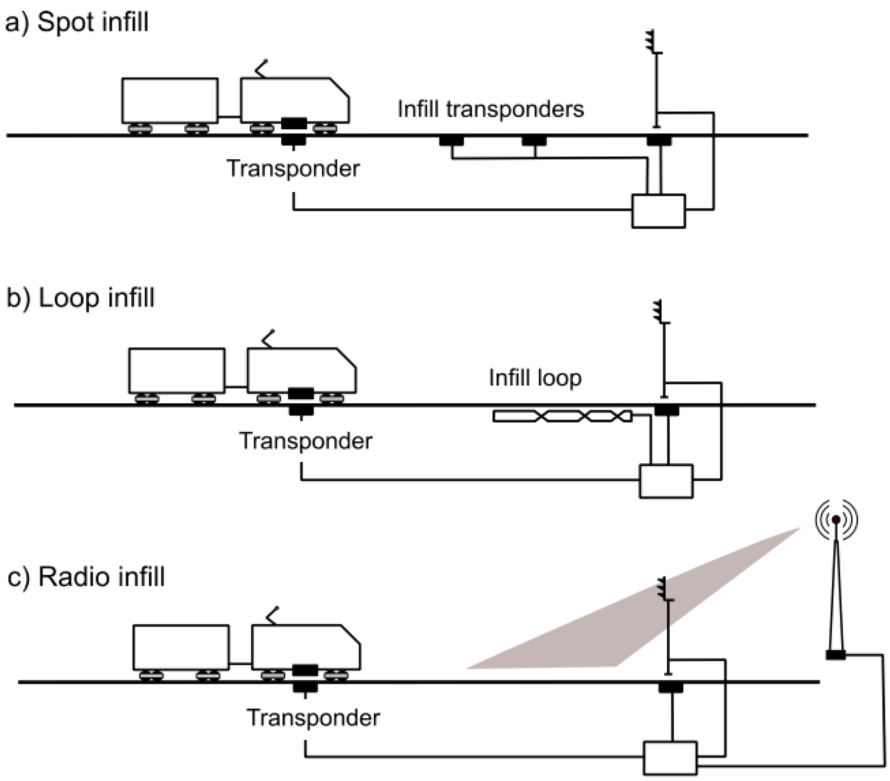


Figure 33 – Infill solutions for ETCS level 1 (Pachl, 2020).

ETCS Level 2

In Level 2, ETCS works as a continuous ATP system in which the train control data is transmitted by digital radio (Figure 34). Non-controlled transponders are used as reference points for the on-board train location system.

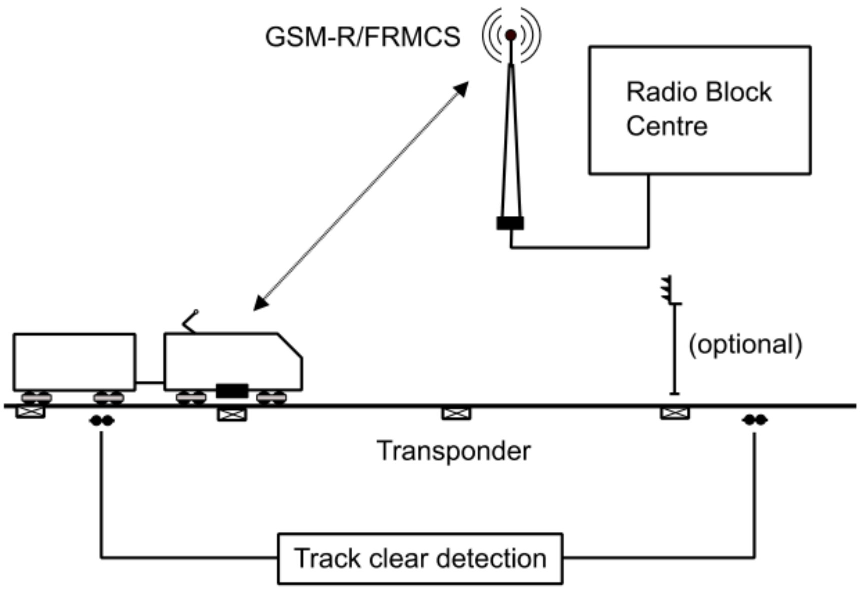


Figure 34 – ETCS level 2 (Pachl, 2020).

In specified intervals, trains automatically transmit their location data to a Radio Block Centre (RBC) that issues the movement authorities to the trains. However, positive train separation is still ensured by fixed block sections equipped with traditional track clear detection technology (track circuits or axle counters). Lineside signals are not needed but may be provided for degraded mode operations. Most railways prefer to replace controlled signals by ETCS stop markers that must not be passed without valid authority. Depending on the operating rules of individual railways, intermediate block sections may be limited by ETCS location markers. Since these ETCS location markers do not provide an absolute stop indication, the design differs from the ETCS stop markers (Figure 35).

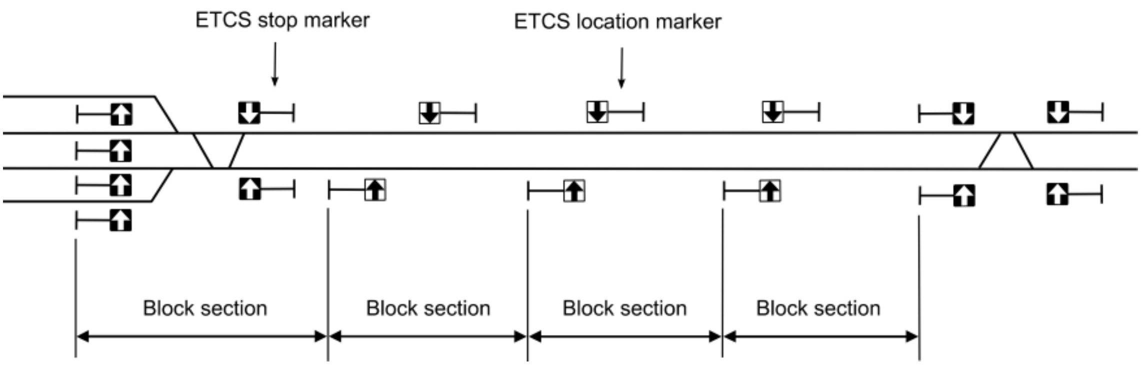


Figure 35 – ETCS markers on a Level 2 line without lineside signals (Pachl, 2020).

ETCS Level 3

ETCS Level 3 finally adds train-borne checking of train integrity (i.e., train completeness) to the system. This eliminates the need for fixed block sections for track clear detection (Figure 36). In contrast to Levels 1 and 2, ETCS Level 3 is not only an ATP and cab signal system but provides also a radio-based train separation replacing the traditional block system. Depending on the operational needs, train separation can be applied by virtual or moving block. Due to the absence of traditional track clear detection technology, lineside signals for degraded mode operations cannot be used.

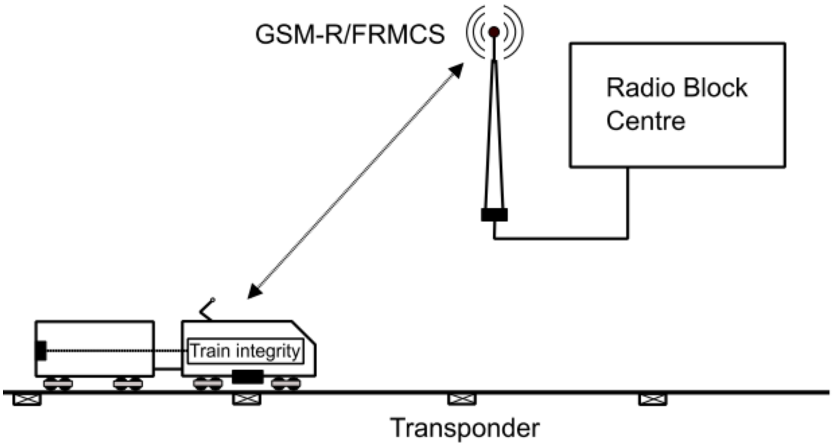


Figure 36 – ETCS level 3 (Pachl, 2020).

With virtual block, virtual block sections are established in the control computer without having real physical block sections on the line. While these virtual block sections are not equipped with trackside track clear detection technology, the block limits may be marked by ETCS location markers for degraded mode operations. The location information received from the trains by radio is transformed into information showing occupied and clear virtual block sections. Movement authority is provided by allocating a number of block sections to a train. The end of movement authority is in any case the limit of a virtual block section (Figure 37a). Different from moving block, the movement authority is not to be upgraded continuously with movement of the rear end of the train ahead but in accordance with the release of the virtual block sections. This will significantly reduce the radio traffic for the transmission of guiding data from the RBC to the train. Depending on traffic demands, the operational performance may be flexibly changed by reconfiguring the virtual blocks in the control computer.

In a radio-based moving block system, a train clears the track behind its rear end in accordance with the tracking intervals of train location (Figure 38b). Moving block makes only sense on lines with a very high density of one-directional traffic with harmonized speed profiles. The typical moving block application is a mass transit railway. On standard railways, in most cases, virtual block will be a more efficient solution. That is why most railways are today rather interested in virtual block than in moving block.

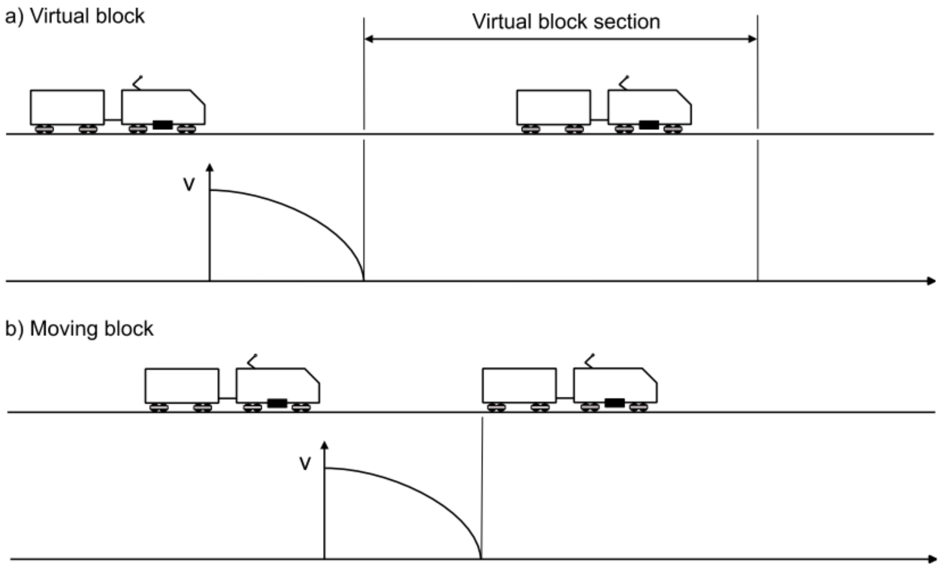


Figure 37 – Virtual block and moving block (Pachl, 2020).

ETCS Hybrid Level 3

ETCS Level 3 requires all trains to be equipped with on-board monitoring of integrity. For passenger trains, this can be achieved by using existing electric lines through the train consist. In conventional freight operations, such an electric communications line through the train consist does not yet exist.

That hybrid solution is based on ETCS Level 3 with virtual block sections that are overlaid by longer block sections controlled by trackside track clear detection technology. Trains with onboard monitoring of train integrity would occupy and release the line according with the virtual block sections. Non-equipped trains may occupy the line according with the virtual block sections but can only release the line according with the longer block sections controlled by track clear detection technology. On some railways, the Hybrid Level 3 is called Level 2 HD (for 'high density') (Cuppi et al., 2021).

Figure 38 demonstrates that principle by a blocking time diagram. For the minimum line headway between two trains, it is always relevant whether or not the first train is equipped with train integrity monitoring. With an increasing share of trains equipped with train integrity monitoring, the capacity will be improving without changing anything on the infrastructure.

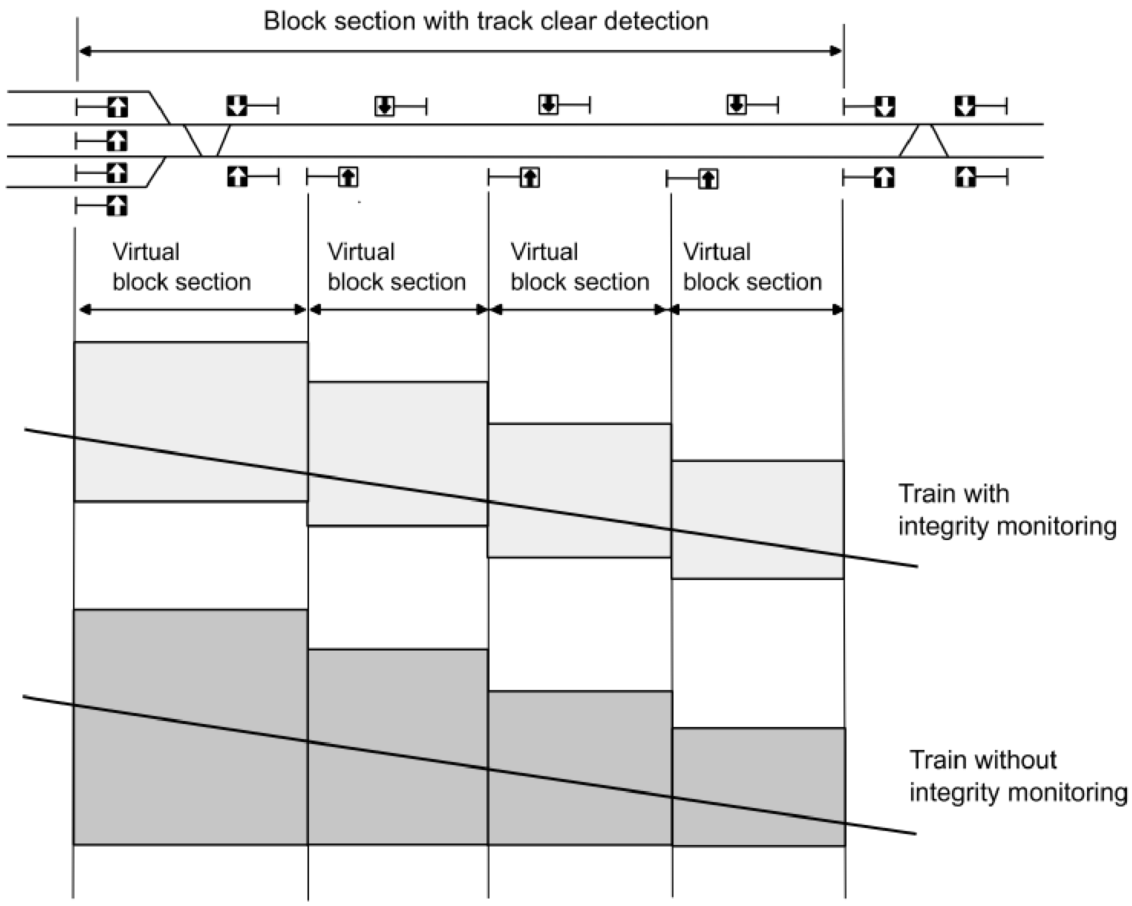


Figure 38 – Blocking time stairways in ETCS Hybrid Level 3 (Pachl, 2020).

1.5 Automatic Train Supervision

The ATS system (Automatic Train Supervisory, Automatic Train Supervision) controls the routes and destinations of the trains. The system can manage the network in different situations: normal service, single track service, or service in case of work. Everything is being kept under control.

1.5.1. Communication Based Train Control (CBTC)

CBTC is a modern, radio-communication-based signalling system. Using radio communication, it enables high resolution and real-time train control information, which increases the line capacity by safely reducing the distance (headway) between trains travelling on the same line, and minimizes the numbers of trackside equipment (Alvarez and Roman, 2013; Martínez, 2013). Usually in conventional signalling systems, the distance between trains following each other is large, as seen in Figure 39 due to the fixed block system, where tracks are divided into blocks (or "track sections"), and track circuits are installed to determine if a train is inside a block. When a train is inside a block, since there is no real-time method to determine its exact location inside the block, the entire block is declared as occupied, and other trains are not permitted to enter it. In contrast, in the "moving block operation" employed in CBTC, thanks to the real-time communication between the train and the wayside, the train location is continuously updated. As a result, the occupancy zone "moves" with the train reflecting its actual location and headways are very short, which means in the event of a communication failure, a train may not receive the location of the train in front of it in time. For these reasons, CBTC systems normally allocate a fixed "protection margin" in the calculation of their safe braking distance (IEEE Std., 2004) and a typical approach is to apply emergency brakes and then drive it in manual mode (Bu et al., 2014; Cortes Alcala et al., 2011).

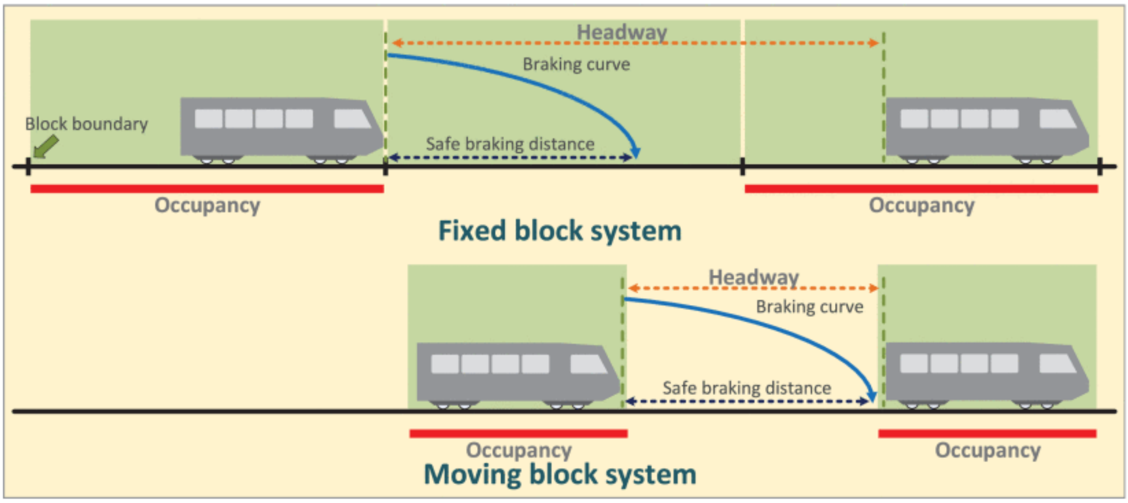


Figure 39 – Fixed vs. moving block (Farooq and Soler, 2017).

In CBTC, continuous, high capacity radio communication is used to exchange train control information between the train and the wayside, enabling automatic train control (ATC) functions, automatic train protection (ATP) and automatic train operation (ATO).

Figure 40 illustrates typical wayside components of a CBTC system. The train continuously sends its current speed, direction, and location to the wayside over the radio connection. Based on this information received from all trains currently on the track, as well as a train's braking capability, the traffic control center at the wayside calculates the maximum speed and distance the train is permitted to travel, collectively known as "limit of movement authority" (LMA), and sends it to the train. Based on this information, the train onboard ATC equipment continuously adjusts the train speed and maintains the safety distance to any preceding trains. Thanks to this real-time information exchange, the trackside equipment used in conventional systems, such as color light signals and track circuits, is not needed, and can be removed.

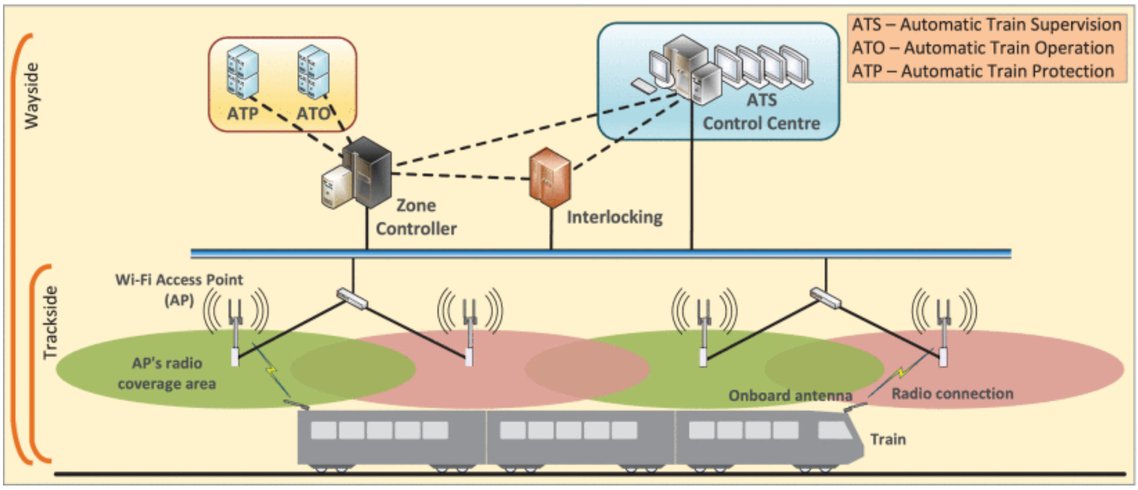


Figure 40 – CBTC wayside components (Farooq and Soler, 2017).

2. RAILWAY CAPACITY

2.1 Definition and parameters

The rising volume of traffic, with simultaneously increasing demands in terms of quality and quantity, requires a unique, harmonized and generally valid understanding to be developed as regards available railway infrastructure capacity (UIC, 2004).

Railway capacity is a complex, loosely defined term that has numerous meanings (Krueger, 1999), and the definitions differ by country (Rothengatter, 1996a). In 2004 the International Union of Railways (UIC) (re)defined railway capacity as (UIC, 2004): *Capacity as such does not exist. Railway infrastructure capacity depends on the way it is utilized.*

This definition of railway capacity is followed by a guideline for how railway capacity can be measured given the actual infrastructure and the actual timetable. Railway capacity is difficult to define because there are several parameters that can be measured. The parameters seen in Figure 41 (number of trains, stability, heterogeneity and average speed) are dependent on each other. This further complicates the definition of railway capacity.

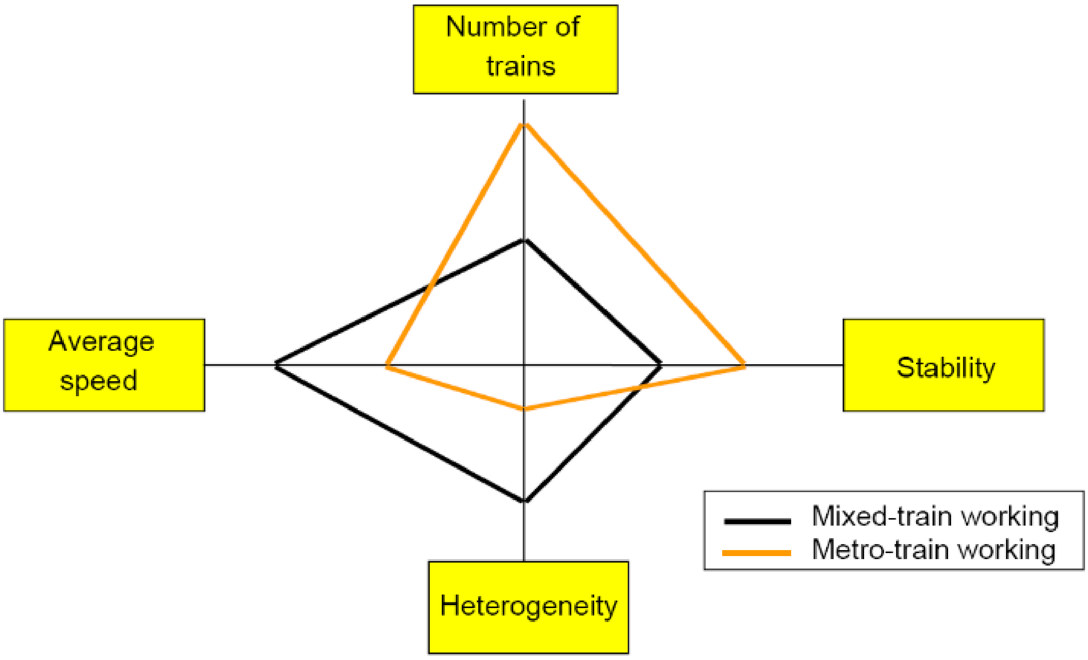


Figure 41 – The balance of railway capacity (UIC 2004).

Figure 41 shows that capacity is a balanced mix of the number of trains, the stability of the timetable, the level of average speed achieved and the heterogeneity of the operation. It may, for instance, be possible to satisfy a market demand for a high average speed by having high heterogeneity, a mix of fast Intercity Express, Intercity and slower Regional trains serving all stations. However, the consequence of having high average speed and high heterogeneity is that it is not possible to operate as many trains with a high stability (punctuality) as when all trains are operated with the same speed and stop pattern. If there is market demand for operating more trains, it may be necessary to have a less mixed operation and thereby have a lower average speed (assuming that the fast trains are adapted to the slower trains) as it is known from, for example, metro systems.

It could be argued that the description of railway capacity presented by the UIC includes only the timetable and not the infrastructure, the rolling stock or the quality of service. However, both the rolling stock and the infrastructure are implicitly included because they are important parameters for the timetable, while the quality is described by the stability (punctuality), the number of trains (frequency), the average speed (travel speed) and the heterogeneity (the mix of trains) (Landex, 2008).

Due to the interaction between the infrastructure and the timetable, and that the capacity depends on the timetable, it is difficult or even impossible to define railway capacity in a consistent way. Therefore, railway capacity has been defined differently over time, e.g.:

- Railway capacity is the ability of the carrier to supply as required the necessary services within acceptable service levels and costs so as to meet the present and projected demand for such services (Kahan, 1979);
- The capacity of a railway line is the ability to operate trains with an acceptable punctuality (Skartsæterhagen, 1993);
- The theoretical capacity is defined to be the maximal number of trains that can be operated on a railway link (Rothengatter, 1996);
- The capacity of an infrastructure facility is the ability to operate the trains with an acceptable punctuality (Kaas, 1998);
- Capacity is a measure of the ability to move a specific amount of traffic over a defined rail line with a given set of resources under a specific service plan (Krueger, 1999);
- The only true measure of capacity therefore is the range of timetables that the network could support, tested against future demand scenarios and expected operational performance (Wood and Robertson, 2002);
- Capacity can be defined as the capability of the infrastructure to handle one or several timetables (Hansen, 2004);
- Capacity is defined as the maximum number of trains which can pass a given point on a railway line in a given time interval (Longo and Stok, 2007);
- Capacity may be defined as the ratio between the chosen time window and the sum of average minimum headway time and required average buffer time (Oetting, 2007);
- The capacity of the infrastructure is room on the track that can be used to operate trains (Jernbaneverket, 2007);
- The number of trains that can be incorporated into a timetable that is conflict-free, commercially attractive, compliant with regulatory requirements, and can be operated in the face of anticipated levels of primary delay whilst meeting agreed performance targets (Barter, 2008);

- Capacity is a measure of the ability to move a specific amount of traffic over a defined rail corridor in the U.S. rail environment with a given set of resources under a specific service plan, known as level of service (LOS) (Lai and Barkan, 2009).

The above definitions of railway capacity show (although many definitions are alike) that there is great variation in how railway capacity can be defined. A reason for this variety is that most definitions of railway capacity are defined nationally or in connection with a specific project. Common to the definitions is that the railway capacity depends on the railway infrastructure and the timetable and, thereby, implicitly on the rolling stock used (Figure 42).

Railway capacity depends not "only" on the rolling stock, the infrastructure and the timetable; sometimes the capacity is reduced due to processes in the operation such as time consuming departure procedures or external factors such as the weather and problems with the rolling stock. Processes can be procedures at departures, staff schedules, many passengers at the stations etc., while the external factors can be, e.g., weather conditions, breakdowns and accidents. Common to the processes and external factors is that it is not possible to predict their influence on the operation; nevertheless, attempts are made to minimize this influence by, for example, adding time supplements in the timetable.

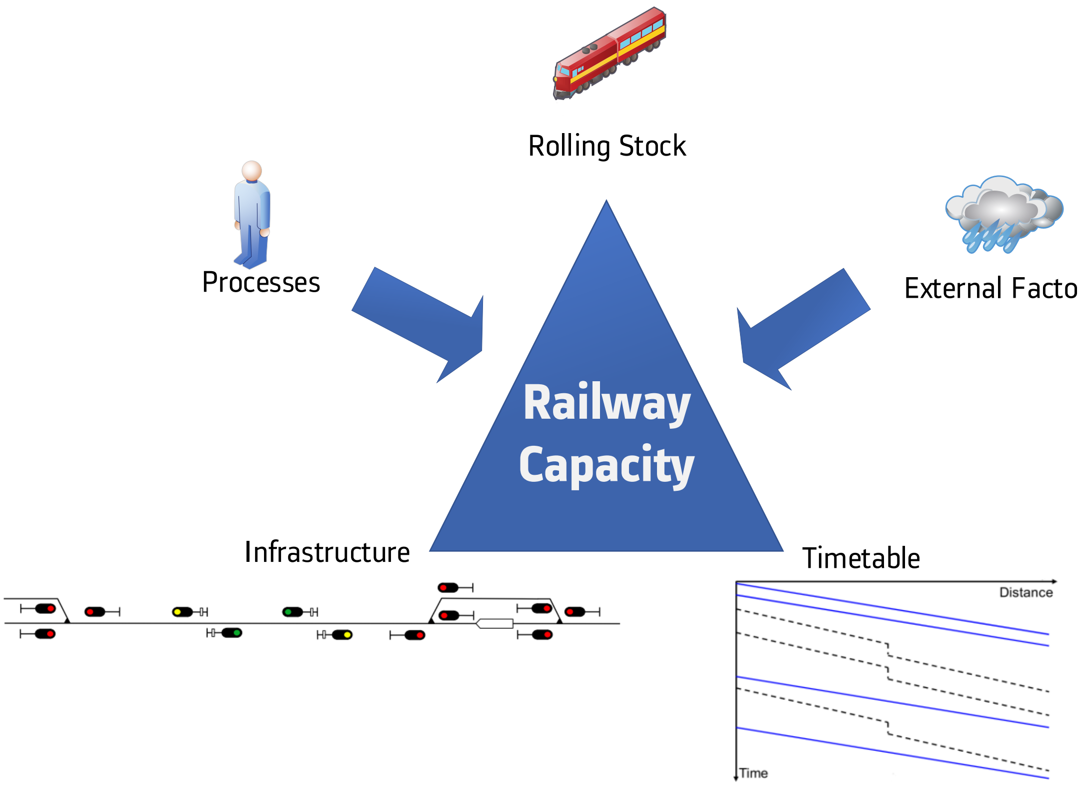


Figure 42 – Parameters in railway capacity.

The definitions above (summarized in Figure 42) are not commonly accepted, although the definitions in themselves are correct. However, using all the capacity to operate trains will (due to almost no buffer times) result in a high risk of consecutive delays and a less attractive timetable. Therefore, the quality of the operation is important (Figure 43).

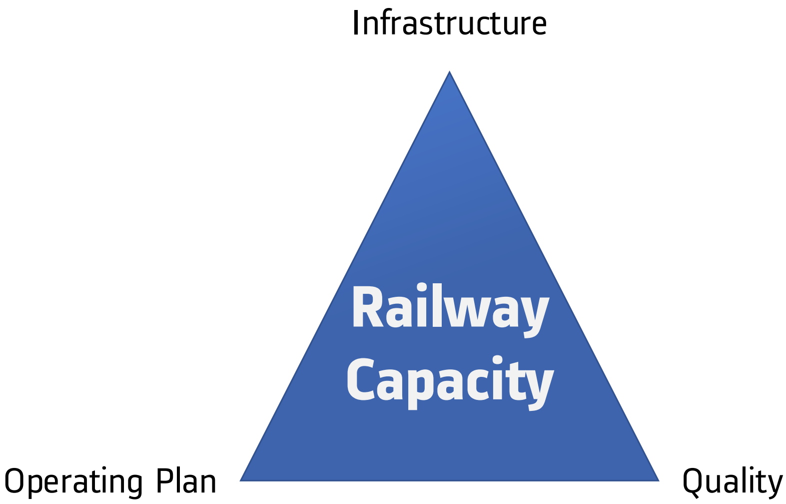


Figure 43 – Definition of railway capacity. Based on UIC (1996).

It could be argued that the definition of railway capacity presented in Figure 43 includes only the operating plan and not the rolling stock as in the earlier described definitions. However, the rolling stock is implicitly included as it is an important parameter of the operating plan (Landex, 2008).

According to Abril et al., 2008 the capacity of railway systems is understood and analyzed in many ways. This is because capacity should be considered during the whole planning horizon. Furthermore, the railway capacity is viewed differently from the market, infrastructure planning, timetable planning and operations as stated by the UIC (UIC, 2004) (Figure 44).

Market (customer needs)	Infrastructure planning	Timetable planning	Operations
expected number of train paths (peak)	expected number of train paths (average)	requested number of train paths	actual number of trains
expected mix of traffic and speed (peak)	expected mix of traffic and speed (average)	requested mix of traffic and speed	actual mix of traffic and speed
infrastructure quality need	expected conditions of infrastructure	existing conditions of infrastructure	actual conditions of infrastructure
journey times as short as possible	time supplements for expected disruptions	time supplements for expected disruptions	delays caused by operational disruptions
translation of all short and long-term market-induced demands to reach optimised load	maintenance strategies	time supplements for maintenance	delays caused by track works
		connecting services in stations	delays caused by missed connections
		requests out of regular interval timetables (system times, train stops, ...)	additional capacity by time supplements not needed

Figure 44 – Different views of capacity (UIC, 2004)

2.1.1. Dependence of capacity on infrastructure characteristics

According to Ciuffini (2019) the dependence of capacity on the characteristics of the infrastructure is due to the constraints of distance, crossing, cutting at intersections and stations. Each of them, defining the spaces of interdiction between the train traces, in fact limits the possibility of insertion of the latter: greater will be the spaces of interdiction, smaller will be the number of traces that can be inserted into certain sections of infrastructure for unit of time.

At the same time and reliability target, capacity shall depend on the following infrastructure characteristics:

- number of tracks,
- signalling system and distance between trains,
- amount and location of intersections along single track lines,
- line and station layout,
- movements rules and sidings.

Concerning the influence of the minimum technical spacing given by the signalling system, considering a double-track line we can see that by reducing the minimum technical spacing between trains, a higher number of traces can be inserted within the same time window T (Figure 45).

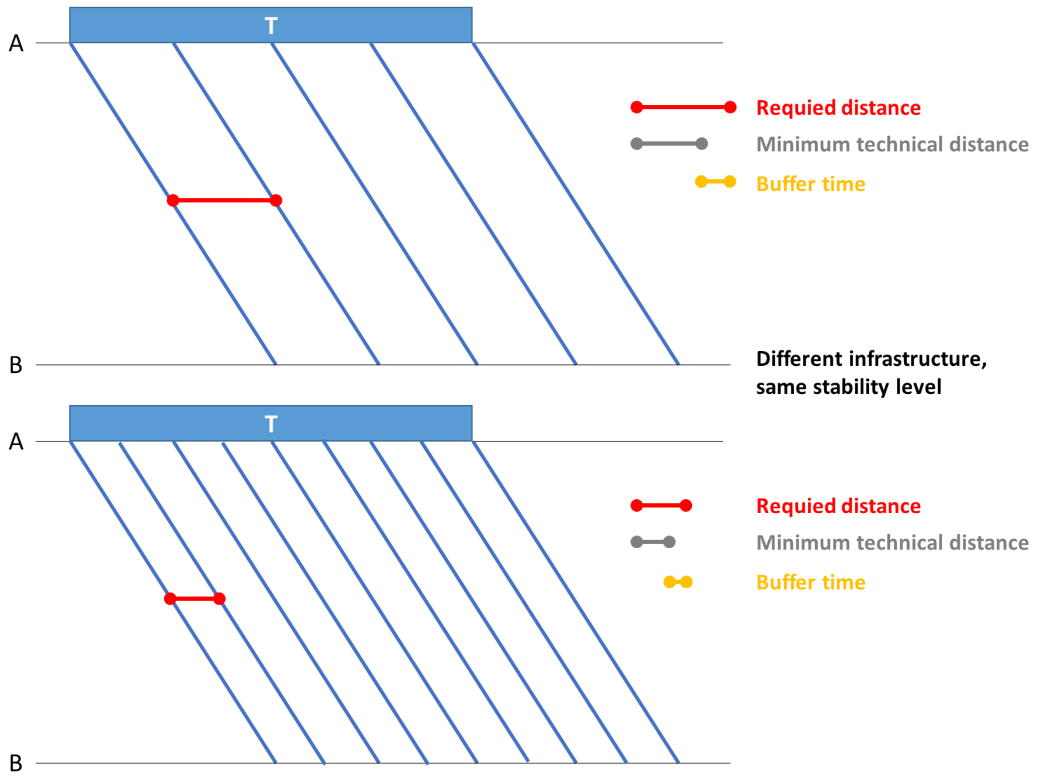


Figure 45 – Different capacity with variation of minimum technical spacing (Ciuffini, 2019).

Concerning the number of crossings, it is clear that if the distance between the traces decreases, the capacity increases, as the number of crossings increases (Figure 46).

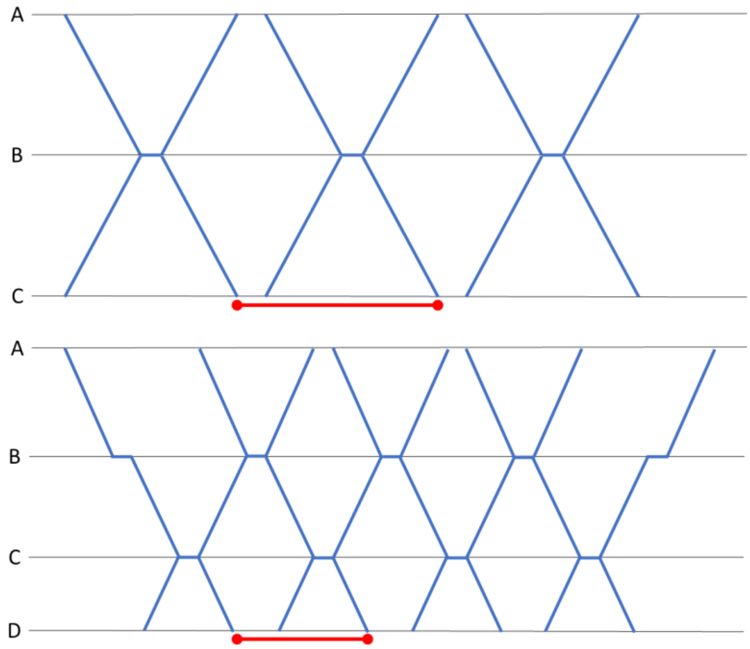


Figure 46 – Different capacity as the number of intersections on a single-track line varies (Ciuffini, 2019).

In Figure 47 we can see instead how in reality also the position of the crossings, to parity of number, can determine a different ability. The latter is conditioned by the longer journey time section.

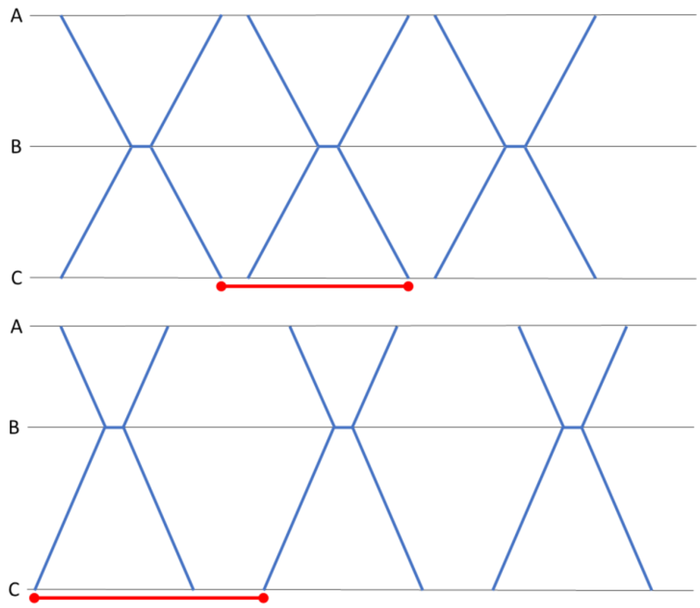


Figure 47 – Different capacity as crossings position changes (Ciuffini, 2019).

The number of precedence locations also affects infrastructure capacity. In Figure 48 for example, the comparison between a line section without and with an intermediate step of precedence, which allows the insertion of a greater number of heterotatic traces, although with a time-waster for slow tracks due to the constraint of precedence.

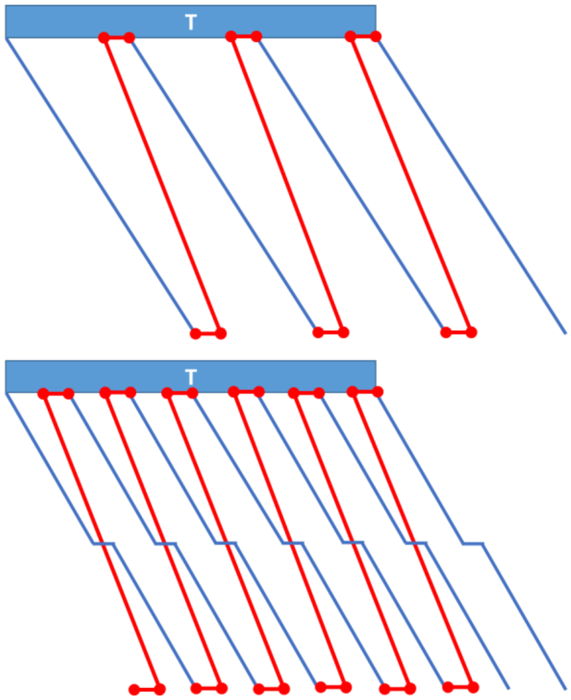


Figure 48 – Different capacity to vary the number of steps of precedence (Ciuffini, 2019).

The possibility to use a precedence in case of heterotatic traffic, besides allowing the increase of the capacity in terms of number of insertable traces in the unit of time, can concur to speed up the traces faster (Figure 49).

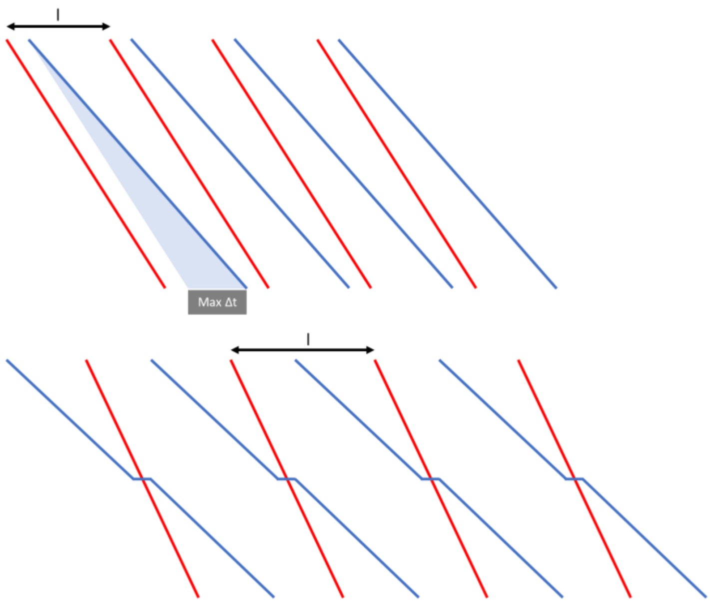


Figure 49 – Different capacity as crossings position changes (Ciuffini, 2019).

With regard to the influence on capacity given by station topology, reference can be made to Figure 50 which shows how the different positions of the tracks of precedence can lead to conflicts between trains in the opposite direction.

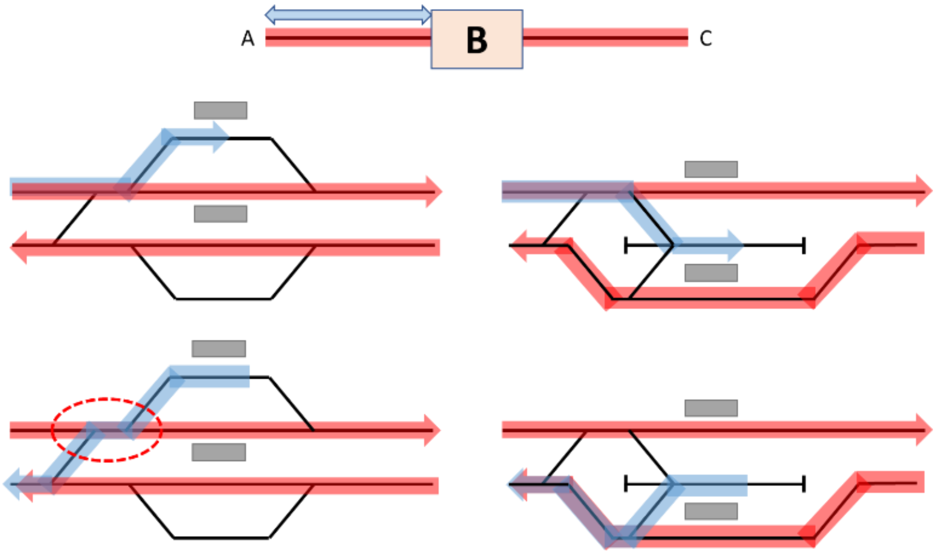


Figure 50 – Cutting constraints in the station (Ciuffini, 2019).

2.1.2. Dependence of capacity on operational plan

With the same infrastructure, capacity also depends on the timetable. In particular on the following elements:

- heterotachy of the traces,
- sequence of the traces at different speeds;
- origin-destination ties;
- constraint about train frequency.

As regards eterotachy and its effect in terms of increased capacity consumption on a line section, is possible to see in Figure 51, how both the insertion of a slower train between the fast traces and of a faster train in the middle of slower tracks, determine a greater consumption of capacity, visible (in grey) from how homotachic tracks are consumed by the train at different speeds.

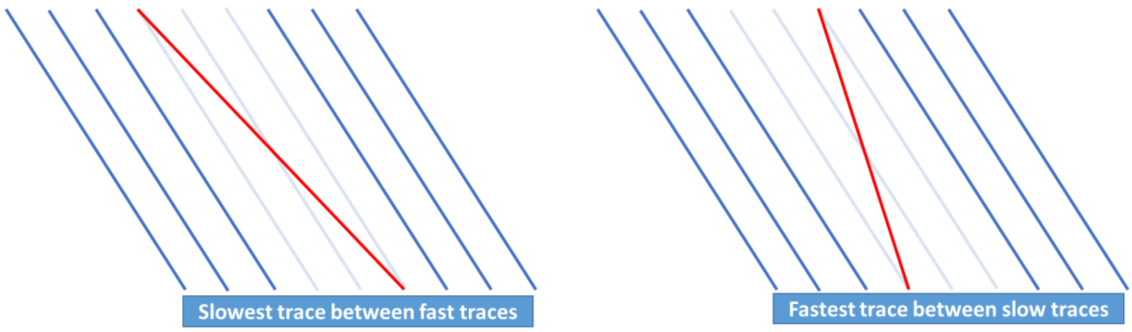


Figure 51 – Effect of heterotachy on capacity consumption (Ciuffini, 2019).

With regard to the sequence of tracks at different speeds, the effect can be analyzed through the example of Figure 52, where, with the same number of fast tracks, the number of slow tracks inserted in the same time window changes depending on the reciprocal sequence.

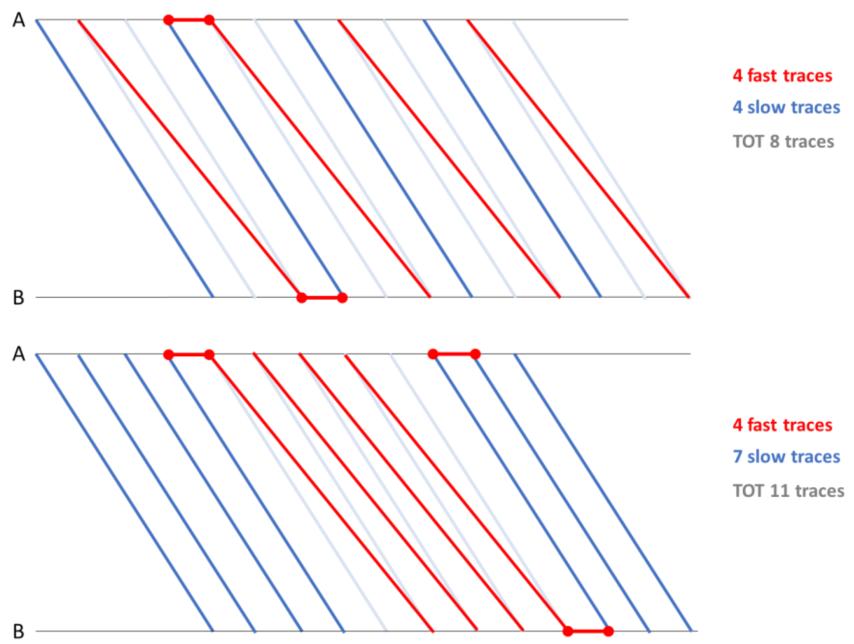


Figure 52 – Heterotachy and succession of traces (Ciuffini, 2019).

Concerning the origin-destination link within the same system, shear conflicts should be identified. These conflicts would not exist if the origin-destination matrices were linked according to the correct routes and in relation to the minor conflicting between traces the capacity will increase. Unfortunately, this will no respect commercial needs linked to the structure of the demand to be served.

Finally, it must be considered that for specific time constraints or intervals between a track and the other imposed by cadencing constraints, there may be some tracks in constrained position, which do not allow the insertion of other tracks (Figure 53).

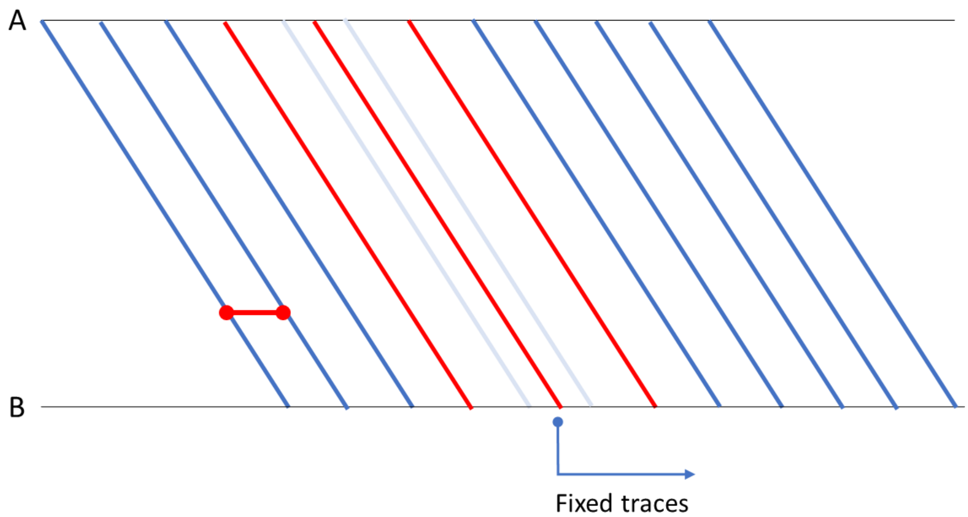


Figure 53 – Capacity and commercial requirements (Ciuffini, 2019).

2.1.3. Dependence of capacity on quality

Finally, capacity also depends on the levels of punctuality that you want to achieve. These levels depend, with the same reliability of the infrastructure and rolling stock, on the extent of the regularity margins (buffer time) that are required to make the timetable more stable.

Higher margins correspond to greater stability of the system taking into account the same infrastructure and minimum technical distance, but also to lower capacity availability for the insertion of trains (Figure 54).

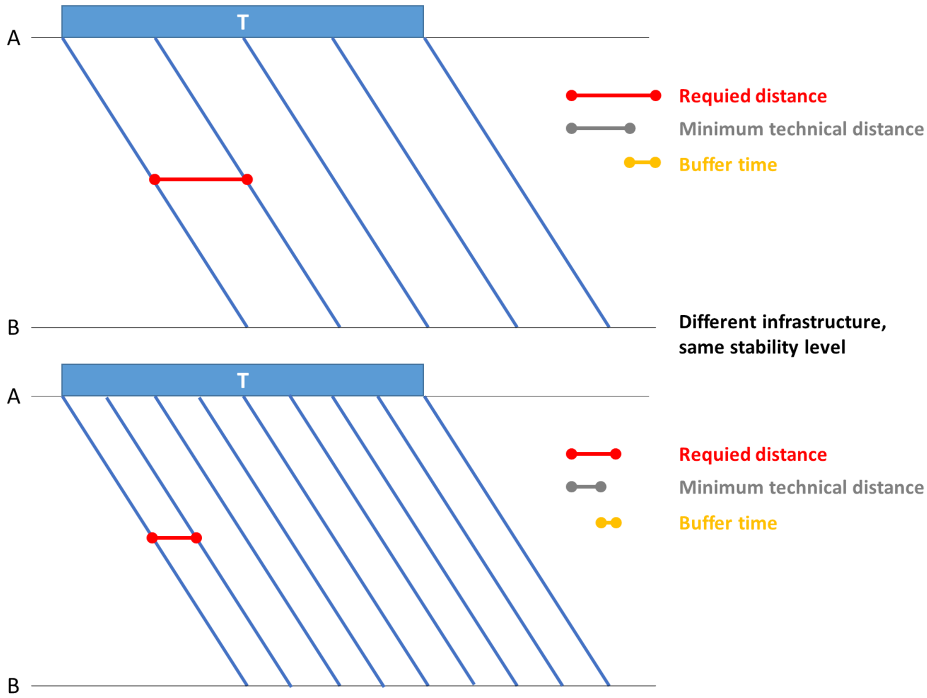


Figure 54 – Buffer time and capacity (Ciuffini, 2019).

2.2 Typologies of railway capacity

Capacity assessment is essential for densely utilized railway networks. To guarantee stable operations, it is necessary to evaluate the capacity occupation and determine possible infrastructure bottlenecks. This requires accurate microscopic models that incorporate detailed infrastructure characteristics, signalling and interlocking logic, train characteristics, and driver behavior. The capacity assessment should be undertaken on corridors, station areas, and networks, and as such, support a better understanding of the existing timetable constraints and possible infrastructure investments.

The possible implications of a capacity assessment could be constructing new infrastructure, improving the existing one, or using the existing one more efficiently. Upgrading the infrastructure may achieve these objectives but is very costly and time-consuming. Therefore, more efficient planning of services may be more appropriate. Thus, understanding railway capacity is important to identify the most effective actions (Bešinović and Goverde, 2018).

In order to discuss railway capacity, it is important to first give some definitions. Railway capacity is highly complex and depends on multiple factors. The <u>theoretical capacity</u> of railway lines and station layouts is defined as the maximum number of train paths (i.e., time-distance infrastructure slots) on the infrastructure in a given time window and represents an upper limit for infrastructure capacity. It usually assumes homogeneous traffic where all trains are identical and optimally spaced throughout the time period (UIC, 2004). In literature is also called "design capacity" (TRB, 2013), "absolute capacity" (Burdett and Kozan, 2006) or "capacity throughput" (Čičak et al., 2004; Sogin et al., 2013).

The <u>practical capacity</u> of railway infrastructure is defined as the maximum number of train paths on the infrastructure in a given time window given the traffic pattern, operational characteristics or timetable structure. Practical capacity thus depends on the mix of train services with different characteristics. In literature is also called "achievable capacity" (TRB, 2013), "effective capacity" (Goverde and Hansen, 2013).

<u>Capacity occupation</u> is defined as the amount of time that the train paths from a given timetable structure in a given time window occupy the infrastructure. Commonly, capacity occupation is expressed in minutes and also can be found in literature with the following synonyms: "infrastructure occupation" (UIC, 2004), "occupancy time" (UIC, 2013), "consumed capacity" (Pachl, 2014), "capacity utilization"(Goverde, 2007), "carrying capacity" (Hu et al., 2013), "used capacity" (Abril et al., 2005). Moreover, the <u>capacity occupation rate</u> (expressed in %) also called as "utilization rate" (Landex, 2009), is defined as the ratio of capacity occupation to the given time window. It provides an indication of how a timetable may perform.

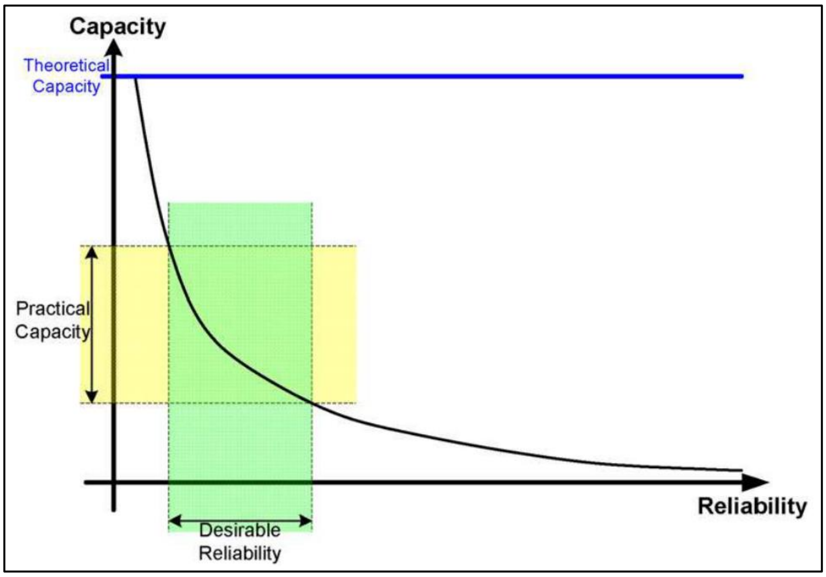


Figure 55 – Correlation between theoretical capacity, practical capacity and reliability (Abril et al., 2008).

Starting from these definitions, it is possible to introduce different methods to evaluate capacity consumption requiring different level of data detail; while the theoretical capacity can be calculated by using empirical or analytical formulas, the calculation of the practical capacity requires the definition of a timetable and of a required level of service (e.g. admissible delays or percentage of on time trains). It is worth noticing that *''it is not possible to give a unique value to the whole railway network because of complexity and diversification of components (lines, stations or their subparts), which require different estimation of capacity itself. Anyway, at network's level it will be possible to estimate a global capacity value by referring to the lower local value*'' (IMPROVERAIL, 2003). Indeed, also Verkehrswisswnschaftliches Institut (2008) and UIC (2010) present a net distinction between line and node (stations, terminals, junctions, etc.) capacity, reporting a comparative analysis of different synthetic or analytical methodologies for their evaluation. Mussone and Wolfler Calvo (2013) and Malavasi et al. (2014), instead, present two different approaches (beside useful literature reviews) for capacity evaluation of complex railway nodes.

A node is a track layout with switches and multiple route possibilities. A node may be a small station with only a few platform tracks and limited interlocking areas, but also a big station with higher number of tracks and more complex interlockings and may serve as a terminal for train lines. In addition, a junction can be considered as a node, which includes only interlocking but does not provide train stopping possibilities. A line section is a railway line between two nodes with a fixed number of parallel tracks and no switches. A line section can have one or more parallel tracks and the sequence of trains cannot change. Trains on a line section are usually separated by a block system, where each block can be allocated to at most one train. A corridor represents a longer railway line that consists of multiple line sections. Finally, a network is an area of various interconnected corridors which are considered at once during the capacity assessment.

2.3 Calculation techniques and method

As described in Dicembre and Ricci (2011), Abril et al. (2008), Pachl (2014), Kontaxi and Ricci (2009), the most relevant approaches to evaluate railway capacity can be classified, according to their methodology, by the required data and the level of detail of the resulting estimations:

- Synthetic and analytical methods describe the problem using mathematical formulae and may represent a good start for identifying major capacity constraints; they are mostly applied for determining a preliminary solution in simple situations, for comparison purposes or as reference. Even if these methodologies often lead to useful results without the need of extensive simulations, it is worth noticing that the results vary from one method to another depending on the considered parameters (Kontaxi and Ricci, 2009). Besides the well-known UIC (1996) approach, detailed reviews and useful descriptions of several synthetic and analytical methods can be found in the scientific literature.
- Asynchronous methods represent in more detailed way capacity estimation, modeling the dynamic scheduling processes utilizing discontinuous events. The asynchronous approach often tries to optimize one or more variables; in practice optimization methods for evaluating railway capacity focus on obtaining optimally saturated timetables, usually through mathematical programming techniques (e.g. Mixed Integer Linear Programming Formulations and Enumerative algorithms). A well-known example is represented by the UIC Code 406: by modifying the base timetable, existing train paths are set as close as possible

to each other and the remaining unused time left in the timetable represents spare time theoretically available for additional train services.

- Synchronous methods (traffic simulation) are even more detailed; they are able to reproduce, by means of specific software, the processes of railway operation over the time and provide with values quite close to reality. Besides purely academic models, several simulation environments have been already produced and are commercially available on the market. They usually perform time-step simulations based on train motion equations. Few examples of these simulation environments are:
  - OpenTrack (OpenTrack Railway Technology) is a railway network simulation program developed as part of a Swiss Federal Institute of Technology Institute for Transport Planning and Systems (ETH IVT) research project (http://www.opentrack.ch/);
  - RailSys is a computer-based software system for analysis, planning and optimization of operational procedures in railway networks developed by RMCON Rail Management Consultants (https://www.rmcon-int.de/railsys-en/);
  - Rail Traffic Controller (RTC) is a Windows-based program developed by Berkeley Simulation Software (BSS) to simulate the movement of trains through rail networks (http://www.berkeleysimulation.com/).

A detailed description of simulation models is reported in TRB (2013) and Watson and Medeossi (2014): by reproducing the railway infrastructure and the rolling stock characteristics (see Figure 5) and after introducing the timetable data (Figure 56), these software applications are able to simulate the railway system, providing different results related either to the operation of trains (Figure 57) or to the platform and track occupation in stations or nodes (Figure 58).

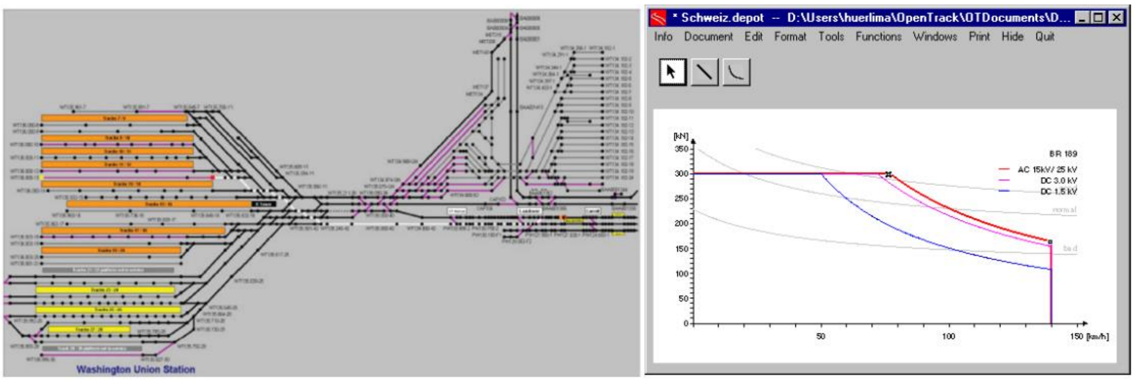


Figure 56 – Washington Union Station scheme (left, source TRB (2013)) and rolling stock data interface by OpenTrack (right).

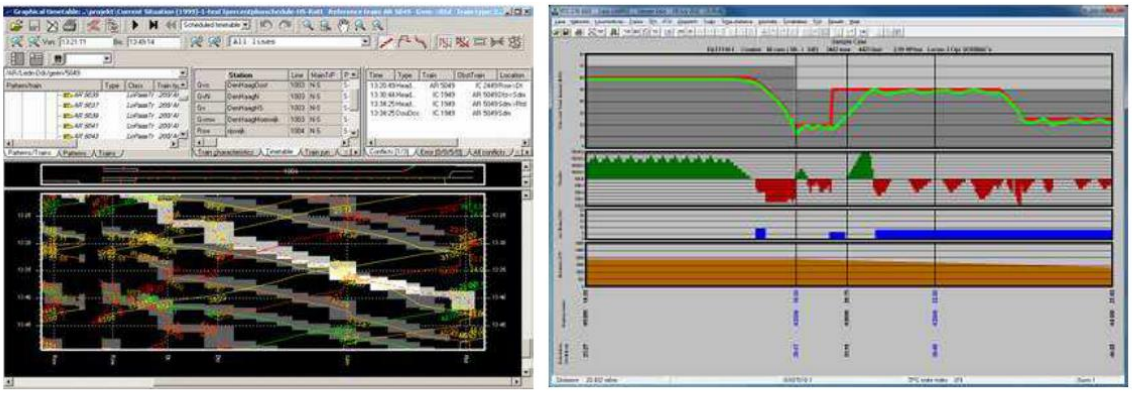


Figure 57 – Timetable Manager Layout by RailSys (left) and Train Performance calculator by RTC (right).

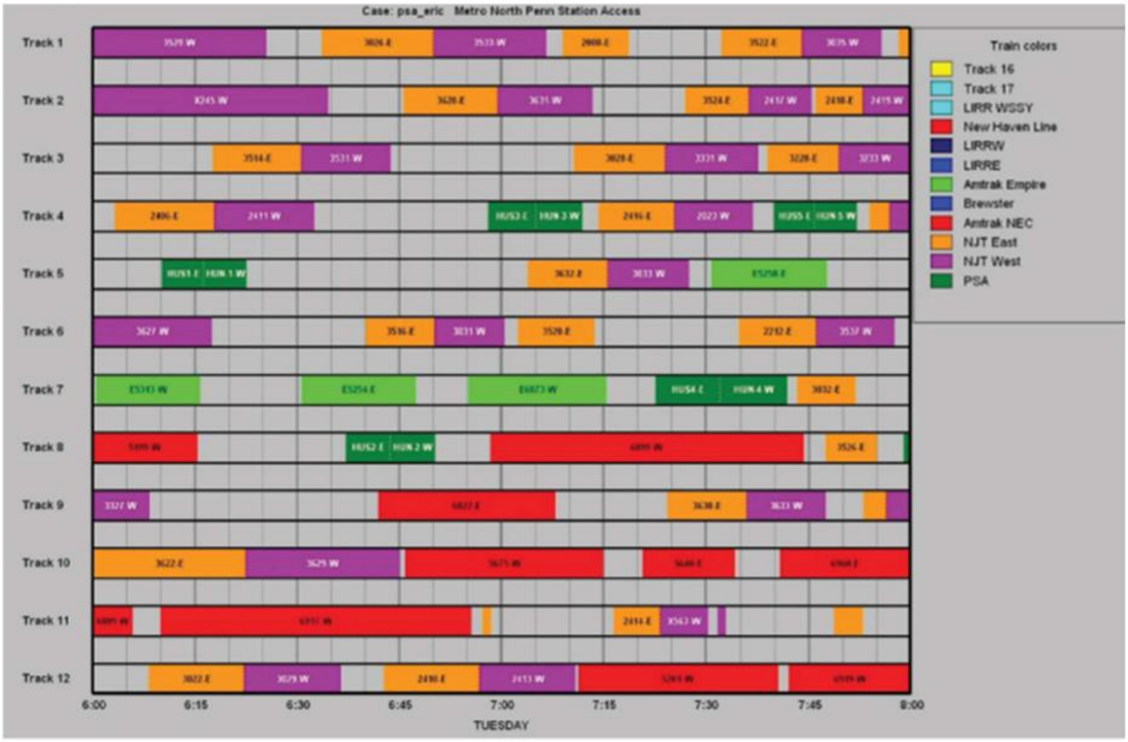


Figure 58 – Example of occupation chart of station tracks (source TRB (2013)).

2.3.1. Synthetic Method

2.3.1.1 FS Formula

The method is based on different formulations. Referring to the one shown on Giuliani et al. (1989) and Vicuna (1986), it takes the following expression:

$$P = \left(N_{pr} + \frac{T - t - \theta}{p_k + t_m}\right) \cdot K_{FS}$$

in which all times are expressed in minutes and is also:

- N_{pr} sum of trains running on the line under consideration (existing);

- T reference period;
- t time of suspension of service due to maintenance;
- θ total time covered by trains running on the line;
- p_k travel time of the relevant section by the train k;
- t_m downtime for setting the train route;
- $K_{FS} < 1$ dimensionless effectiveness coefficient.

In calculating the number in parentheses, it is necessary to pay attention to the sum $(p_k + t_m)$, which has a minimum value defined by the minimum headway. For the test line and by varying the only parameter K_{FS} in the range $0.6 \div 0.8$, it is obtained that the value of the resulting capacity can vary up to 25% (Figure 59). At the same time, by varying the downtime for setting the routes in the range $1 \div 3.5$ minutes, the capacity may be reduced up to 26% (Figure 60).

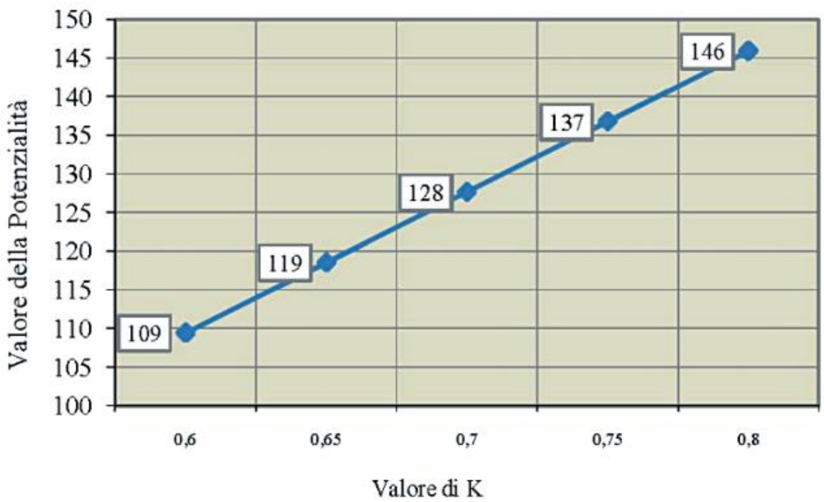


Figure 59 – Variation of capacity [trains/day] as a function of the KFS coefficient.

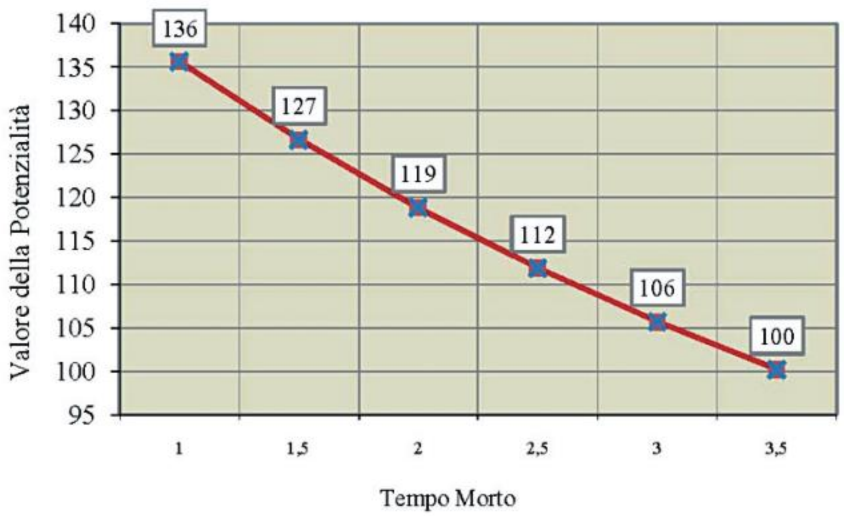


Figure 60 – Variation of capacity [trains/day] as a function of downtime [minutes].

The formula does not take into account the heterogeneous traffic.

In order to calculate the capacity of a line run by different speeds traffic, it is not sufficient to consider the block section ($p_k$term of the formula outlined above) but a larger section including two stations in advance.

2.3.1.2 Canciani Method

Canciani (1991), on the basis of what was determined by Tolotti, treats the capacity of double-track lines with alternating movement of two classes of speed considering the delay time due to overtaking.

In this scheme the two speed classes (fast and slow) have the same train number and are alternated in between them (Figure 61).

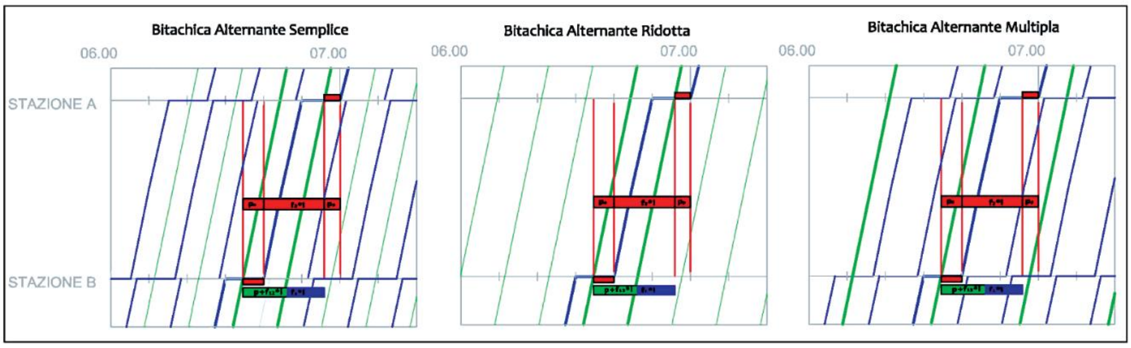


Figure 61 – Traffic alternation according to CANCIANI.

Additionally, a method for calculating the delays due to crossing in the event of a degraded service of a double track into single track is defined.

The formula takes the following expression:

$$P = \frac{T}{p + (f_{12} \cdot l)} \cdot n$$

where:

- p is the minimum time to perform an overtaking in arrival and departure;
- $[f_{12} \cdot l]$ is the time lost due to heterogeneous speed (traffic delay);
- f_{12} is the difference between the inverse of the speed of slow (v_2) and fast (v_1) trains;
- n takes into account the amount of slow trains running between two fast trains (type of traffic alternation, as defined in Figure 61);
- T is the time period taken as reference.

2.3.1.3 RFI Formula

According to RFI (2011), the method treats values drawn up in a medium headway plus margin expansion and extra time. The margins consist in increasing $1/3$ the hourly capacity and $2/3$ the daily capacity, with extra time calculated according to the number of stations on the line (0.25 minutes per station).

The calculation of capacity, which assumes decreasing values with block sections length, is carried out according to distances between following trains longer than the minimum spacing of trains derived from the operational experience.

The method defines the theoretical (CT) and the commercial (CM) capacity.

For single line tracks theoretical capacity is calculated using the following formulas:

- Daily Theoretical Capacity:

$$CTG = \frac{N * 1320}{D_n}$$

where:
$D_n$indicates the line's headway defined as "normal" in the technical scenario, if it should be derived from the time of release, this should be calculated on the critical section considering the average running time, i.e. in a first approximation the running time at rank A, neglecting, any dilation.
The commercial capacity is lower than the theoretical one due to the coefficient K, which takes into account the variety of the commercial speeds.
The formula is as follows:

- Daily Commercial Capacity:

$$CMG = \frac{CTG}{K}$$

where

CMG is less than CTG and depends on K coefficient that takes into account the different values of commercial speed on the line (Table 2).

For bidirectional tracks the theoretical capacity is calculated using the following formula:

- Daily Theoretical Capacity:

$$CTG = \frac{1320}{T_d + z}$$

where T_d indicates the time required to travel at the speed of the slowest trains (rank A) the relevant section, without regard to any lengthening of distance; and z dilation for crossing manoeuvres.

In this case is:

- Daily Commercial Capacity:

$$CMG = \frac{CTG}{K_1}$$

The values of coefficients K and K_1 are shown in Table 2.

Livello di velocità *Speed level*	1	2	3	4	5
K	1,2	1,4	1,5	1,8	1,9
K_1	1	1,3	1,3	1,5	1,5

Table 2 - Values of coefficients K and K1 for the RFI formula.

2.3.1. Analytical Methods

2.3.1.1 Bianchi Method

In his first contribution Bianchi (1964) applies the queuing theory analyzing the distribution of intervals between trains and service times, thus providing a contribution to the relationships between capacity and characteristics of tracks lay-out and operation of double and single track lines, by taking into consideration the influence of the promiscuous running of trains with reciprocal priority rights in case of crossing and overtaking.

It is also introduced the parameter "traffic interruption" to take into account that, due to the fastest trains overtaking, brief periods of broken operation happen. The capacity of a double track line is expressed by:

$$W = \frac{\rho \cdot U \cdot (1 - \delta_p) \cdot (1 + \varepsilon)}{p_x \cdot (1 + \varepsilon \cdot \eta)}$$

where:

- ρ is the utilization rate;
- ε is the ratio between the number of slow trains (non-priority) and the number of fast trains (priority);
- η is the ratio between the reciprocal distances of slow trains (non-priority) and fast trains (priority);
- δ_p is the ratio of the complex movement of the interruptions and the period available;
- p_x is the running time of priority trains;
- U is the operation period.

In case of a single track line the capacity is obtained by an almost similar expression.

The proposed method is based on the assumption of exponential distribution of trains arrivals, therefore the results are closer to the reality when applied for a sufficiently long period of time.

It is possible to compare the results obtained with this method and those which does not consider variation in service times with queuing theory, which states that the potential for movement is given by:

$$W = \frac{K \cdot (T - R)}{P_m} = \frac{K \cdot U}{P_m}$$

where:

- K is the empirical coefficient of correction, less than 1, by which means tender account of the uneven distribution of trains during the period and the actual performance of movement;
- P_m is the average of travel times;
- T is the time period;
- R the ranges required for the maintenance of the line;
- U the grace period for the movement.

This leads to the plot shown in Figure 62. Consequently, the same author, in his contribution of 1967, extended the previous analysis by including the calculation of delays caused by the priority of a train slow to a fast train on the lines of double track. In particular two types of distribution have been considered: the uniform distribution and random distribution. The increase in pure running time of a slow due to overtaking is given by the following formula:

$$I_l = \frac{W_v \cdot r_m \cdot (\eta - 1)}{\eta \cdot (U - W_v \cdot r_m)}$$

where:

- W_v is the number of fast trains;
- r_m is the average delays of slow trains;
- η is the ratio between the distances run by slow trains (non-priority) and the number of fast trains (priority).

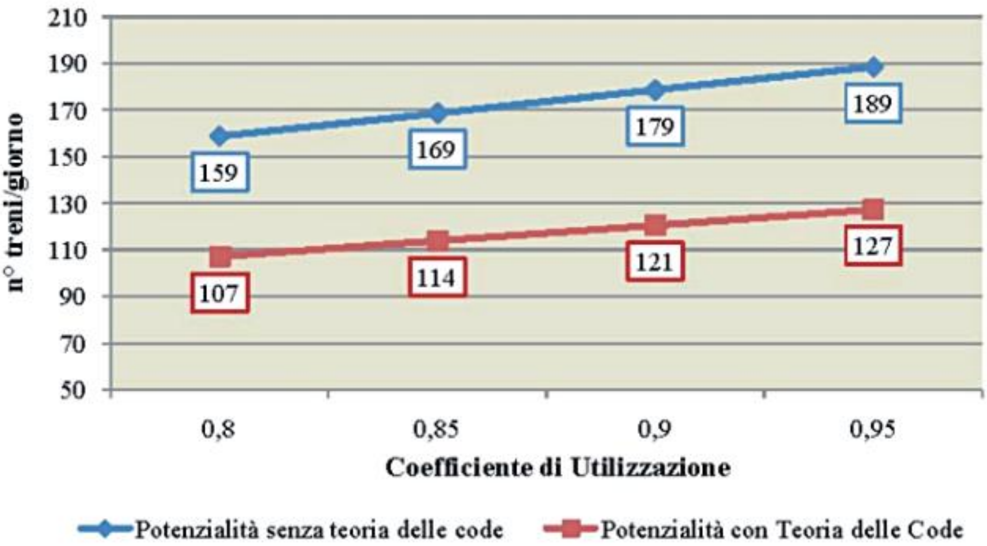


Figure 62 – Application of the method of BIANCHI with the determination of capacity values by utilization rate.

2.3.1.2 DB formula

The German Federal Railways (DB) have developed a probabilistic method for the quantification of the capacity of railway lines, based on principles similar to the UIC approach, albeit with some significant peculiarities (Vicuna, 1986). The expression of the capacity for whole day is in this case:

$$P = \frac{T}{t_{fm} \cdot (1 + q)}$$

where:

- t_{fm} is the average value of the minimum headways between two following trains;
- q is the buffer time, which takes into account the timetable situation and the desired quality to be calculated by setting two parameters (degree of fluidity and transfer factor), and the use of diagrams linking these three factors in Figure 63.

For the calculation of t_{fm} two types of trains are considered in this case, the two speed classes rapid (v) and slow (l) and the expression which is used is the following:

$$t_{fm} = \frac{(t_{vv} \cdot n_v^2) + (t_{vl} \cdot n_v \cdot n_v) + (t_{lv} \cdot n_v \cdot n_l) + (t_{ll} \cdot n_l^2)}{(n_v + n_l)^2}$$

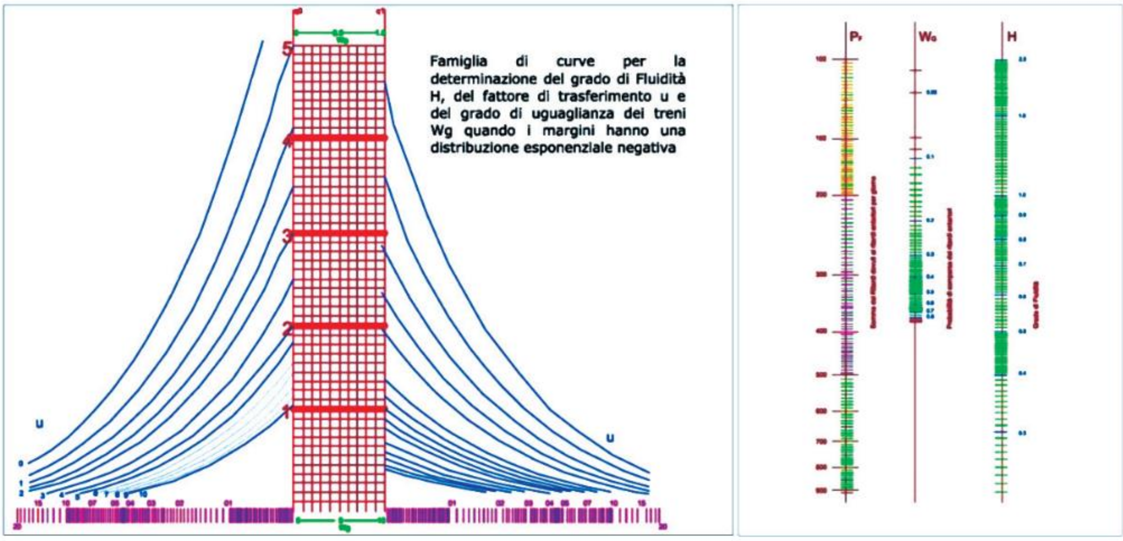


Figure 63 – Parameters defining the margins of regularity in the DB method.

2.3.1.3 UIC 405 R method

This method belongs to the category of analytical methods as reported in the first edition (1978) of the calculation procedure reported in a UIC Fiche 405R (UIC, 1996) officially replaced in 2004 by the compression method (UIC's Leaflet 406) as a standard on capacity, anyway offering an efficient estimation of the capacity of a line. We included this approach, given the clarity and the easiness of application and the modest need of data; in our opinion it represents a simple but valid method, recognized and appreciated at European level.

To summarize briefly the main characteristics of this approach, it is based on the following formula for the capacity:

$$P = \left(\frac{T}{t_m + t_r + t_{zu}}\right)$$

where:

- P is the capacity (daily, hourly etc.);
- T is the reference time (usually 24 hours for the daily capacity);
- t_m is the average minimum headway;
- t_r is an expansion margin;
- t_{zu} is an extra time based on the number a of the intermediate block sections on the line and calculated by means of the formula $t_{zu} = 0.25 \cdot a$; this parameter takes into account that the increase of capacity on the determinant section, following its division into more block sections, is less than proportional to the reduction of the travel time.

The average minimum headway for each line is:

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

Where $t_{h,ij}$ is the minimum line headway for the train j following the train i and f_{ij} is the relative frequency of combination: train j following train i; this parameter is calculated based on the frequencies F_{ij} according to the timetable:

$$f_{ij} = \frac{F_{ij}}{N-1}$$

The expansion margin t_r is defined as a running time margin added to train headways in order to reduce knock-on delays and to achieve an acceptable quality of service; it is calculated applying the queuing theory considering the critical section as a service (i.e. a M/M/1 queuing system). In particular, the length of the queue for entering the section is equal to the number of trains encountering a disturbance (delay).

It depends on the intensity of traffic Ψ (track occupation rate of the single channel) given by the ratio between the distribution of the headway times of arriving trains ($\lambda = 1/\left(t_{fm} + t_r\right)$, i.e. inverse of the expected interarrival time) and the distribution of the minimum headway times of trains which utilize the section ($\mu = 1\ /t_{fm}$, i.e. inverse of expected service time):

$$\psi = \rho = \frac{\lambda}{\mu} = \frac{t_m}{t_m + t_r}$$

An extensive test campaign, carried out by UIC, led to the identification of the following threshold values for Ψ:

- 0.60 (corresponding to 1.5 users waiting in the queue) valid for an unlimited period of time (normal operation of the system), hence the condition $t_r \geq 0.67 \cdot t_{fm}$;
- 0.75 (corresponding to 3.1 users waiting in the queue) valid for a short period of time (peak hours), hence the condition $t_r \geq 0.33 \cdot t_{fm}$.

By having assumed an M/M/1 system, the mean queue length (average number of delayed trains) will be equal to:

$$L_q = \frac{\rho}{(1-\rho)}$$

While the average waiting time (average delay per train) is:

$$w = \frac{\rho}{(\mu - \lambda)} = \left(t_{fm} + t_r\right) \cdot \frac{\rho^2}{(1-\rho)}$$

The presented approach is based on very simple formulas and does not require a big amount of data, besides easy to get values such as number of trains, reference period, etc. Anyway, the length (or the travel time) of the relevant block section of the line should be measured or at least hypothesized. It is for these reasons that we propose a possible simplified approach of this procedure in case of limited available data.

2.3.1.4 Corriere Method

Corriere (1982) proposed a method that takes into account the effect of delays in analogy to the road flows.

The proposed formulation analyses the delays in presence of perturbations causes as crossing and/or overtaking maneuvers, also describing the capacity speed dependence in presence of delay randomly generated.

The expression of the daily capacity is in this case:

$$P = \left(\sum_j N_j + \frac{T - \sum_j N_j \cdot \left(A_j + B_j \cdot V_j + \frac{C_j}{V_j} \right) \left(1 + D_j \cdot V_j \right)}{\left(A_i + B_i \cdot V_i + \frac{C_i}{V_i} \right) \left(1 + D_i \cdot V_i \right)} \right) \cdot k$$

where:

- N_j is the number of trains of class j (priority over i);
- A and B are terms depending upon the spatial distance;
- C is the length of the trains;
- D_i is the average delay calculated on the basis of PETERSEN's theory.

2.3.1.5 Genovesi and Ronzino Method

Genovesi and Ronzino (2006) proposed an extension of what is considered by Corriere (1982) in order to extend the concept of delay coefficient to stops perturbations. In addition, they introduced the coefficient of stability, in order to obtain more realistic capacity values. It is expressed by the following formula related to the whole line:

$$x_{line} = \frac{\sum x_{ij} \cdot L_{i-j}}{\sum L_{i-j}} \text{ and } x_{0,i-j} = \frac{L_{i-j}}{\frac{n-1}{n-2} \cdot b_{medio} + L_t + f}$$

where:

- L_{i-j} is the distance between the stations;
- L_t is the trains length;
- b_{medio} is the average length of the block sections;
- n is the number of signal aspects;
- f is a safety margin.

On this basis the final expression of the capacity of a line with fixed block is:

$$C = \frac{1}{x_{linea}} \cdot \frac{\frac{\sqrt{2\gamma b/k}}{1 + D \cdot \sqrt{2\gamma b}}}{\frac{n-1}{n-2} b + L_t + f}$$

- D is the specific delay;
- b is the block section length;

- n is the number of aspects of signals;
- L_t is the trains length;
- f is a safety margin;
- χ is the coefficient of stability;
- γ is the train deceleration;
- k is a safety factor.

2.3.1.6 Capacity Utilization Index (CUI) Method

Whenever the scheduled timetables for analyzed lines are available, it could be possible to follow the CUI approach (Armstrong and Preston, 2013; Gibson et al., 2002; Maunsell, 2007) for the calculation of capacity; the Capacity Utilization Index is "*the time taken to operate a squeezed or minimum technically possible timetable compared to the time taken to operate the actual timetable*".

Network Rail uses the CUI method in the UK for capacity analysis based on the minimum headways of a nominal set of train pairs and it requires less details compared to the UIC's 406 method described below; the main idea is to take an ideal train graph and to squeeze it such that all the trains are scheduled with only a standardized minimum headway.

The capacity utilization is evaluated as a proportion of the time taken to operate the squeezed timetable compared to the time taken to operate the actual timetable (e.g. in Figure 64, CUI = 45/60 = 75%). Of course, the method, even if worthy, provide an estimation of capacity sensitive to the way the timetable is compressed.

According to Gibson et al. (2002) there is a relationship between CUI and the Congestion Related Reactionary Delay (CRRD) per train mile; this subset of delay is the portion that should increase more than linearly with an increase in traffic.

Based on a fitting test with observed real data, the method proposes an exponential function to link the CUI and the CRRD:

$$D_{it} = A_i \cdot \exp(\beta \cdot C_{it})$$

where are:

- D_{it} the reactionary delay on track section i in time period t;
- A_i a route section specific constant;
- β a route specific constant;
- C_{it} the capacity utilization index on section i in time period t.

The values of A_i and β are calculated and regularly updated for the UK network and they could be generalized to other networks only based on a specific investigation (Gibson et al., 2002).

By compression of the timetable based on the occupation time between two consecutive stations results the capacity utilization index, whereas the UIC 406 method (see next subparagraph) considers each block section along the line, which requires more detailed information on infrastructure and signalling systems, but also guarantees more detailed results; in particular, here it is worth to notice that, unlikely the UIC 406 index, the CUI can present unrealistic value higher than one, e.g. in case of long distances between consecutive stations, low speeds or great heterogeneity of services and high frequency on the section (Rotoli et al., 2015).

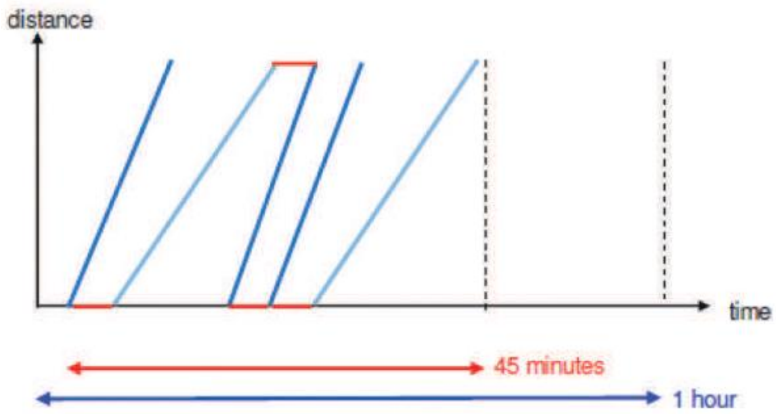


Figure 64 – Capacity utilization calculation according to CUI method (Maunsell, 2007).

2.3.1.7 UIC 406 Method

The UIC 406 capacity method is based on the blocking time theory. Originally, UIC (2004) described a method for evaluating capacity of line sections. In the 2nd edition, UIC (2013) expanded the approach to the capacity assessment of nodes. The method requires a timetable and a division of the network into line sections and nodes. The original purpose of the UIC 406 capacity method was to measure the capacity occupation of a given timetable, which is achieved by compressing the train blocking time stairways. In addition, the method has been used for assessing practical capacity. This has been done by adding extra trains in the timetable, called timetable enrichment (Bešinović and Goverde, 2018).

The first step of the methodology is to build up the infrastructure layout and the timetable of the line (Figure 65) and then to compress the timetable in order to obtain the capacity consumption (Figure 66). The block sections remain occupied, depending on signalling systems, as long as the point behind them (to be cleared for safety reasons) becomes free of the end of the train and the route is released (Figure 67).

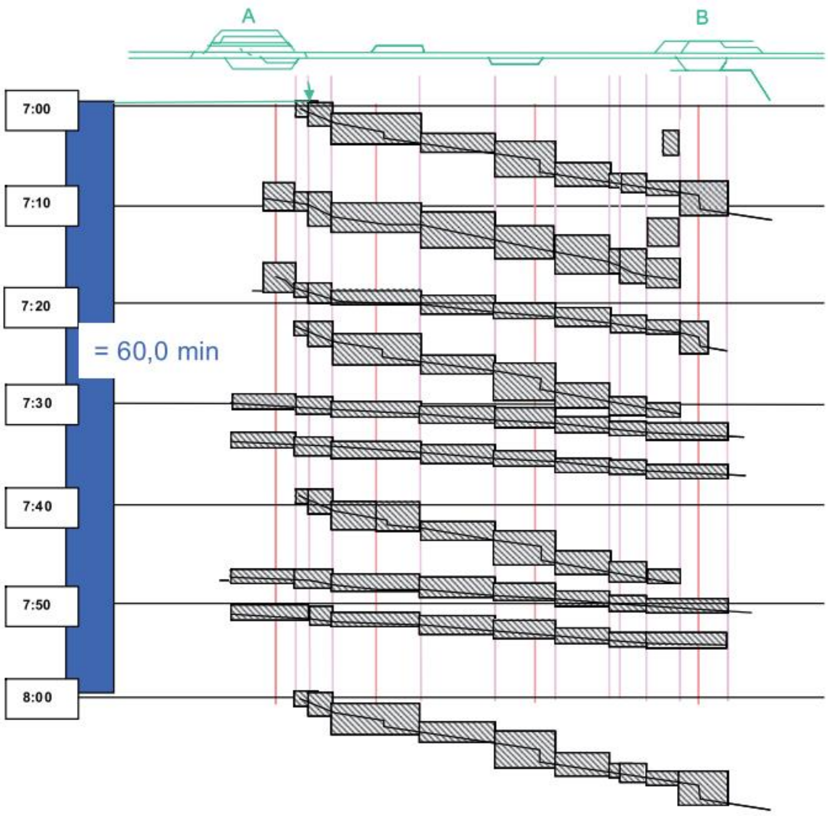


Figure 65 – Original timetable (Verkehrswisswnschaftliches Institut, 2008).

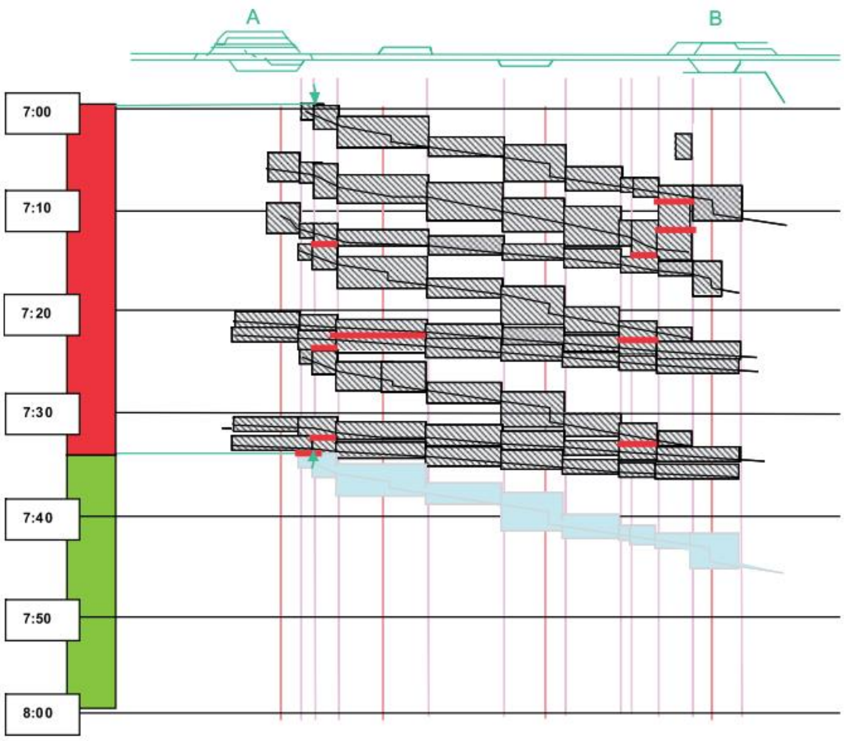


Figure 66 – Compressed timetable (Verkehrswisswnschaftliches Institut, 2008).

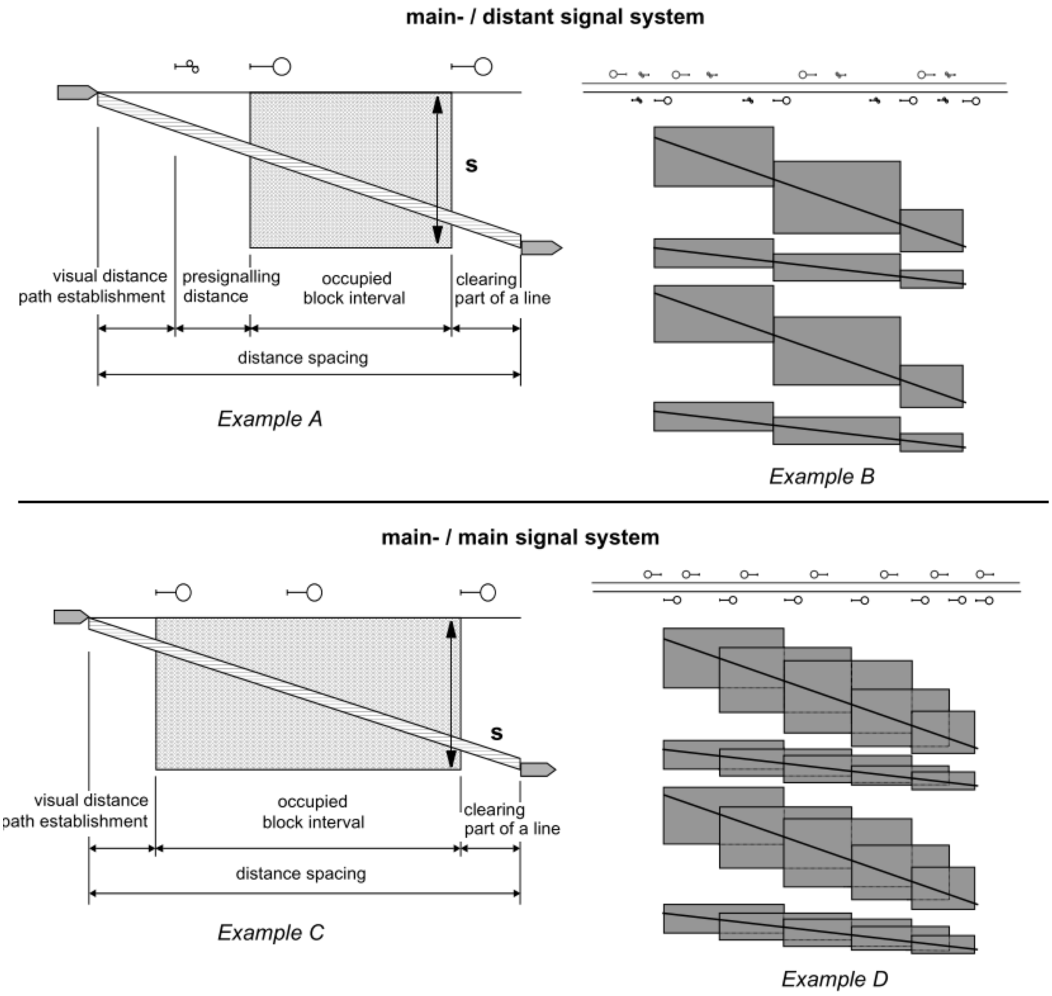


Figure 67 – Example of occupation times in different signalling system (UIC, 2013).

The capacity consumption calculation method suggested in UIC Code 406 is based on blocking time sequences: for each block section, the occupation time is a sum of times for (Figure 21 and Figure 67):

- route formation;
- visual distance/driver reaction;
- approach the block section;
- track occupation of the block itself;
- clearing time.

All depending on the timetable, infrastructure and vehicle characteristics. Verkehrswisswnschaftliches Institut (2008) reports some samples of practical values of occupational times to apply for various signaling systems. In order to estimate the total capacity consumption, it is necessary to consider time reserves for timetable stabilization (i.e. buffer time B) and for maintenance requirements (i.e. D) besides the minimum occupation time A and supplement for single-track lines (i.e. crossing buffer C); hence the total consumption time k will be:

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

Part of the remaining slots are not usable due to market requirements, while a share of the unused capacity represents still available capacity (Figure 68). Given a reference time, t_u the capacity consumption $K[\%]$ is defined as:

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

UIC specifies a guideline for standard values of infrastructure occupation in order to achieve a satisfying operating quality. These values are a function of the type of line and the infrastructure use (Table 3).

The method does not consider an explicit interrelation between capacity and quality; thus, as it is, can be used for a rough benchmark calculation of capacity consumption, but not for an estimation of railway infrastructure's performance.

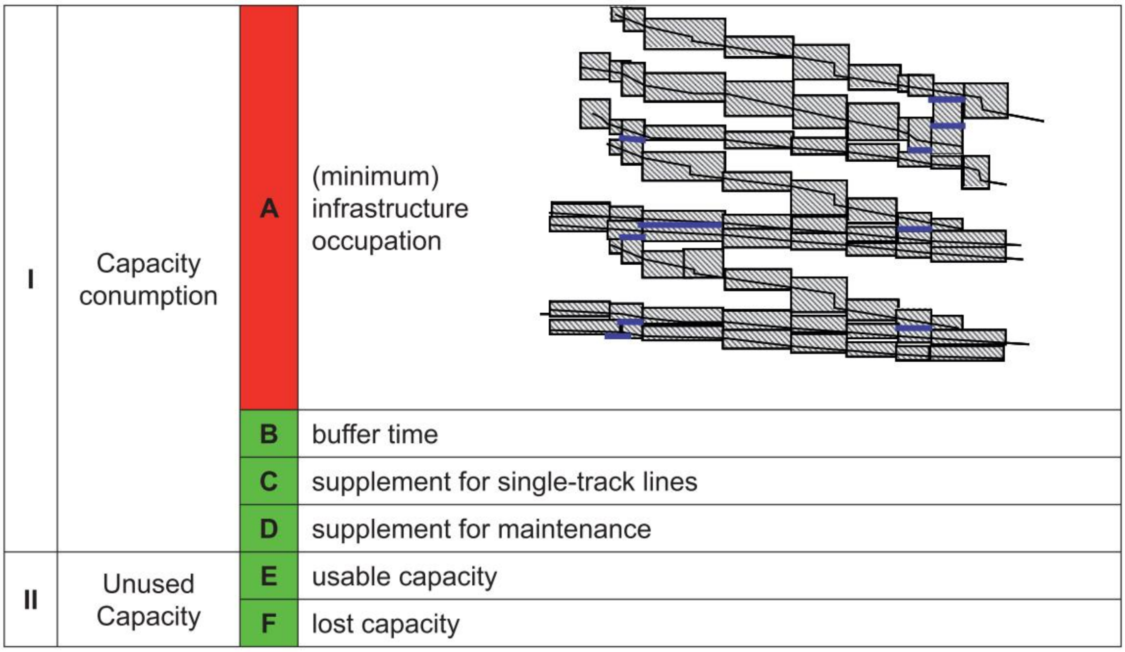


Figure 68 – Determination of capacity consumption.

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

Table 3 - UIC's recommended values for infrastructure occupation (Verkehrswisswnschaftliches Institut, 2008).

2.3.1.8 STRELE Formula (Method of Schwanhäußer)

In order to calculate the average buffer time t to achieve an adequate level of service, it is possible to use the following equation:

$$t = \frac{z \cdot (1-\rho)}{\rho} = \frac{A \cdot (1-\rho)}{N \cdot \rho}$$

where:

- ρ recommended value for the infrastructure occupation by UIC 406 (Table 3);
- z average minimum headway time;
- A minimum infrastructure occupation and N actual number of running trains.

The method considers that both the entering delays and primary delays (generated on the section itself) induce new secondary delays; these last ones arise from threading trains into the line section. According to Schwanhäußer (Verkehrswisswnschaftliches Institut, 2008), the average secondary delays (unscheduled waiting times) on line's sections can be expressed by the formula:

$$ET_w = \left(\rho_{ve} - \frac{\rho_{ve}^2}{2}\right)\frac{t_{ve}^2}{t_p + t_{ve}\left(1 - e^{-z/t_{ve}}\right)} \cdot \left(p_g\left(1 - e^{-z_g/t_{ve}}\right)^2 + (1-p_g)\frac{z_v}{t_{ve}}\left(1 - e^{-2z_v/t_{ve}}\right)\frac{z_v}{t_p}\left(1 - e^{-z/t_{ve}}\right)^2\right)$$

with:

- t_p average buffer time;
- z average determinative minimum headway time;
- z_g average determinative minimum headway time of equal-ranking successions of trains;
- z_v average determinative minimum headway time of different ranking successions of trains;
- t_{ve} average delay at entry;
- ρ_{ve} probability of delay at entry;
- p_g probability of an occurrence of equal-ranking successions of trains.

The average buffer time to reach a satisfying operating quality depends by the acceptable value of the unscheduled waiting time. It is worth to notice that the equation requires the definition (by measurements or assumptions) of the average delay t_{ve} and of the probability of delay ρ_{ve} at entry.

2.3.2. Asynchronous methods

2.3.2.1 Cascetta and Nuzzolo Method

According to Cascetta and Nuzzolo (1980), the model allows to take into account the headway between trains and the actual number of overtaking and crossing tracks in the stations and requires, however, some simplifying hypotheses, such as the completely random pattern of trains departures.

In fact, the hypotheses that the number of departures of trains of each class forms an independent homogeneous Poisson process is accepted.

In short, the method allows to calculate the running time required, through the resolution of a system of equations in matrix form of order i, as expressed by:

$$t_i(t_{percorrenza}) = \frac{L}{v_i} = \frac{L}{s_i} + \sum_j R_{ij} \cdot M_{ij}$$

where:

L is the length of the line section;

v_i is scheduled commercial speed;

s_i is the actual commercial speed;

R_{ij} is the average delay resulting interference between a train of class i and a train of class j;

M_{ij} is the average number of interferences occurring between trains i and j.

2.3.2.2 Corriere Method (1984)

Following its earlier formulation (1982), Corriere (1984) analyzed the reduction of capacity due to the insertion of slow trains in an homogeneous timetable, considering as an unusable dead time the difference of journey times of a block section for the two speeds typologies multiplied the number of sections between the two block stations previously addressed. Corriere applies to each class of trains defined in the FS method, a delay per line unit length. The expression of the daily capacity is in this case:

$$P = (\sum_i N_i + \frac{T - t - \sum_i N_i \cdot d_i \cdot (1 + D_i \cdot V_i)}{d_j \cdot (1 + D_j \cdot V_j)}) \cdot k$$

where:

- D_i is the average delay of class i;
- D_f is the average delay of priority class j (priority trains);
- N_i is the number of trains without priority;
- T is the time period;
- t is the maintenance time;
- k is the performance coefficient.

2.3.2.3 Reitani and Malaspina method

This method offers a fusion between the analytical and static formulas by integrating the assumptions of the general formulas of static methods with analytical proper elements as the introduction of a coefficient taking into ac- count the likelihood that the delay (calculated with the CORRIERE method) occurs.

This method allows to consider several classes of speed and the priority rules and quantify the delays similarly to CORRIERE.

The expression of the global capacity is:

$$P = \frac{T}{k \cdot z}$$

With

$$z = \frac{D}{\sum N_i} \cdot \sum_{i=1}^{n} \left(\frac{N_i}{v_i} + \sum_{j=1}^{n} c_{ij} \cdot \frac{p_{ij}^2 \, N_i \, N_j^2}{2 \cdot (\sum N_h - N_i)} \cdot \left|\frac{1}{v_i} - \frac{1}{v_j}\right|\right) + t_m$$

- D is the distance between two following trains;
- N_i is the number of trains belonging to i class;
- N_j is the number of trains belonging to j class;
- p_{ij} are the coefficients translating the priority rules between the trains classes;
- v_i is the actual average commercial speeds classes i and;
- v_j is the actual average commercial speeds classes j and;
- c_{ij} is the relationship between different types of delay.

2.3.2.4 Delfino and Galaverna Method

The proposed method (Delfino and Galaverna, 2003) quantifies the capacity increase achievable on lines with mixed traffic by the introduction of the moving block.

The method is based on Reitani and Malaspina (1995) considerations and provides a procedure for calculating the delays in case of automatic electric block (fixed block) and moving block, with the addition of an expression for the delay given by:

$$D_{ij} = \frac{S_i^2}{2d_i} + \left(S_j \cdot t_r\right) + L_{ij} + H$$

where

- D_{ij} is the specific delay;
- S_{ij} is the delay acquired by a slow train overtaken by a fast one;

- t_r is the reaction time;
- L_{ij} is the train length;
- H is a spatial safety margin.

2.3.1. Synchronous methods

The simulation methods provide a model, as close to reality as possible, to assess the performance of the rail network. The data required for simulation are similar to analytical methods, but typically at a higher level of detail. Today, simulation methods use computer tools to manage sophisticated calculations and stochastic models more quickly and efficiently. Simulation approaches generally use commercial software specifically designed for rail transport, such as RTC (used in North America) Multirail, RAILSIM, Opentrack, Railsys and CMS.

Non-commercial software also exists that may require the user to develop models, equations and constraints step by step (often manually). This requires more experience, creativity and commitment, but can also offer greater flexibility and customization of results and outputs. Commercial railway simulation tools are more user-friendly, but the models and decision-making processes are not easily customizable or serviceable, which can reduce the flexibility of application of these tools. The simulation methods are used in the capacity studies because simulating the running of trains on the lines and in the plants return the use of the infrastructure, then the capacity consumed and the residual capacity. Moreover, integrated with optimization methods, the simulation software allows to generate saturated operating hours, thus determining the maximum capacity of a railway network.

Simulation methods are gaining ground in national railway infrastructure management administrations, as a result of new sectoral policies, both at European and North American level.

By encouraging free access to rail networks and a general modal shift towards rail, these policies lead to a significant increase in the demand for capacity on lines and at nodes. Simulation software, which is much more effective and efficient than analytical methods, therefore offers substantial help to railway operators to carry out capacity studies to optimize schedules and assess the capacity of lines and nodes to meet demand.

The potential of simulative methods derives from the high degree of detail in the modelling of the system. This allows you to consider all the significant parameters that characterize the railway operation, but at the same time requires a large amount of data, very detailed and a demanding and long work for the construction of the model. Close cooperation between researchers/service providers and railway infrastructure managers/purchaser is therefore essential to ensure that the results are properly reflected and to achieve the objectives of such a study.

3. SIMULATIONS

Simulation has been defined by Robinson (1994) as "a model that mimics reality" and by Gamerman and Lopes (2006) as "treatment of real problem through reproduction in an environment controlled by the "experimenter".

This computer simulation is undertaken by firstly creating a detailed scale map or plan of the infrastructure that includes all important features. The model then needs to know details about the physical characteristic of the trains that will be operated, for instance how fast they can go, acceleration and braking rates. The intended operational plan (timetable) must be provided, as the basis of the simulation.

Usually the computer model takes the decisions that the signaller takes in real life, although with some models the modeller can make decision as the simulation runs. If the timetable has accuracy, then it will be possible to see these on screen as the simulation runs or in the model outputs. The usual final stage of the simulation process is to add delays to the trains running in the model to properly "mimic reality" and to see what level of punctuality will be achieved when problems occur.

Simulation of railways timetables is used to test the impact on performance of changing range of variables, including:

- Different timetable options (more trains, different timetable structures);
- Different train performance characteristic (mechanical or human factors);
- Different infrastructure configurations;
- Changes to level and nature of delays/lateness.

Simulation can be based on macroscopic or microscopic models. Macro-simulation models use a simplified infrastructure model to reduce computational time and therefore allow simulation of larger network, while micro-simulation offers a description of infrastructure which reproduced the functionality of interlocking, safety and block system.

Also, simulation can be deterministic, where the results are entirely predictable, or stochastic where behaviour cannot be entirely predicted, though some statement may be made about how likely certain events are occur (Pidd, 2004).

3.1 Macroscopic Models

In general, macroscopic model are usually preferred for long term planning task or special routing problems. Macroscopic infrastructure model contains far fewer links and nodes in comparison with microscopic models and have a more abstract view of the infrastructure.

A node in macroscopic model represents a station or a junction in the network. Figure 69 illustrates the basic principle of a macroscopic railway network. The microscopic model of the element station, line and junction may include a couple of hundred microscopic links and nodes, depending on the complexity. The macroscopic model illustrated in Figure 69 contains only two nodes and four links (Radtke, 2014).

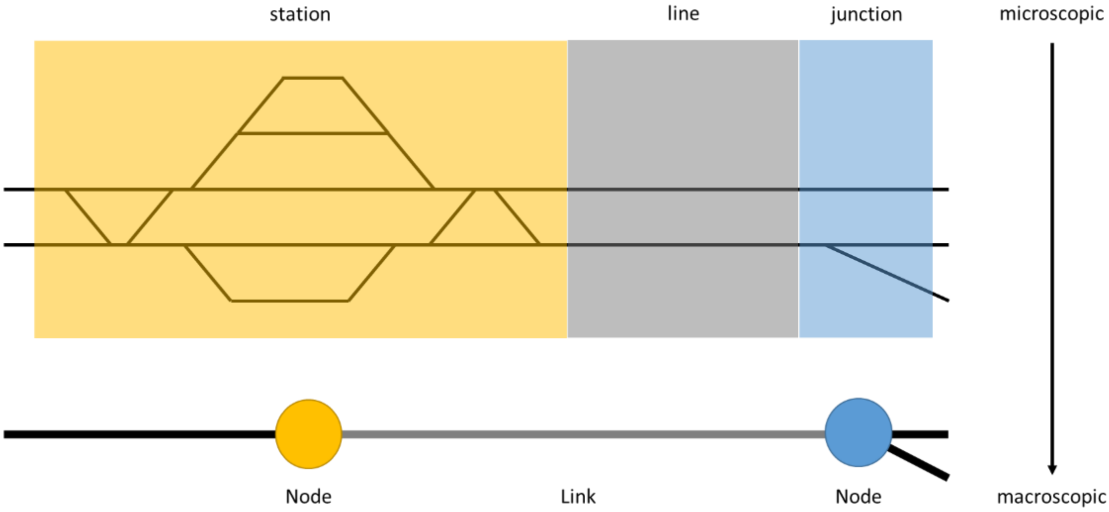


Figure 69 – Principle of macroscopic infrastructure modelling (Radtke, 2014).

3.2 Microscopic Models

According to Radtke (2014), a detailed node-link model can be used to model infrastructure in a so-called microscopic infrastructure model. This model combines tracks information such as speed, gradient or radius, with the signalling system (signal, block sections, release point) and some operational information like routes, alternative platforms, timing point and availability (time stamps).

A typical microscopic infrastructure model contains all tracks on lines and especially in stations. Figure 70 shows how the single links build a complete railway infrastructure. A block section, defined as a section protected by signals, can be formed by few links. The block section itself has a section starting and an ending node; both of these nodes belonging to existing individual links. Therefore, in the model, no additional nodes to describe the block are necessary.

Several block section can be abstracted to route section, which are subsequence of links guiding the trains through the station. They are provided by the interlocking system in the respective station.

The following list contains infrastructure attributes, sorted by importance for correct modelling of infrastructure for the calculation of running times, timetable construction and simulation:

- Length of a link;
- Gradient;
- Permissible speed (variation for different train types);
- Speed indicator and speed boards;
- Electrification and different electrical systems;
- Radius;
- Signalling system (ATC, LZB, ETCS, CBTC);
- Overlaps;
- Release contact and clearance location;
- Track circuits;

- Stop boards;
- Blocks and routes;
- Interlocking techniques;
- Exclusion of routes;
- Availability of infrastructure.

During recent years, the modelling of infrastructure has been extended to include the availability (time stamp) of infrastructure elements. These time stamps can be assigned to a single group or groups of nodes and links of a microscopic infrastructure model. It is evident that with these time stamps in the infrastructure model, it is straightforward to automatically generate matching model of microscopic infrastructure and the related timetable.

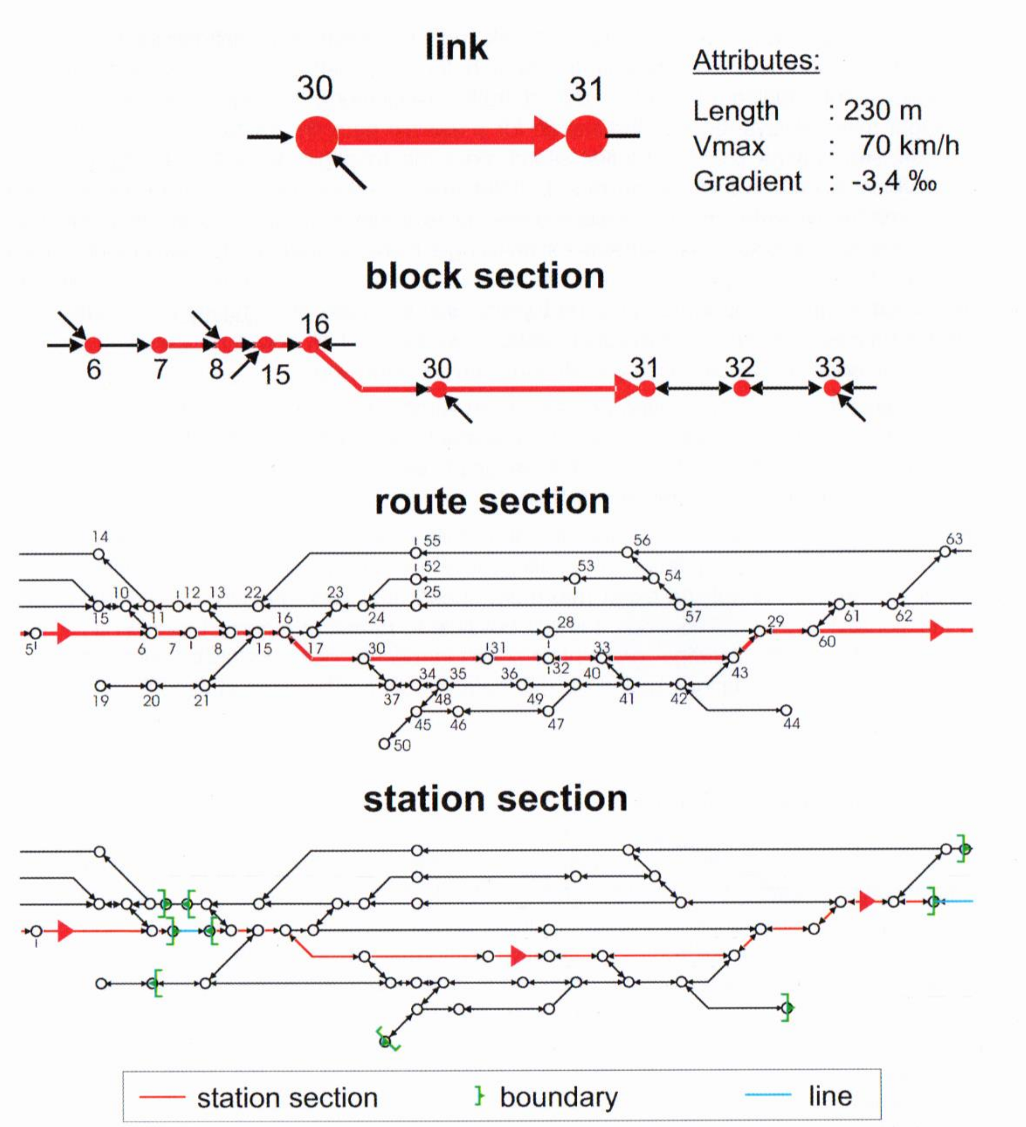


Figure 70 – Possible hierarchy in microscopic infrastructure models (Radtke, 2014).

3.3 Simulation methodology

According to Medeossi and de Fabris (2018) more and more operators own the microscopic model of their network, in several cases already prepared for simulation or even available to the public. However, if the model is not available or validated, or a different tool has to be used, it is necessary to carefully create or check the model before running the simulations. Figure 71 shows a typical workflow for a simulation study.

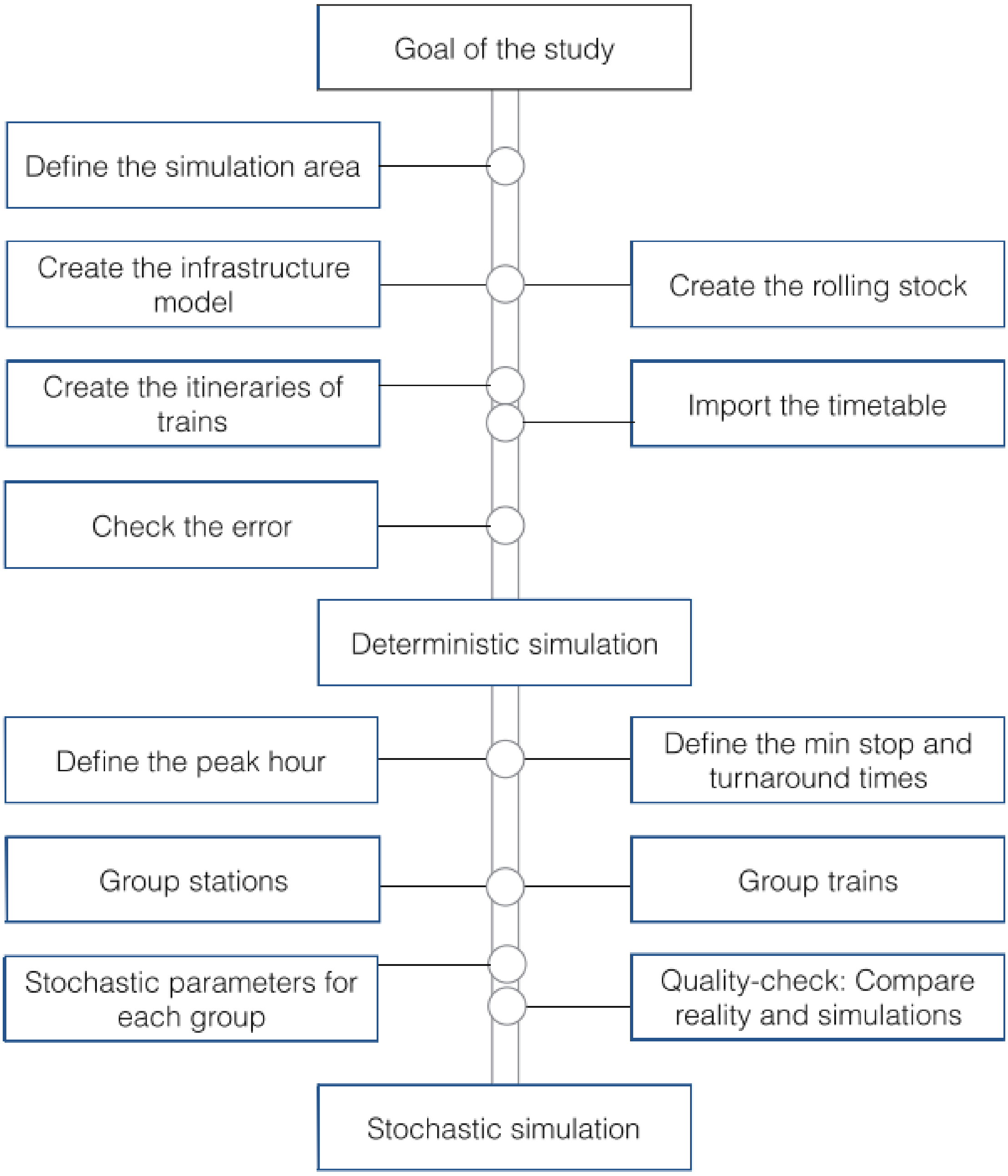


Figure 71 – Workflow of a simulation study (Medeossi and de Fabris, 2018).

3.3.1. Definition of the Simulation Area

This simple step appears very important, since choosing properly the simulation area allows including all elements that might have an impact on the outputs by at the same time limiting the time required to set up the model. No fixed criteria exist for the definition of the simulation area; however, there are a few "rules of thumbs":

- On the analysis line(s), consider the entire section between two important stations. This section is further extended to the next station when the first (or last) station is not a terminal one.
- On all lines diverging from the analysis line(s), consider the section to the first station. However, there is no need to simulate a branch line if its trains start/end at the junction station without any possible conflict with the analysis line(s). The same criteria apply to the other lines converging in the first and last station of the analysis line(s).
- At least the peak hour(s) should be simulated. To allow all planned trains at the beginning of the peak hour to be simulated, the simulation should start at least a complete running time on the line before the peak hour. Similarly, it is important to simulate at least 1 h after the end of the peak. This means that if a line has a running time of 2 h, and the peak hour is 7–9, the simulation time should be at least 5–10.
- Although normally less dense than the morning peak, the evening peak often shows higher delays. Thus, it appears important to simulate it, too.

3.3.2. Creation of the Infrastructure Model

To obtain the highest precision, a microscopic simulation model contains all characteristics of the real world that have an influence on train movements and dynamics. On the other hand, since simulation and especially infrastructure modeling are quite time-consuming, parameters which have a very limited influence could be ignored, in order to obtain results more efficiently. Regarding the line alignment, gradients have to be considered in detail if they are significant for train dynamics (normally >5‰). While in many running time calculation software mean gradients for longer sections are used, each gradient has to be modeled, especially when heavy freight trains are considered. The combination of low adhesive weight and wet rails reduces significantly freight train acceleration also if the ramp is just some hundred meters long. Tunnel position and kind (single or double-track, smooth or rough) are also to be inserted into the model, since their additional resistance significantly affects train resistance even at low speed ($V > 60\ km/h$). On heavy railway lines, a detailed description of curve radii can be strongly simplified considering mean curves on longer sections or adding the curve resistance to the gradients obtaining a total resistance due to line alignment.

The interlocking and block system must be modelled in high detail, comprehending the complete station layout with all track circuits and all signals with their respective aspects associated to the possible routes. Also, the way that routes are released has to be modelled, considering overlaps and release groups or other technical parameters, including release times or interdependencies among routes which are not simply identified when creating the track layout.

All of this information comes in different data format to the simulation engineer:

- Drawings (Figure 72);
- Tables (Figure 73);
- Database (Figure 74).

In the last years, usually the data are generated in database format following the RailML guideline. RailML is an open source data structure that has been developed to simplify the transfer of data between various railroad simulation and operations computer programs. It is a simple and efficient way to transfer data between computer programs used to model different aspects of railroad operations. Programs using the RailML language produce export files with the RailML structure; these files can then be used directly by other programs. The receiving program parses the incoming file to obtain only the data it needs, which allows many different programs to use the same data file (Nash et al., 2010).

Drawings are generally made using commercial or proprietary tools to draw the entire project; Figure 72 shows a drawing example of a station of the NCRTC Delhi-Meerut corridor project in India. All the elements position is reported using progressive kilometric values (m) while curves, gradient and speed information are generally reported as profiles in different colors above or below the tracks.

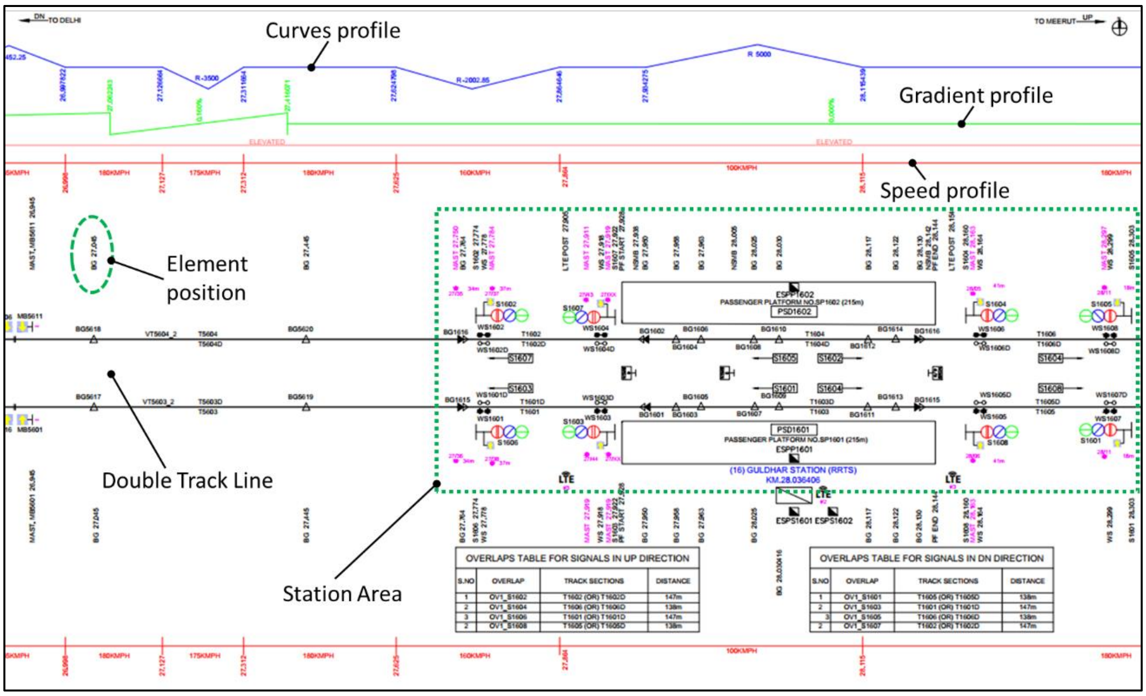


Figure 72 – Project drawing example.

Sometimes when the data are coming from track survey activities, the preferred format to collect all the information is the table. Figure 73 shows an example of results coming from track survey activities performed with LIDAR drones on the Faenza-Ravenna regional line in Italy. All the elements of the lines are identified with name, belonging station area and track, direction, kilometric position, geographical coordinates, and unique id.

Item	Name	Station	Track	Direction	KP (meter)	KP	Posicion_X	Posicion_Y	Posicion_Z	ID
Level Crossing	PL1	FNZ	5	FNZ	16300	16+300	252049,695	4908986,400	32,275	FNZ_LX_PL1
Level Crossing	PL1	FNZ	5	RVN	16290	16+290	252057,540	4908991,780	32,220	FNZ_LX_PL1
Rail Element	RE	FNZ	5		16225	16+225	252105,965	4909034,755	31,630	FNZ_RE_RE
Track Circuit Joint	70_69	FNZ	5		16215	16+215	252112,525	4909042,320	31,600	FNZ_TC_70_69
Balise	S22_a	FNZ	5		16194	16+194	252125,830	4909059,300	31,635	FNZ_BAL_S22_a
Signal	S22	FNZ	5	FNZ	16194	16+194	252128,410	4909057,340	31,930	FNZ_SIG_S22
Balise	S22_b	FNZ	5		16191	16+191	252127,540	4909061,705	31,625	FNZ_BAL_S22_b
Level Crossing	PL	FNZ	5	FNZ	16141	16+141	252153,575	4909103,690	31,320	FNZ_LX_PL
Signal	AvvS22	FNZ	5	FNZ	16141	16+141	252156,755	4909102,735	31,745	FNZ_SIG_AvvS22
Balise	AvvS22_a	FNZ	5		16133	16+133	252157,770	4909111,085	31,335	FNZ_BAL_AvvS22_a
Balise	AvvS22_b	FNZ	5		16130	16+130	252159,095	4909113,495	31,310	FNZ_BAL_AvvS22_b
Level Crossing	PL	FNZ	5	RVN	16116	16+116	252165,965	4909126,170	31,185	FNZ_LX_PL
SSP Signage	SSP	FNZ	5		16113	16+113	252164,750	4909130,045	31,150	FNZ_SSP_SSP
KP Marker	KPM	FNZ	5		16021	16+021	252214,250	4909207,825	31,015	FNZ_KPM_KPM

Figure 73 – Data Tables example.

Finally, the most recent format is showed in Figure 74, that is an XML-based language, this means that data files include both data and descriptions of the data that they contain. All XML derived languages use a very simple and flexible ASCII title format for their documents. In all cases the documents are hierarchical, they form of a tree layout, i.e. each document has a clear root element, from which navigation can start using the general document structure (common to all RailML documents) as a guide (Nash et al., 2010).

```xml
<?xml version="1.0" encoding="UTF-8"?>
<railml xmlns="http://www.railml.org/schemas/2016"
        xmlns:dc="http://purl.org/dc/elements/1.1/"
        xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
        xsi:schemaLocation="http://www.railml.org/schemas/2016 http://www.railml.org/schemas/2016/railML-2.3/schema/railML.xsd"
        version="2.3">

  <metadata>...</metadata>

  <infrastructure id="inf01">
    <tracks>
      <track id="tr01" name="track a02" type="secondaryTrack" mainDir="none">
        <trackTopology>
          <trackBegin pos="0" id="tr01_tb">
            <bufferStop id="tr01_bs01"/>
          </trackBegin>
          <trackEnd pos="500" id="tr01_te">
            <connection ref="tr03_c03" id="tr01_c01"/>
          </trackEnd>
          <crossSections>
            <crossSection id="tr01_cs01" name="Gleis 1" xml:lang="de" ocpRef="ocp02"
                          pos="300.0" absPos="300.0" type="station"/>
          </crossSections>
        </trackTopology>
        <trackElements>
          <platformEdges>
            <platformEdge id="tr01_pe01" name="Gleis 2" xml:lang="de"
                          pos="200" dir="up" absPos="200" side="left"
                          height="550" length="200"/>
          </platformEdges>
        </trackElements>
        <ocsElements>
          <signals>
            <signal id="tr01_si01" code="68N1"
                    pos="450" absPos="450" dir="up"
                    function="exit" type="main" ocpStationRef="ocp02">
              <etcs switchable="false" level_2="true"/>
            </signal>
          </signals>
          <trainDetectionElements>
            <trainDetector id="tr01_td01" pos="475" absPos="475"
                           axleCounting="true" directionDetection="true" medium="inductive"/>
          </trainDetectionElements>
        </ocsElements>
      </track>
      <track id="tr02" name="track a01" type="mainTrack" mainDir="none">
        <trackTopology>
```

Figure 74 – RailML Database example.

3.3.3. Characteristics of the Rolling Stock

Inserting the characteristics of rolling stock is significantly less time-consuming, since the required data set is limited, and includes: number, weight, length, position of locomotives and coaches, adhesion weight, tractive effort vs speed curve, and description of braking as function of Braking Weight Percentage (BWP) or as deceleration intervals. The same characteristics should be inserted for all ATP/ATC systems under which the train operates if they influence the braking behavior of drivers (such as the European Train Control System (ETCS) Level 2). The coefficients of resistance formulas are given as default in the simulation tools and can be customized only when the specific ones are available. This subject is extensively described by Wende (2003); the book also includes the coefficients to be used for several types of locomotives, trailers and multiple units considering both the Davis and Strahl & Southoff formulas. Besides these basic parameters, others have a significant influence but neither often available nor easy to estimate (adhesion, acceleration/deceleration delay, correct deceleration on gradients, coasting). Figure 75 shows an example of rolling stock data provided by the supplier.

	5 casse/bodies	7 casse/bodies
Quantità/ Quantity	68	48
Lunghezza [mm]/ Length [mm]	26450	35350
Larghezza [mm]/ Width [mm]	2400	2400
Altezza [mm]/ Height [mm]	3414	3414
Altezza pavimento dal p.d.f. [mm]/ Floor height from t.o.r. [mm]	350	350
Diametro ruote [mm]/ Wheel diameter [mm]	660	660
Scartamento [mm]/ Rail gauge [mm]	1445	1445
Passo carrello [mm]/ Bogie wheelbase [mm]	1700	1700
Rodiggio/ Wheel arrangement	Bo-2-Bo	Bo-2-2-Bo
Posti a sedere / Seating places	54	71
Posti in piedi (6 pass/m^2)/ Standing capacity (6 pass/m^2)	152	214
Posti riservati HK/ HK reserved area	1	1
Capacità totale/ Total capacity	206	285
Velocità massima [km/h]/ Max speed[km/h]	70	70
Potenza nominale [kW]/ Nominal power [kW]	4x106	4x106
Alimentazione [V cc]/ Voltage [V dc]	600	600

Figure 75 – Sirio Tram (Ansaldo Breda).

3.3.3.1 Characteristic of Braking Curve

In railway engineering, is common hear talk about "braking curve", often in connection with train performance, platform occupation times or signalling. A braking curve is used to calculate how long it will take a train to stop from a given speed. It can be used to determine both service and emergency braking distances and it can give braking times, if needed. Here we look briefly at the braking curve and what it means.

The braking curve is the shape formed on a speed/distance chart by a train as it slows down from normal speed to a stop. A typical curve is showed in Figure 76.

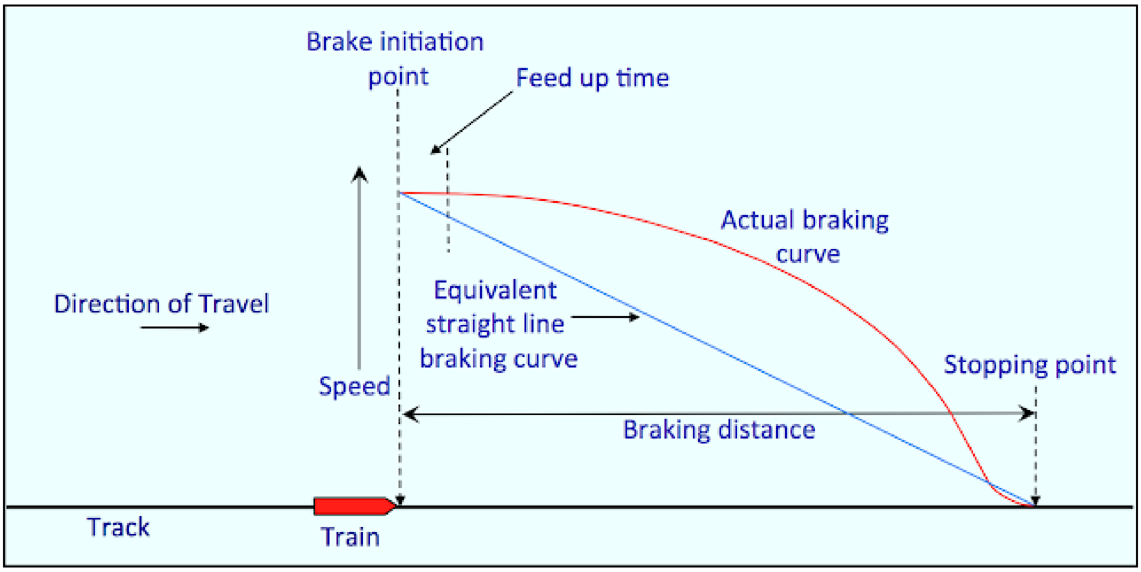


Figure 76 – Braking Curve.

The curve begins when the driver applies the brake. The brake system takes a few seconds to build up to the required braking rate (the "feed up" time) and then the train begins to slow down.

With a constant brake demand, as selected by the driver, the train slows down more rapidly as the speed falls. This is because, at the lower speed, the train has less energy to dispose of. If the brake is left on at the same level all through the stop, eventually the curve will get steeper and steeper until it ends vertically at the stop. If this is allowed to happen, the train will stop with a sharp bump. To prevent it, a skilled driver will ease off the brake as the speed falls and this will allow him to stop the train gently. The effect of this can be seen on the read curve (Figure 76) as it nears the stopping point.

Figure 76 also shows an "equivalent straight line" curve. This is a simple way of showing the stopping distance that we can expect a train to cover, given an equivalent deceleration rate. It can be used to calculate stopping distances for rough signalling calculations, for example, although today, computer programs make accurate and detailed calculations simple.

ETCS Braking Model

According to ERA (2020) the braking curve related to the speed decrease due to the emergency brake is called EBD (Emergency Brake Deceleration) curve. Each specific target location (corresponding either to a speed reduction or to a stop location) given by the ETCS trackside is used by the ETCS on-board to compute a fully deterministic EBD curve, which depends on both train and track characteristics. The shape of the EBD curve, for a given piece of track, will therefore vary according to the type of rolling stock: the less the emergency braking system is efficient, the flatter the EBD curve will be.

From the EBD and the measured (i.e. estimated) train speed, the ETCS computer calculates in real time, several times per second, the distance necessary to stop (or decelerate) the train from the time the ETCS on-board would command the intervention of the emergency brake. To do so, it is necessary to make worst case assumptions:

- on the train dynamics during the lapse of time before the full emergency brake effort is developed (emergency brake build up time), by taking into account the measured acceleration;
- on the actual speed of the train, by taking into account the inaccuracy of the speed measurement.

This distance determines a location called the EBI (Emergency Brake Intervention) supervision limit, i.e. the point beyond which ETCS will bypass the human in charge (Figure 77).

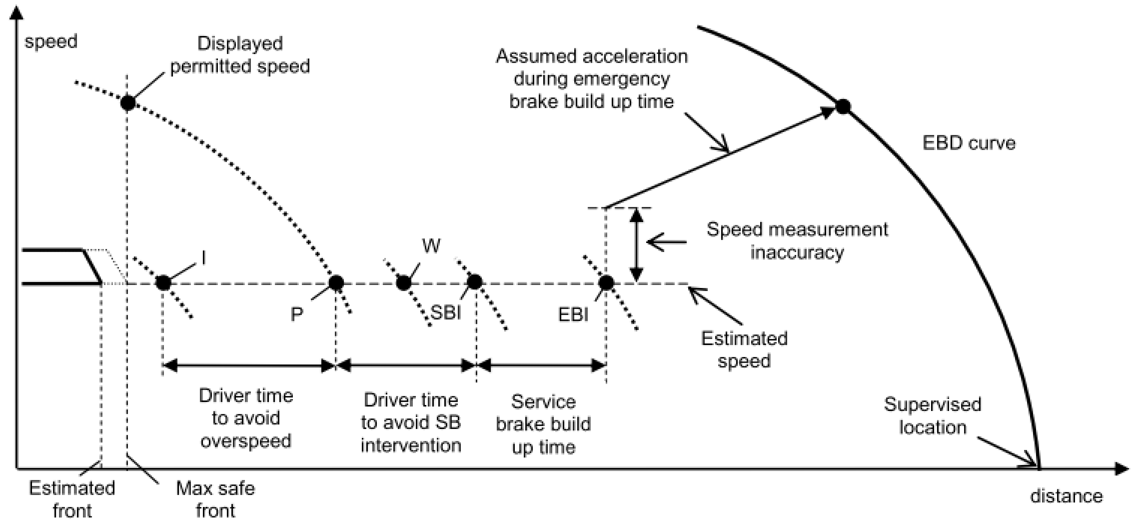


Figure 77 – Overview of the EBD braking curve and its related supervision limits (ERA, 2020).

The EBD curve and the resulting EBI supervision limit are the elements of the ETCS speed and distance monitoring function, which materialize the so-called ETCS parachute.

In addition to the parachute functionality, ETCS provides the driver with advance information related to braking. Its purpose is to assist the driver and to allow him to drive comfortably, by maintaining the speed of the train within the appropriate limits.

Therefore, the ETCS on-board calculates in real time other supervision limits: Indication (I), Permitted speed (P), Warning (W) and Service Brake Intervention (SBI) (only if the ETCS on-board is designed to command itself the service brake). They consist of locations that, when crossed by the train, will trigger some information to be given to the driver through appropriate graphics, colors and sounds on the Driver Machine Interface (see ERA (2016) for details).

These locations are defined in order to:

- For the "I" supervision limit: leave the driver enough time to act on the service brake so that the train does not overpass the Permitted speed when this latter will start to decrease. Without the indication it would not be possible for the driver to perform a transition from ceiling speed supervision to the target speed supervision without overpassing the Permitted speed (Figure 78);
- For the "P" supervision limit: in case of overspeed, to leave the driver an additional time to act on the service brake so that the train will not overpass the point beyond which ETCS will trigger the command of the brakes;
- For the "W" supervision limit, to give an additional audible warning after the Permitted speed has been overpassed;
- For the "SBI" supervision limit, to take into account the service brake build up time so that the EBI supervision limit is not reached after the command by ETCS of the full service brake effort. The SBI supervision limit is facultative and can be implemented on-board the train in order to avoid too frequent emergency braking, which can be damaging for both the rolling stock and the track.

Moreover, the ETCS computer has to continuously display the Permitted speed to the driver.

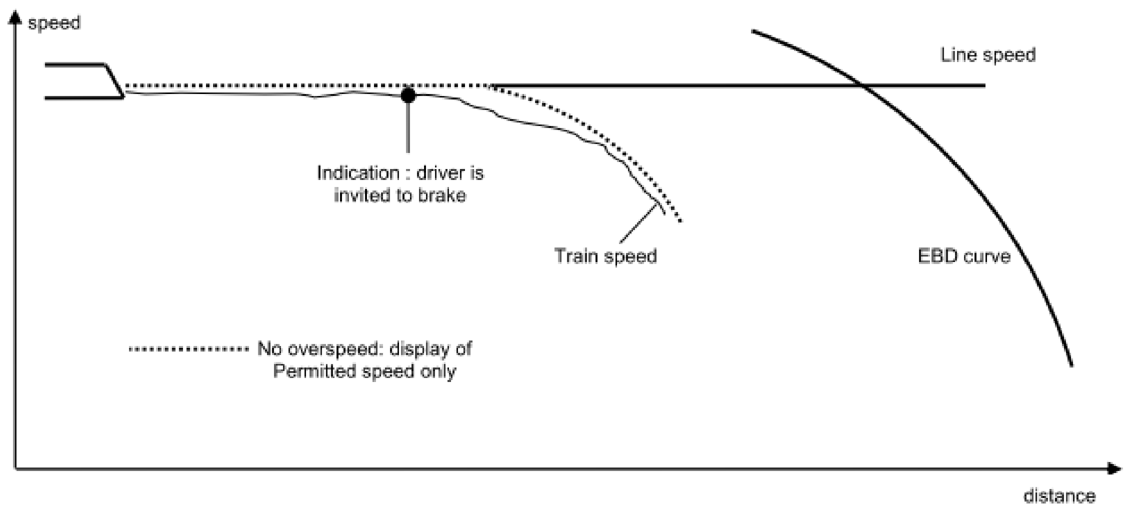


Figure 78 – Indication to the driver before the Permitted speed starts to decrease (ERA, 2020).

The main purpose of the ETCS display is to invite the driver to keep the train speed as close as possible to the Permitted speed (Figure 78). However, the driver might eventually fail to do it and should be the case, ETCS offers him/her a second chance to brake the train, before it takes over the responsibility to command the brakes. This is materialized by a more visible and audible warning and an additional time left to act on the service brake in order to avoid the ETCS intervention, i.e. to avoid that the EBI or the SBI supervision limit (depending on whether the ETCS command on the service brake is implemented) is reached (Figure 79).

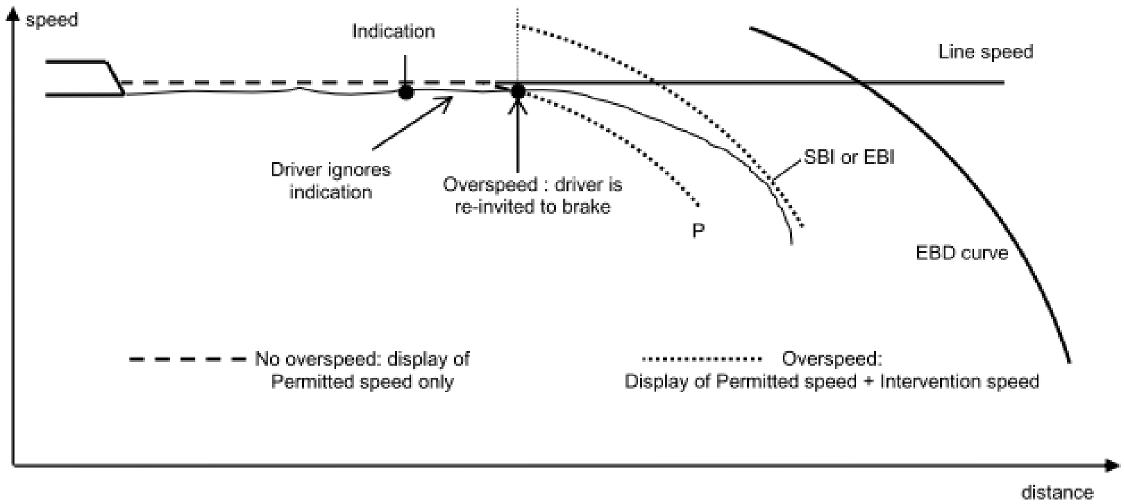


Figure 79 – Overspeed, driver is left additional time to avoid the ETCS intervention (ERA, 2020).

Numerous input parameters are necessary to feed the ETCS braking curve algorithms and to allow the ETCS on-board computer to perform in real time its supervision and advisory functions; they can be classified in four categories:

- Physical parameters, which results from the real time measurements by the ETCS on-board equipment: instantaneous position, speed and acceleration;
- ETCS fixed values, which are invariant within a given ETCS baseline. They mostly relate to the ergonomics of the braking curve model itself (e.g. driver reaction times, see Figure 77);
- ETCS trackside data. It consists of signalling data (target speed/locations), infrastructure data (downhill/uphill slopes) and also some of the so called ETCS National Values, which can affect the ETCS braking curve model. These parameters are under the strict control of the Infrastructure Manager and are transmitted through the relevant ETCS transmission medium (balise, loop or radio).
- On-board parameters, which are captured before the Start of mission as part of the so called ETCS Train Data. They mostly relate to the rolling stock braking system itself.

Amongst the two last categories of input parameters, a particular care must be paid to the ones contributing to the computation of the EBD curve. Indeed, the responsibility of the ETCS being solely to command the emergency brake in due time, the overall safety of a railway system highly relies on the fact that the trains will be effectively braked according to the predicted EBD.

Therefore, the EBD curve must fulfil the relevant safety, which is required for the operation of ETCS trains on a given infrastructure. This is materialized in the ETCS braking curve model by the so called “correction factors” (see Rail Industry Standard (2017).

CBTC Braking Model

Figure 80 is a typical safe braking model recommended by IEEE 1474.1 (IEEE Std., 2004). In the figure, the emergency brake curve is the worst-case, open-loop, speed/distance curve that a train will follow once the ATP has initiated an emergency brake application. This emergency brake curve must always be less than or equal to the safe speed curve, where safe speed is defined as the speed above which a critical hazard (derailment or collision) could occur. In this model, safety factors are accounted for in the emergency brake curve, train position uncertainties, and other additional measurement tolerances incorporated in the CBTC system design, and there is no requirement to add additional safety margins. The ATP over speed detection curve is the speed-distance curve that the ATP subsystem uses to immediately initiate an emergency brake application, if the ATP subsystem detects that the measured speed exceeds this curve at the measured train location. When the ATP subsystem has initiated an emergency brake application, the ATP subsystem is no longer in the control loop, and the train will emergency brake at or below the emergency brake curve. The emergency brake curve includes an initial propulsion runaway period, until propulsion is disabled. The ATP profile curve is the speed-distance curve that is an ATP over speed allowance below the ATP over speed detection curve. The ATP profile is the base curve used by the ATP subsystem.

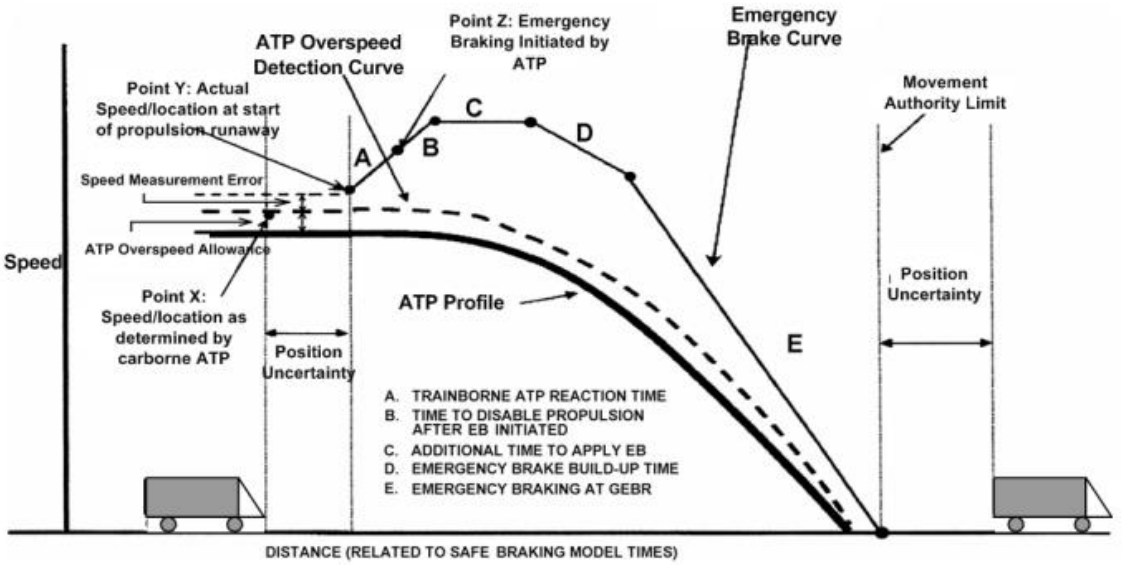


Figure 80 – Typical safe braking model (IEEE Std., 2004).

Figure 81 is the Safe Braking Model used in the Simulator. The model defines the principle, assumptions, process, and parameters of Safety Distance calculation. All these parameters are imported from the configurable database and can be adjusted to meet the particular project requirements. This Safe Braking Model is an application of the typical safe braking model recommended by IEEE 1474.1 to calculate the Braking Distance, Safe Braking Distance, and the Safety Distance. Braking Distance is the distance to the normal stop point with the normal brake rate. Safety Braking Distance is the braking distance in the worst case. The relationship is:

$$SafetyBrakeDistance = BrakeDist + SafetyDist$$

$$SafetyTrainSeparation = SafeBrakeDist + PositionUncertain$$

In the simulator, ATO curve is N seconds (it is configurable) afterward the ATP enforcement curve. System will always try to drive the train along with the ATO profile in the simulation.

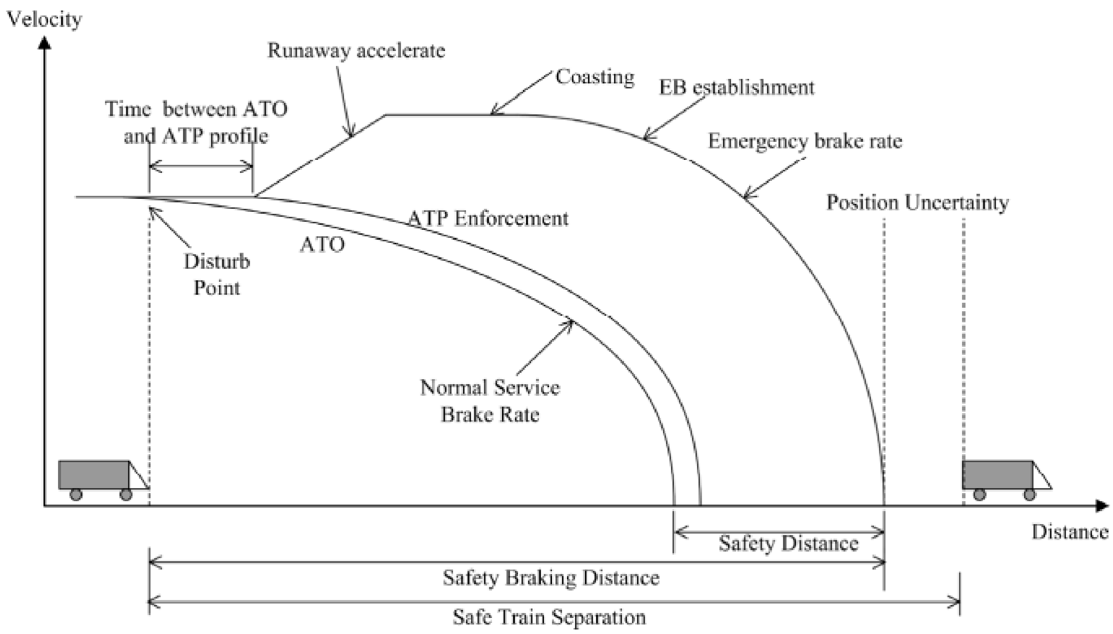


Figure 81 – Safe braking model and the train separation.

3.3.4. Creation of Trains Itinerary

A train path or itinerary describes the usage of the infrastructure for a train movement on a track and in time. As a basic requirement, a timetable must not contain any schedule conflict between train path. It is not sufficient to describe a train path just its time-distance graph. There must also be a model to describe a train path "time channel" a train movement produced around its time-distance line. A model that describe that time channel very exactly is the so-called blocking time model (Pachl, 2014).

Starting from a defined or an expected timetable it is necessary define in detail which are the train movement allocated to specific tracks at well-defined location of the infrastructure; those locations are forks (Figure 82), depot (Figure 83), looping tracks (Figure 84) and terminal stations (Figure 85) where the higher number of track could generate different combination of movements.

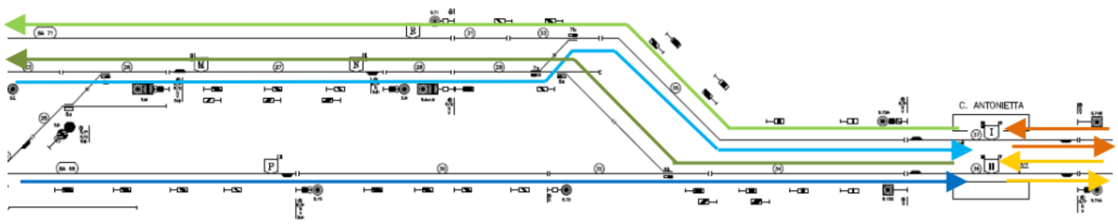


Figure 82 – Trains Movement at C.Antonietta fork on Metro Milan Line 2.

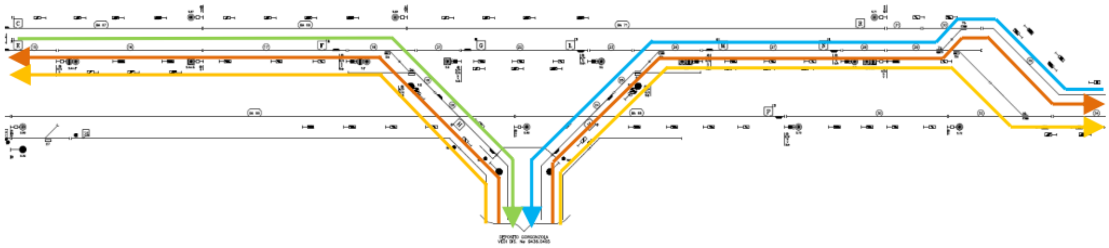


Figure 83 – Trains Movement at Gorgonzola Depot on Metro Milan Line 2.

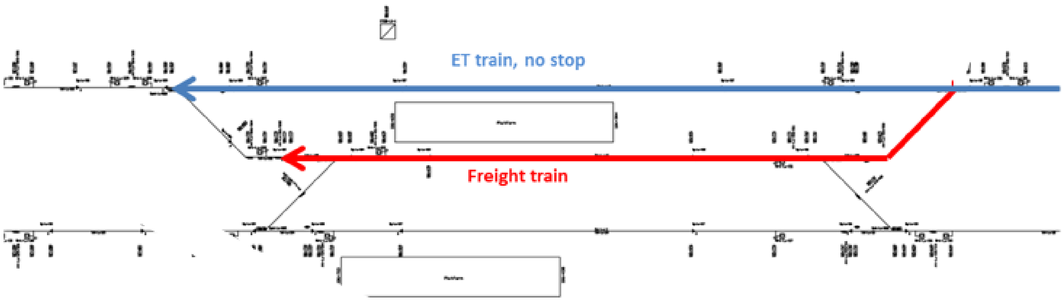


Figure 84 – Trains Movement at Looping Track in Lundby Station on RollOut 7.

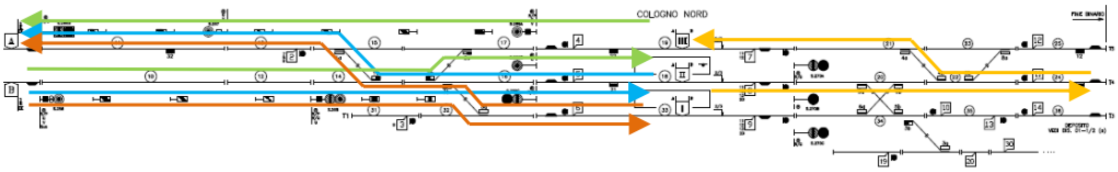


Figure 85 – Trains Movement at Cologno Nord terminal station on Metro Milan Line 2.

From these train movements it is possible to isolate single pairs of movements and catalogue them in specific scenarios from which to derive the operational and technical headway values.

The list of scenarios is reported below:

- Case A: the headway is related along the entire line section, following trains of the same type stopping at different platforms (Figure 86). The slitting point, that is the latest point in common between the two-train path, is suggested location to measure the headway;
- Case B: the headway is related along the entire line section, a stopping train following a through train (Figure 87). The defined headway is measured along the line until the first stopping location of the second train; all the next values measured along the line will be defined as derived headway where the value is the sum of the defined headway and the given dwell time of the stopping location.
- Case C: the headway is defined at the splitting point, where a freight train is caught up by a through train in front of a passing loop (Figure 88);

- Case D: the headway is related along the entire line section, following trains stopping at the same platform (Figure 89);
- Case E: single-track: alternating train run direction (Figure 90);
- Case F: the headway is related to the junction in open line (Figure 91).

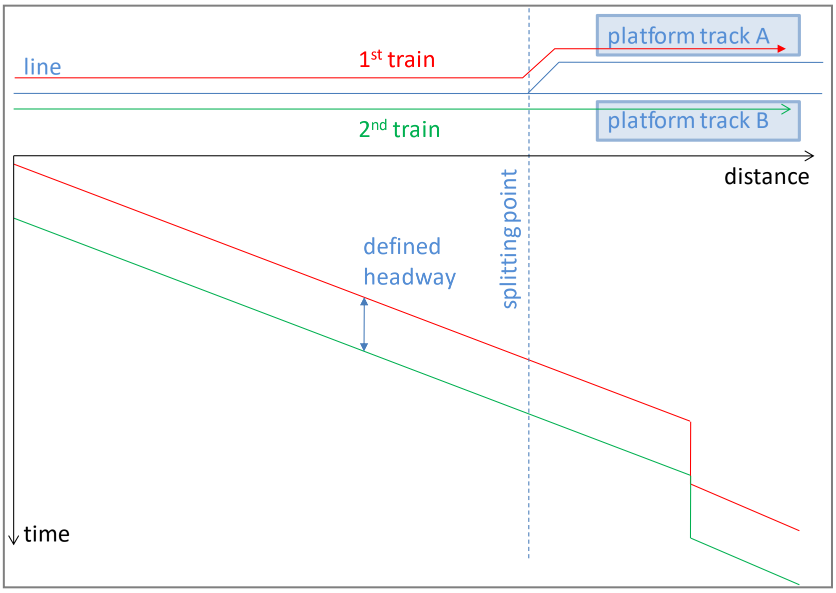


Figure 86 – Case A Headway.

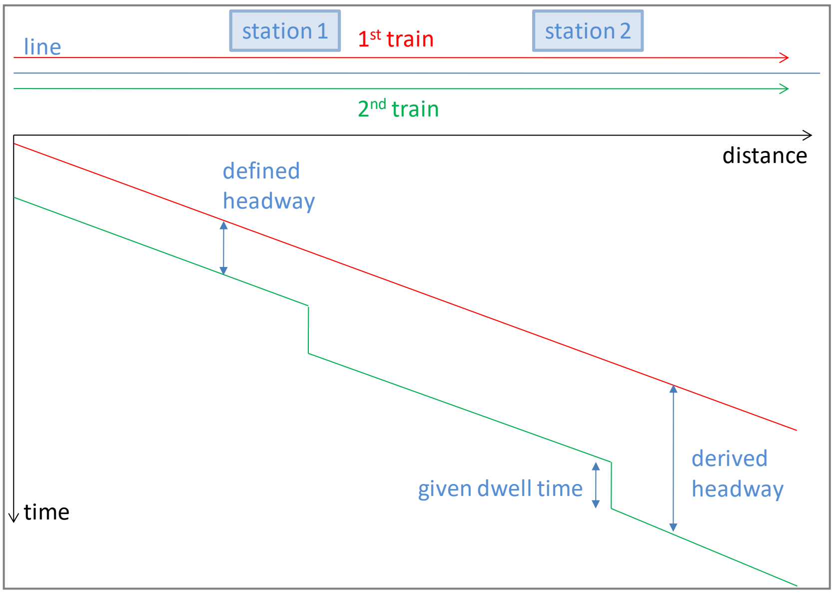


Figure 87 – Case B Headway.

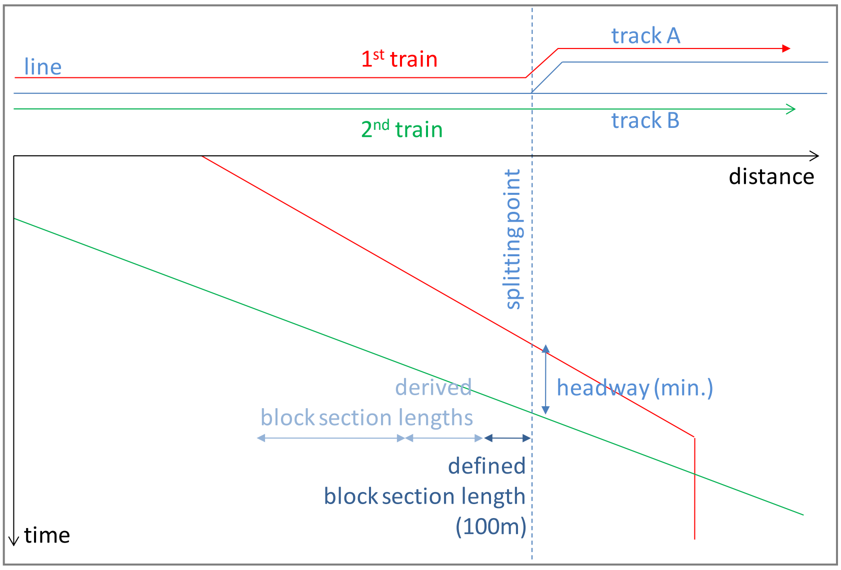


Figure 88 – Case C Headway.

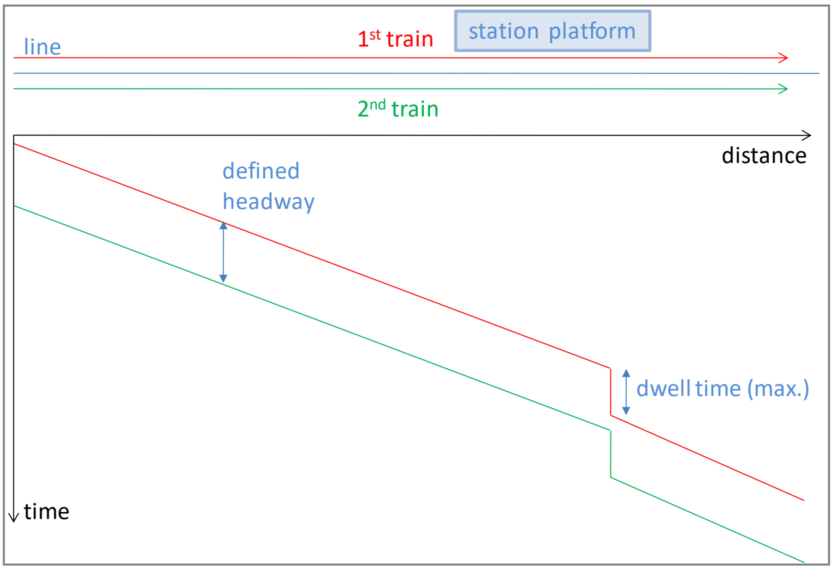


Figure 89 – Case D Headway.

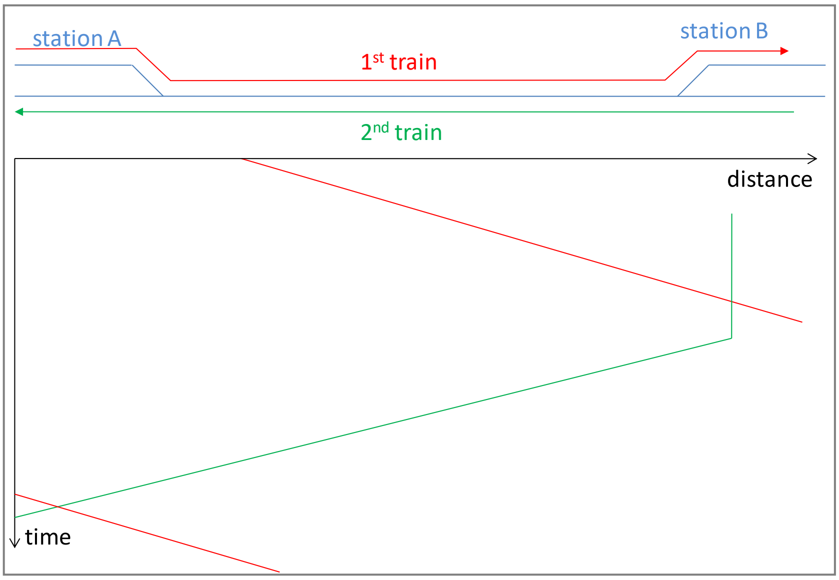


Figure 90 – Case E Headway.

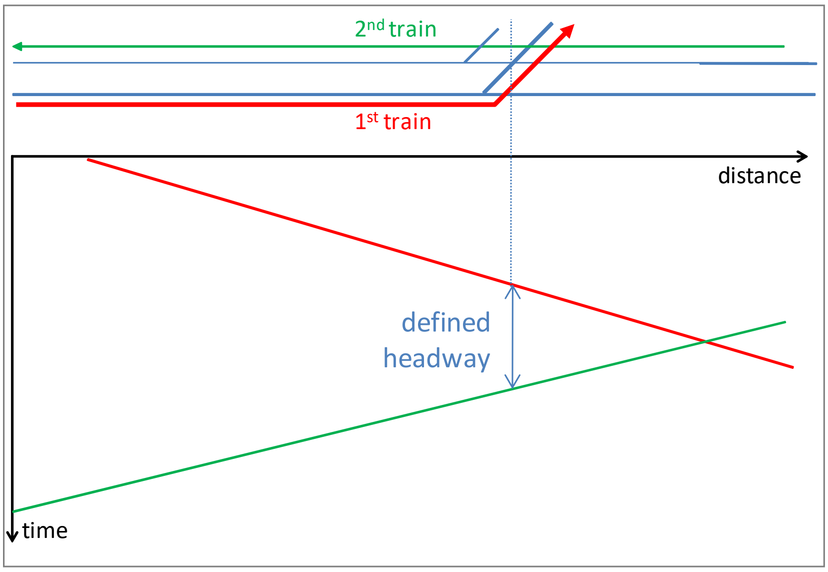


Figure 91 – Case F Headway.

3.3.5. Import of Timetable

The traditional form of timetable representation is the one in matrix form where the departure and arrival times for each train are indicated in correspondence of the stops from this carried out (Figure 92).

54 **København - Næstved - Nykøbing F - Rødby Færge**
Gyldig 9. december 2018 - 23. marts 2019 DSB

Køredage	①-⑤	①-⑤	①-⑤	①-⑤ 1			①-⑤			
Østerport						6.00	6.23	7.00	7.23	8.00
Nørreport						6.03	6.26	7.03	7.26	8.03
København H		5.05	5.35			6.09	6.35	7.09	7.35	8.09
Valby		5.10	|			6.14	|	7.14	|	8.14
Høje Taastrup		5.20	5.49			6.24	6.49	7.24	7.49	8.24
Roskilde ○		5.28	5.58			6.32	6.58	7.32	7.58	8.32
Roskilde		5.29	5.59			6.33	6.59	7.33	7.59	8.33
Viby Sjælland		|	|			|	|	|	|	|
Borup		|	|			|	|	|	|	|
Ringsted ○		5.46	|			6.50	7.14	7.50	|	8.50
Ringsted		5.47	|			6.51	7.15	7.51	|	8.51
Glumsø		5.55	|			7.00	7.22	8.00	|	9.00
Næstved		6.06	6.30	7.00		7.10	7.32	8.10	8.30	9.10
Lundby		6.16	|	7.09		7.20	|	8.20	|	9.20
Vordingborg ○		6.25	6.47	7.18		7.30	7.48	8.30	8.47	9.30
Vordingborg		6.26	6.48	7.19		7.31	7.50	8.31	8.49	9.31
Nørre Alslev		6.42	|	7.32		7.43	|	8.43	|	9.43
Eskilstrup		6.51	|	7.37		7.49	|	8.49	|	9.49
Nykøbing F ○		7.03	7.17	7.45		7.59	8.15	8.59	9.14	9.59
Nykøbing F	6.45				7.53				9.16	
Rødby Færge ○	7.07				8.15				9.37	
Rødby Færge									2 9.38	
Oldenburg (Holst) ○									11.05	
Lübeck Hbf ○									11.37	
Hamburg Hbf ○									2 12.16	
Tognummer	4217	2217	1221	4221	4221	2221	4225	2225	EC 38 1229 ◆	2229

Figure 92 – Timetable of Kobenhavn – Rodby Faerge line in Denmark.

3.3.6. Running and Checking the Correctness of a Simulation Model

The correctness of a model must be verified accurately before running the complete simulation. The model can be verified simply based on experience by checking a few aspects of the simulation output of the existing timetable (if available) and lead to a validation report. It is suggested to start with a "single-train" simulations, where only one train is considered each time. This simulation is used to verify the following things:

- Verify the speed-distance diagrams of at least one example train per line. Evaluate If the distances and speed limits are correct, if the trains reach their maximum speed and if acceleration and deceleration parameters is similar to their expected rates;
- Run a complete simulation and watch the animation to evaluate if all trains use the correct itinerary, if the stopping positions are correct, if the entrance orders in junction stations are correct and if the routes released and blocked are as expected.

3.3.7. Deterministic Simulation

According to Watson and Medeossi (2014), at this stage it is possible to run "nominal" or "deterministic" timetables simulation. The nominal timetable simulator can be used to highlight direct conflicts between trains (which can occur as a result of inaccuracies or lack of precision in the scheduled timetable) and their consequences. In this mode, the simulator is run without adding delays. Conflicts that will be identified include headway conflicts, double occupation or crossing conflicts, as well as any incidence where a train driver will see and react to a restrictive aspects signal.

Running a “nominal” simulation is also an essential step in ensuring that the model is setup correctly comparing the trains running in the simulation with the timetables and, if possible, real train running data to find and resolve model set up errors.

Once errors have been resolved, the nominal timetable simulation is suitable for:

- Running time analyses, to check values used currently (although comparison with real data is most important) and provide new figures for future infrastructure and rolling stock;
- Headway and junction margin calculations;
- Conflict detection as part of the timetable construction process;
- Capacity analyses (some model include calculation of UIC 406 capacity utilization indices as part of their standard product);
- Generating timetables from scratch (although unless the problem is very simple is usually better use other approaches);
- Searching for additional path in an existing timetable (for instance for short notice freight services);
- Modelling and testing of current and future timetable for conflicts;
- Certain types of what-if-analysis, for example checking whether the timetable can still be operated in full without incurring delays when track possessions are planned.

3.3.8. Initial Delay

The initial delay is one of the parameters involved in the calculation on the “stochastic” simulation; it represents the distribution of departures for each train from its first station within the simulation area. After this first departure, trains move along their route according to their running time distribution and stop at stations for a variable time according to the stop time distributions. If these data are estimated accurately, and the simulation model correctly represents the interactions among trains, the departure distribution at each following station is quite like the real ones.

When defining the expected initial delays for a new timetable based on the past data collected at each station, it is important to exclude all major perturbations and all secondary delays (delays due to traffic conflicts). In literature there are some studies focused on this topic; Yuan and Hansen (2007) use interlocking data and sophisticated mathematical models to identify primary and secondary delays. However, these methods require using blocking times collected at block sections of the network, which, currently, are not stored in most countries.

If such accurate methods for filtering out secondary delays cannot be used, a rough filtering process developed by Medeossi et al. (2011) can be deployed with the goal of defining a realistic initial delay distribution (removing the effects of conflicts with arriving trains) rather than analyzing conflicts in detail based on track occupation.

3.3.9. Dwell Times

According to Medeossi and de Fabris (2018) a precise estimation of stop times appears normally more important than that of initial delays, especially if entire train courses are simulated. At the same time, it appears less important on freight lines, as well as on single-track lines, where the stopping times are more influenced by the crossings than by the passengers boarding and alighting. Stop time variability includes two phenomena affecting trains at stations: departure imprecision and dwell time variability. Departure imprecision occurs if a train, which arrived early or punctually at a station, does not depart punctually although all passengers are already on board. Departure imprecision is generally short for regional trains, with mean values between 10 and 20 s, while it is often more than 30 s for long-distance trains. The dwell time depends on the number of passengers boarding or alighting, the presence of late-arriving passengers and on the physical layout of the trainset. The two phenomena must be considered separately to model stop time variability correctly. This process is complicated because, often, the only data available are arrival and departure times. A detailed stop time calculation model was proposed by Longo and Medeossi (2012), based on a previous work by Buchmueller et al. (2008). The model can also be used to estimate the effect of an increased demand or different rolling stock, but it requires a set of measures to be collected manually at some stations. However, in most studies it is quite demanding to collect those inputs, so a simpler method was developed by Medeossi et al. (2011).

Although this separation appears extremely easy, it is not supported by most commercial simulation tools. In such cases the user is forced to use only one of the two distributions. A quick analysis of real world data allows deciding which to use: when the variability of dwell times is high, the distribution of dwell times should be used, but if the number of passengers boarding and alighting is limited a fixed dwell time plus a distribution of departure times appears more accurate. It must be noticed that this way of considering the dwell times appears not correct for services with frequencies higher than 10 min, in which passengers arrive at stations independently from the expected train departure time.

3.3.10. Train Performances

The estimation of the variability of running times to be used in simulations is more complex. It is modeled through one or more performance parameters in the simulation tools. The performance parameters represent the way drivers drive during one or more phases of motion (braking, acceleration, etc.): they are inserted in the motion equation as factors that reduce the maximum performances of the train. During acceleration, the performance parameter reduces the tractive effort of the locomotive; during cruising it reduces the speed limit while during braking it reduces the deceleration. The estimation of performance parameters is by far more complex than that of the initial delay and stop time distribution. It requires to find the performance parameter that splits the motion into five or six phases and reproduces the measured running time at best. A method for the estimation of the set performance parameters was presented by Medeossi et al. (2011) and is based on train event recorder or GPS log files; more recently Bešinović et al. (2013) presented a method to use track circuit logs instead.

While these algorithms lead to very accurate results, they cannot be used for simulations, because commercial software only uses one performance parameter for the entire motion. Since the best parameter is the one that leads to the same running time between two stations, it could be obtained by simply estimating the distribution that fits at best the running times as recorded in the train describer data. Train performance parameters are normally between 90 and 98%, with the lower end more common on stopping trains and values quite close to the upper limit for high-speed services.

3.3.11. Incidents

The simulation allows users to examine the impact of disturbances (called "incident") in the infrastructure, rolling stock and schedule systems. Incidents can either be operational failures or operational problems (which allow operations to continue but at a reduced speed or capacity). Examples of the first type of incident include signal failures and broken tracks; examples of the second include slow orders or unplanned train delays. Incidents can be combined into sets of incidents that can be applied during the simulation. Given the relative detail required to model them, incidents are normally inserted to reproduce specific disturbances and not the normal stochastic behavior; an exception is represented by a few specific cases in which they are used to represent the systematic interaction of operations with external elements, such as a traffic light on tram operations. Since the set of possible (real) incidents is extremely wide, and the frequency of each extremely low, it is not possible to draw general criteria to define the most significant incidents to be tested on a railway line. Moreover, since most commercial simulation tools are not able to automatically cancel partial or complete train courses, the impact of serious breakdowns can only be simulated by manually and gradually modifying the timetable to reproduce these decisions. The possibility to control dispatching in simulations using an ad-hoc external tool, as possible, for instance in OpenTrack, opens a broad spectrum of applications, since it is possible (at least in theory) to simulate the correct impact of a much broader set of incidents with very limited manual interventions.

3.3.12. Evaluating the Quality of a Simulation Model

Evaluating the quality of the model means comparing it with the reality to obtain a quantitative measure of the differences between simulation and reality. Since the reality is always influenced by stochastic factors, this comparison should be made comparing the real collected data with the stochastic simulation of the same timetable. Obviously, simulations will use the initial delays, as input, dwell times and train performances taken from the same set of collected data.

Once a model is checked for its errors in the deterministic simulation, it must be briefly checked for errors again when running a stochastic one, at least considering a couple of iterations. The goal of this check is to understand whether delays occur and were propagated correctly. In fact, there might be errors in the distributions of dwell times, but also in the settings of the signalling system, whose effect is negligible under deterministic conditions. This check is performed on the graphic timetable, simply pointing out the conflicts and trying to investigate their origin and consequences.

3.3.13. Stochastic Simulation

Whilst nominal simulation has their uses, most timetable simulation studies require as an output a prediction of the delay and lateness, which is achieved using stochastic simulation. In stochastic simulation random di delays are inserted, and the simulation repeated several times to obtain statistically relevant outputs.

The most useful outputs of stochastic simulation are the delay statistics, which give planners an estimation of the capability of the system to recover the delays or longer dwell times.

The easiest way of inserting these variables is to use the functions already integrated in the simulation tools, in which is possible to select the mean initial delays and the variability of dwell times for each train category. The tool will then automatically choose the delay and dwell times to be assigned to each train and station based on an integrated distribution. The use of these predefined function allows them to be defined quickly, much reducing the time required before starting a set of simulation. Moreover, since no real operational data is required, it is possible to test the robustness on lines that are not yet in operation.

The stochastic simulation is suitable for any test in which it is possible to measure the robustness of operations under realistic conditions:

- Testing of current and future timetables for robustness (and systematic conflicts);
- Capacity analysis in which the robustness corresponding to a certain level of saturation must be considered explicitly;
- Certain types of what-if-analysis, for example checking whether the timetable can still be operated in full without incurring delays when possessions are planned.

4. OPENTRACK RAILWAY SIMULATOR

This chapter will describe the structure of the software used for the simulations: the OpenTrack software.

OpenTrack is a user-friendly railroad network simulation program developed at the Swiss Federal Institute of Technology's Institute for Transportation Planning and Systems (ETH IVT) (Nash and Huerlimann, 2004). It is a microscopic model that simulates rail system operations based on user defined train, infrastructure, and timetable databases. OpenTrack functions as a railroad laboratory, by allowing users to define incidents and take infrastructure out of service to evaluate alternative scenarios. The program uses a mixed discrete/continuous simulation process that calculates both the continuous solution of train motion equations and the discrete processes of signal box states and delay distributions. It generates a wide variety of data that can be easily presented in many formats including graphs (e.g. time-space diagrams), tables, and images (Figure 93). OpenTrack's main uses have been to evaluate and test infrastructure plans and operating schedules to optimize network and timetable design.

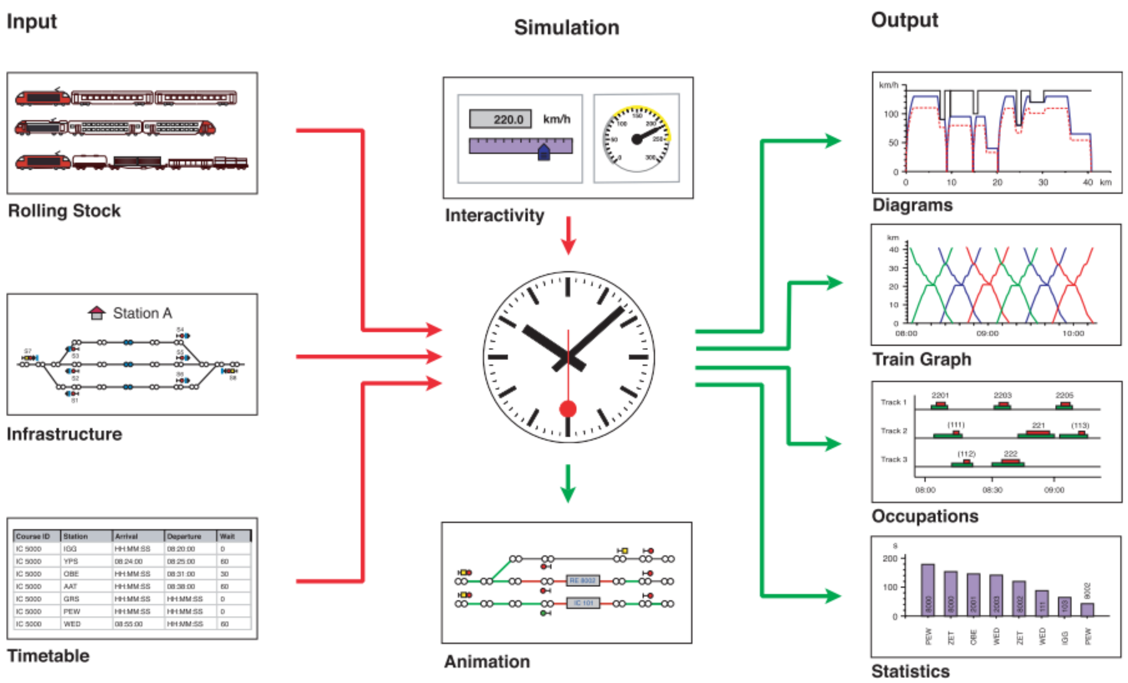


Figure 93 – Main elements of OpenTrack (Huerlimann and Nash, 2019).

4.1 Tool Structure

As described in Figure 93, OpenTrack is structured into three macro groups:

- input data, distinguishing between rolling stock, infrastructure and hourly table data;
- the simulation;
- the output data.

4.1.1. Input Data

4.1.1.1 Engines and Trains

Rolling stock is defined by the description of locomotives and wagons and their combination to build the train.

The locomotive data is contained in a database called Depot. This database describes all possible types of locomotives in terms of technical specifications, such as traction force diagram, weight, length, and adhesion values. The user has the option to enter new data into the database to use a specific type of locomotive or can use one of the predefined locomotives by the program.

In contrast, wagon data are not defined in Opentrack since only full length and weight are required for the simulation.

As a result, the program builds trains, coupling the selected locomotive within the database with the number of wagons entered.

4.1.1.2 Infrastructure Layout

The infrastructure layout shall include the physical description of the infrastructure on which the simulation will be conducted, in terms of rail line, signalling system and stations. It is represented through a graph, consisting of vertices and arcs.

All geometrical characteristics of the track are described as link attributes, while vertices represent stations, light signals, balises, switches and other components. In this module it is also managed the creation and visualization of block sections, paths and itineraries; for the station vertices it is also possible to specify the type of station apparatus (interlocking) with the relative system time parameters (shunting switches, route formation, etc.). It is also possible to define several signalling systems: from multi-aspect to ETCS.

Figure 94 shows an example of the worksheet in Opentrack and how the infrastructure is represented.

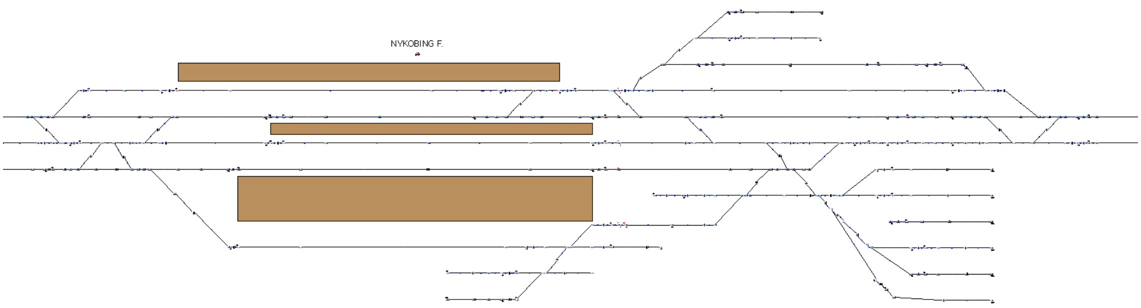


Figure 94 – Infrastructure Layout of Nykøbing Falster Station in Opentrack.

4.1.1.3 Timetable

The timetable is defined by the information on the operating time with which the movements of trains take place. They include scheduled departure and arrival times, minimum times for stops, information on connections.

The Opentrack software manages the timetable data through a "timetable database".

4.1.1.4 Train Movements

Opentrack simulates train movements along the rail network. To describe the infrastructure and the movements of trains can be used different terminologies, which often change depending on the type of simulation program used.

4.1.2. Simulation

The objective of the simulation with the software Opentrack is obtain combine all the input data defined by the user in order to obtain a correct model in output.

As mentioned in the beginning of paragraph 4, Opentrack uses both continuous and discrete models to represent railway activity. Train movement is modelled by combining the solution of the differential equation of motion (continuous) with the information given by the signalling system (discrete).

The differential equation of motion calculates the train’s movement in the direction of travel, based on the maximum acceleration value possible to make a safe stop; The acceleration value is determined by considering the performance of the train and the infrastructure data, such as maximum traction effort, resistances, gradient, radii of curvature and maximum speed.

Train movements are also governed by the signalling system in operation along the infrastructure concerned. The sections occupied, the time necessary for the movement of the exchanges, the states of the signals are all elements that influence the performance of the trains.

During the simulation each train feeds a virtual tachograph, which records a series of data such as acceleration, speed and distance traveled. In this way, once the simulation is finished, different evaluations can be carried out.

The simulation can be performed in "normally" or "animation mode". In the case of the animation mode, it is possible to see the movement of each train, the occupation and locking of the track circuits and the aspects of the signals.

4.1.3. Output Data

Through Opentrack is possible to obtain countless output values through which different analyses can be carried out. They can be carried out from different perspectives, such as, for example, from the point of view of the type of trains used, from the chosen routes or stations.

4.2 Rolling Stocks Management

The term rolling stock refers to the combination of locomotives and wagons (trailer load). Opentrack classifies trains into the following three categories:

- Fast trains;
- Regional trains;
- Freight trains.

As already mentioned, Opentrack has a database within is possible to choose, among those provided by default, the type of locomotive to be used for the simulation or gives the user the possibility to enter new data to use a specific type of locomotive. In addition, each train has a tabulated mean deceleration value, which can be modified by the user depending on the characteristics of the train.

4.2.1. Trains

Below is the dialog box through which is possible to view the characteristics of the train chosen for the simulation or create a new train (Figure 95, Figure 96).

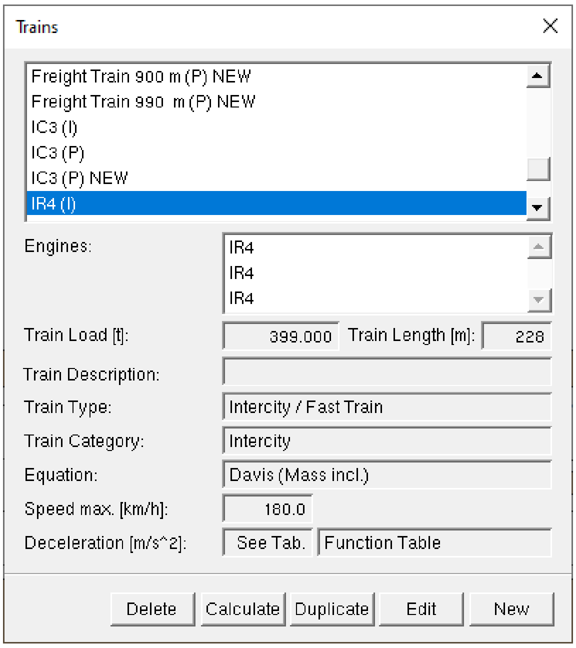


Figure 95 – Trains dialog box.

Through this interface, obtained selecting *Tool --> Trains* in the tool, it is possible to view countless data related to the train in use. The main ones are:

- Name, description, type and category;
- Composition as Engine and Trailers;
- Resistance Equation;
- Acceleration parameters;
- Deceleration parameters.

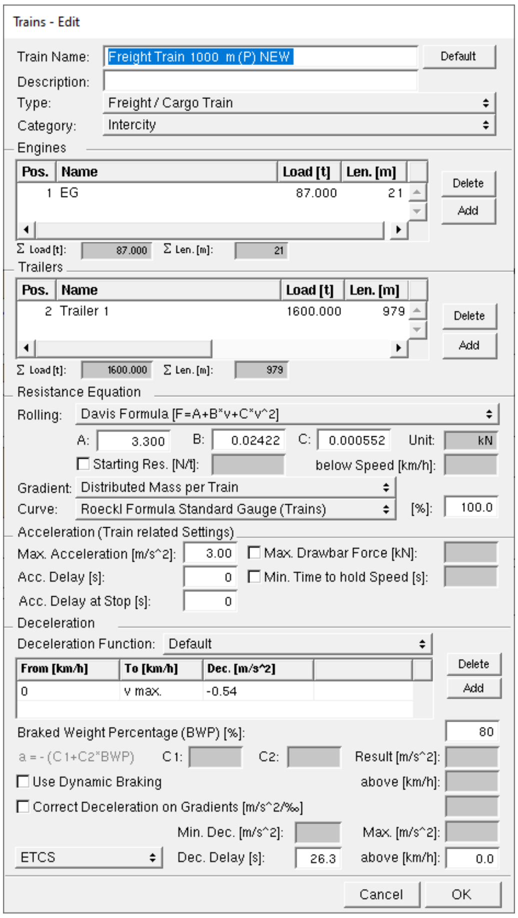


Figure 96 – Trains detailed dialog box.

4.2.1.1 Train Resistance Calculation

Trains experience resistance while traveling. This resistance must be overcome by the locomotive's tractive strength as applied to the rails. The total resistance experienced by the train (R) is a sum of the traction resistance and acceleration resistance. This can be expressed in the following formula:

$$R = R_F + R_a$$

where:

- R is the total resistance in N;
- R_F is the traction resistance in N;
- R_F is the acceleration resistance in N.

The traction resistance and the acceleration resistance can each be divided and sub-divided into components as outlined below.

Traction Resistance

The traction resistance can be divided into the rolling resistance and the distance resistance as shown in the following formula:

$$R_F = R_L + R_{Str}$$

where:

- R_F is the total resistance in N;
- R_L is the rolling resistance in N;
- R_{Str} is the distance resistance in N.

Rolling Resistance

The rolling resistance consists of air resistance, the bearing friction, rolling resistance, and inertial resistance. Formula to approximate running resistance of train was developed by Strahl in 1913 and by Davis in 1926 (Lukaszewicz, 2007). In practice three formulas: *Sauthoff's formula* (for passenger wagons), *Strahl's formula* (for locomotives), and an improved *Strahl's formula* (for freight wagons) are used together or a general formula in form of a quadratic equation (*Davis formula*) can be used to calculate rolling resistance. A special formula is used for Maglev trains. All these formulas are presented below.

Locomotive Rolling Resistance: Strahl's formula for calculating rolling resistance of locomotives is as follows:

$$R_{LT} = g \cdot \left\{ \left[f_L \cdot \frac{m}{1000} \right] + \left[k_{St1} \cdot \left((v + \Delta v) \cdot 3.6 \right)^2 \right] \right\}$$

where:

- R_{LT} is the locomotive resistance in N;
- g is the acceleration due to gravity in m/s²;
- m is the weight of locomotives in kg;
- v is the train speed in m/s;
- Δv is the wind resistance in m/s;
- f_L is the resistance factor (default value 3.3);
- k_{Str1} is the resistance coefficient (0.03 kg*s²/m²).

Passenger Wagon Rolling Resistance: Sauthoff's formula for calculating rolling resistance for passenger wagons is:

$$R_{LP} = g \cdot \left\{ \left[1.9 \cdot \frac{m}{1000} \right] + \left[k_{Sa1} \cdot v \cdot 3.6 \cdot \frac{m}{1000} \right] + \left[k_{Sa2} \cdot (n + 2.7) \cdot \left((v + \Delta v) \cdot 3.6 \right)^2 \right] \right\}$$

where:

- R_{LP} is the resistance for passenger wagons in N;
- g is the acceleration due to gravity in m/s²;
- m is the weight of passenger wagons in kg;
- n is the number of passenger wagons;
- v is the train speed in m/s;
- Δv is the wind resistance in m/s;

- k_{Sa1} is the resistance coefficient (0.0025 s/m).
- k_{Sa2} is the resistance coefficient (0.00696 kg*s²/m²).

Freight Wagon Rolling Resistance: The improved Strahl's formula for calculating rolling resistance for freight wagons is:

$$R_{LG} = g \cdot \frac{m}{1000} \cdot \left[2.2 - \frac{k_{St2}}{v \cdot 3.6 + k_{St3}} + k_{St4} \cdot (v \cdot 3.6)^2 \right]$$

where:

- R_{LG} is the freight wagons resistance in N;
- g is the acceleration due to gravity in m/s²;
- m is the weight of freight wagons in kg;
- v is the train speed in m/s;
- k_{St1} is the resistance coefficient (80 m/s);
- k_{St2} is the resistance coefficient (38 m/s);
- k_{St3} is the resistance coefficient (0.00032 s²/m²).

Davis Formula*:* The Davis formula is available in a mass-dependent and in a mass-independent form. The three parameters A, B and C are typically presented in tabular form.

The mass-dependent Davis formula (result in N) is:

$$R_{LZ} = m \cdot g \cdot \frac{r'}{1000} \quad \text{with} \quad r' = A + B \cdot v + C \cdot v^2$$

where:

- R_{LZ} is the train air resistance in N;
- r' is the special air resistance in N/kN;
- g is the acceleration due to gravity in m/s²;
- m is the weight of wagons in kg;
- v is the train speed in m/s.

The mass-independent Davis formula (result in kN) is as follows:

$$R_{LZ} = A + B \cdot v + C \cdot v^2$$

where:

- R_{LZ} is the train air resistance in kN;
- v is the train speed in m/s.

Maglev Train Resistance Formulas: The formulas for determining resistance for Maglev trains are as follows:

$$R_{LZ} = F_{Lig} + F_{Ws} + F_{Ae}$$

$$F_{Lig} = 0 \ \text{for} \ v < v_{Ein}$$

$$F_{Lig} = n_w \cdot \left(P_{Lig} \cdot \frac{3.6}{v} - 0.2\right) \text{ for } v \geq v_{Ein}$$

$$F_{Ws} = n_w \cdot \left[0.1 \cdot \sqrt{v/3.6} + 0.02 \cdot (v/3.6)^2\right]$$

$$F_{Ae} = C \cdot v^2$$

where:

- R_{LZ} is the train air resistance in N;
- F_{Lig} is the linear generator resistance in N;
- F_{Ws} is the Eddy current resistance in N;
- F_{Ae} is the aerodynamic resistance in N;
- m is the weight of wagons in kg;
- v_{Ein} is the switching speed of linear motors in km/h;
- n_w is the number of wagons;
- P_{Lig} is the linear motor power per wagon in kW;
- C is the aerodynamic parameters (same as Davis formula).

Tunnel Air Resistance

Trains traveling in tunnels experience substantially higher air resistance. The amount of resistance depends upon the exterior surface of the train, the tunnel form, the tunnel cross section and the smoothness of the tunnel walls. The train's rolling resistance increases by the tunnel resistance R_T. For normal track sections (i.e. not in tunnels) $R_T = 0$.

$$R_T = f_T \cdot v^2$$

where:

- R_T is the tunnel resistance in N;
- f_T is the tunnel factor in kg/m;
- v is the train speed in m/s.

Total Rolling Resistance

A train's total rolling resistance will be the sum of its locomotive resistance, wagon (passenger or freight) resistance, and tunnel resistance. This can be expressed by the following formula:

- $R_L = R_{LT} + R_{LP} + R_T$ --> Strahl/Sauthoff (Personenzüge / Passenger Trains);
- $R_L = R_{LT} + R_{LG} + R_T$ --> Strahl/Sauthoff (Güterzüge / Freight Trains);
- $R_L = R_{LZ} + R_T$ -->Davis, Maglev.

Distance Resistance

The distance resistance consists of gradient resistance, curve resistance and switch resistance as expressed in the following formula:

$$R_{Str} = R_S + R_B + R_W$$

where:

- R_{Str} is the distance resistance in N;
- R_S is the gradient resistance in N;
- R_B is the curve resistance in N;
- R_W is the switch resistance in N.

The switch resistance is neglected in the simulation due to its small influence on train operations in large networks.

Gradient Resistance: Gradient resistance is the portion of the train mass working against the train's direction of motion. Figure 97 illustrates the resistance forces acting due to gradient.

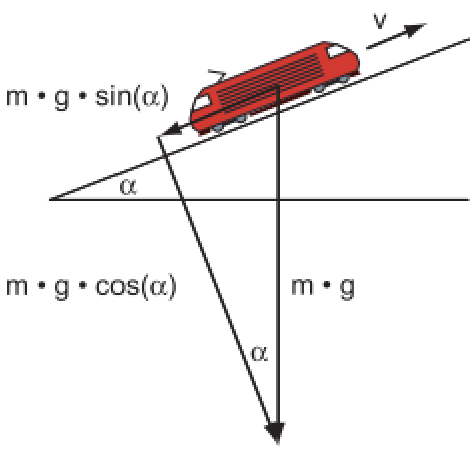


Figure 97 – Gradient Resistance.

$R_S = m \cdot g \cdot \sin\alpha$

$R_S = m \cdot g \cdot \tan\alpha = m \cdot g \cdot \frac{I}{1000}$ for small α

where:

- R_S is the gradient resistance in N;
- m is the train weight in kg;
- g is the acceleration due to gravity in m/s^2;
- α is the angle inclination in ° or rad;
- I is the upward gradient (slope) in ‰.

For small angles of inclination (α), $\sin(\alpha)$ can be replaced by $\tan(\alpha)$. In railway applications $\tan(\alpha)$ is called inclination (I) and is expressed in per thousand.

By default, OpenTrack distributes the train mass evenly over the length of the train (*Distributed Mass per Train*). If a more detailed calculation is needed users can select (*Distributed Mass per Engine and per Trailer*), in which case the gradient resistance for each locomotive and trailer will be calculated separately, based on their current position in the train and the track slope under the respective locomotive or trailer.

Curve Resistance: Trains experience resistance when traveling through a curve. This resistance is caused by rigid wheel sets traveling over interior and exterior radii of different lengths, and because of the transverse shift friction of the drive assemblies. The curve resistance depends on the curve radius and the track gauge (Chandra and Aqarwal, 2008).

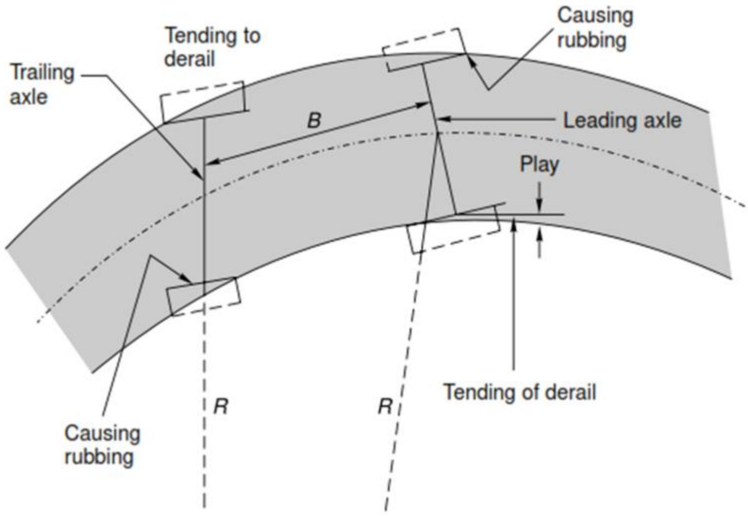


Figure 98 – Resistance due to curve (Chandra and Aqarwal, 2008).

An example of an empirical curve resistance formula is Roeckl's formula (Deutsch Bahn) for standard gauge tracks. OpenTrack can calculate curve resistance very precisely by allowing users to enter the parameters D and E in the Roeckl formula. Furthermore, these two parameters can be defined individually for both locomotives and trailers (wagons).

$$R_B = \frac{D}{r - E} \cdot m \text{ for } r \geq 300\, m$$

$$R_B = \frac{4.91}{r - 30} \cdot m \text{ for } r < 300\, m$$

where:

- R_B is the curve resistance in N;
- r is the curve radius in m;
- m is the train weight in kg.
- User-defined D-Parameter in m²/s² (default value is 6.3 if r ≥ 300 otherwise 4.91);
- User-defined E-Parameter in m (default value is 55 if r ≥ 300 otherwise 30).

In addition to the Roeckl formula for calculating curve resistance, OpenTrack provides a second formula for calculating curve resistance for trams:

$$R_B = \frac{1 + c}{r} \cdot 0.17 \cdot m \cdot g$$

where:

- R_B is the curve resistance in N;
- c is the distance of axles per bogies in m ($c = 2m$);
- r is the curve radius in m;
- m is the train weight in kg;
- g is the acceleration due to gravity in m/s².

During the simulation OpenTrack calculates the curve resistance for each part of the train (locomotives and trailers) separately. The sum of the partial resistances gives the total curve resistance for the entire train in the current position.

Starting Rolling Resistance: The starting rolling resistance is the extra resistance experienced by a train when it starts from a stopped position. The following starting rolling resistance parameters can be defined in OpenTrack:

- *Use Starting Resistance:* determines if the starting rolling resistance will be used or not;
- *Starting Resistance* (r_{st}): starting rolling resistance factor in N/t;
- *Below Speed:* the speed in km/h below which the starting rolling resistance will be used.

The starting rolling resistance force R_{St} is a linear function between the speed $v = 0$ and the *Below Speed*. At the speed $v = 0$ the value of $R_{St} = r_{st} \cdot m$ and when $v = v(\text{Below Speed})$, then the rolling resistance is calculated using the selected rolling resistance formula (Strahl/ Sauthoff, Davis, etc).

The relationship between rolling resistance and speed is shown in Figure 99. The example shows the rolling resistance calculated using the Strahl/Sauthoff formula with a starting rolling resistance (r_{st}) of 50 N/t from 0 to 8 km/h, a train mass of 550 t, and a maximum speed of 140 km/h.

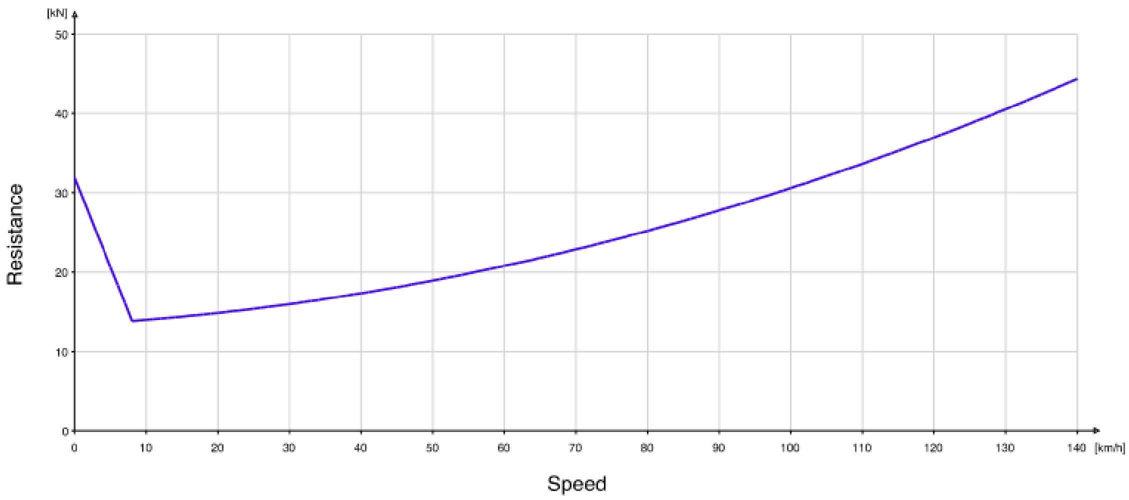


Figure 99 – Rolling resistance as a function of speed.

Acceleration Resistance

When a train accelerates or decelerates (brakes) it experiences acceleration resistance. A train's acceleration resistance is proportional to the train's mass and to its rate of acceleration and consists of a portion for the translation and a portion of the rotary masses. For the portion of the rotary masses an empirical mass factor ρ is introduced. The formula for acceleration resistance is:

$$R_a = m \cdot a \cdot (1 + 0.01 \cdot \rho)$$

where:

- R_a is the acceleration resistance in N;
- m is the train weight in kg;
- r is the acceleration rate m/s^2;
- ρ is the empirical mass factor.

For passenger and freight trains the mass ρ lies between 6 and 10 (Weidmann, 1991).

4.2.1.2 Braking Behavior

By default, OpenTrack uses a value table (which lists speed dependent braking deceleration values) to define the braking curve. Normally the following typical values for braking deceleration are used unless no more detailed value are given (Brunger and Dahlhaus, 2014):

- $a = 0.525\ m/s^2$ for suburban trains (service braking);
- $a = 0.375\ m/s^2$ for passenger trains (service or comfort braking);
- $a = 0.225\ m/s^2$ for freight trains (service braking);
- $a = 0.7\ m/s^2$ for suburban trains (sharp braking);
- $a = 0.5\ m/s^2$ for passenger trains (sharp braking);
- $a = 0.3\ m/s^2$ for freight trains (sharp braking).

If train is fitted with an automatic system like ETCS a detailed estimation of the deceleration has to be made. However, users can also define locomotive braking using a percentage factor.

In normal travel time calculations, i.e. those in which the trains brake under normal operations, it is recommended to use OpenTrack's default table-based braking function. The percentage definition is most suitable for analysis of a train's braking potential, based on use of a percentage of braking ability.

The deceleration formula follows the form:

$$a = -(C1 + C2 \cdot BWP)$$

where:

- $C1$ is the independent coefficient;
- $C2$ is the coefficient dependent on braking percentage;
- BWP is the braked weight percentage.

Users can either develop their own values for the coefficients $C1$ and $C2$ or use a pre-defined value (Table 4).

Formula	C1	C2
UIC	0.069	0.006
SBB ZUB	0.06	0.006
SBB FSS	0.063	0.0067

Table 4 – C1 and C2 predefined table value.

4.2.2. Locomotive (Engine)

OpenTrack manages locomotives in a database called Depot.

Locomotive data included in the database includes tractive effort/speed diagram, braking force/speed diagram, locomotive weight, length, resistance factors, etc. OpenTrack allows the user through the interface obtained selecting *Tool --> Engines* to edit the diagrams and data graphically using an editor (Figure 100).

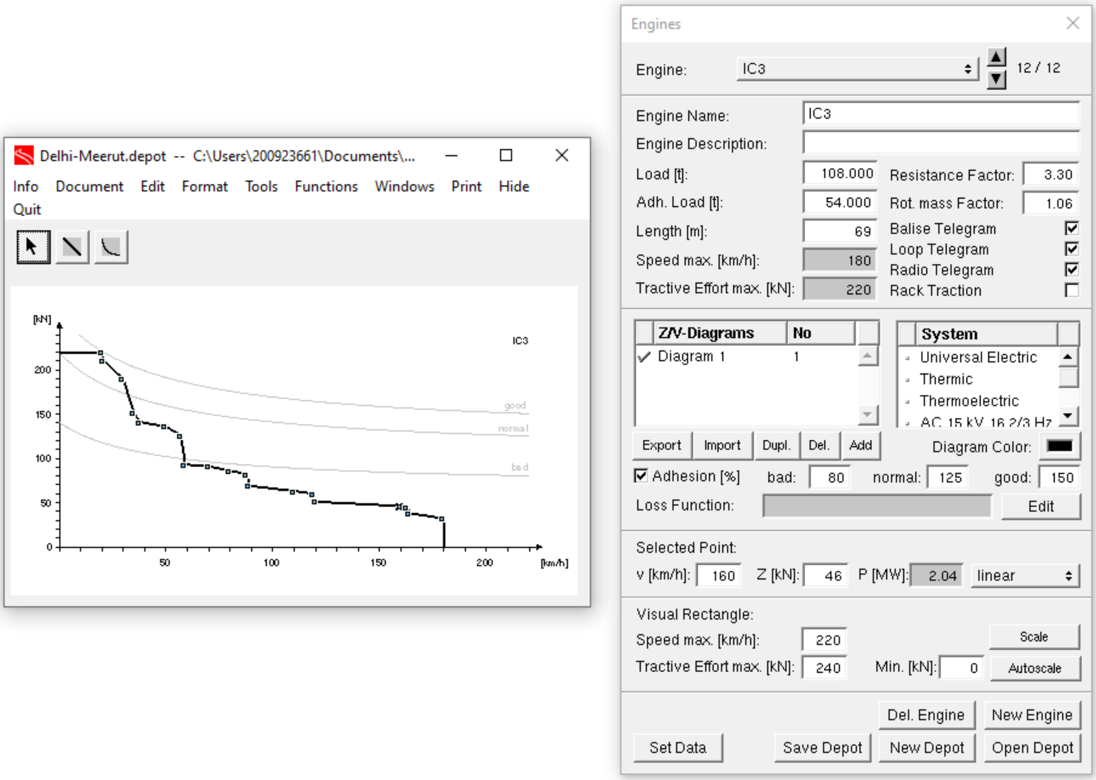


Figure 100 – Engines Window.

The locomotive or the power equipment of the multiple units generates which is intended to move the train. It is called induced tractive effort F_{Ti} in N.

However, not the whole amount of this effort can be used, due to three principle assumptions:

- The internal power transmission of the locomotive or the multiple units consumes between 2% and 3% effort;
- The effort can be limited to a constant maximum amount to prevent the power equipment from overheating;
- The wheels will spin if the effort exceed the maximum adhesion between wheel rim and rail.

The induced tractive effort is reduced by the transmission losses and limited by traction motor overheating and the adhesion limit. Additionally, some (older) power units have different characteristics, so that the effort cannot be deduced directly from the engine power. Instead, the tractive effort at wheel rim F_{Tr} (depending on speed) is normally given by a diagram which often looks live that shown in Figure 101.

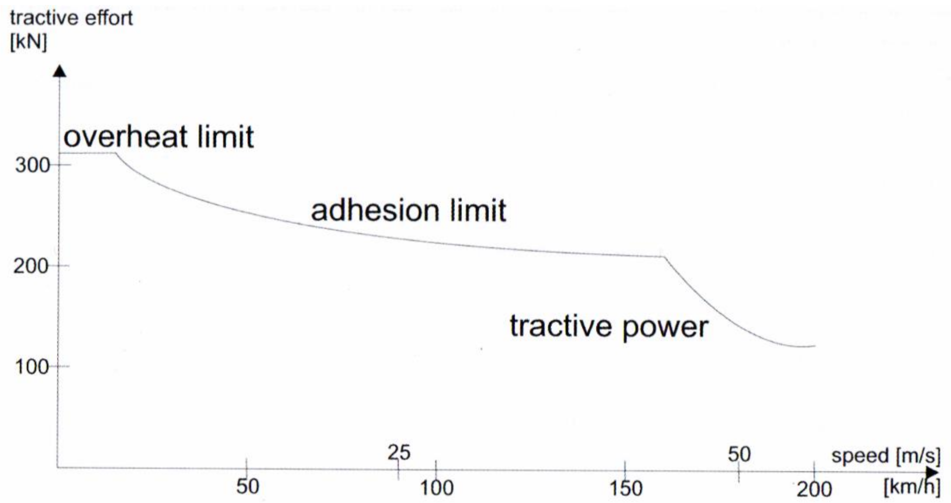


Figure 101 – Tractive Effort at Wheel Rim Dependent on Speed (Brunger and Dahlhaus, 2014).

4.2.2.1 Adhesion behavior

Empirical formula exists to estimate the friction traction power. The most well-known beginning comes from Curtius and Kniffler and describes the frictional behavior between wheel and rail in a speed-dependent manner as follows:

$$\mu = \frac{2.1 \text{ m/s}}{v + 12.2 \text{ m/s}} + 0.161$$

where:

- μ is the friction coefficient;
- v is the train speed in m/s.

A locomotive's adhesion behavior can be described under three scenarios: good, normal and bad to account for various different conditions (for example weather related). The percentage value is then used in the Curtius and Kniffler formula to estimate the adhesion coefficient. For modern locomotives the following pre-set values are used as defaults by OpenTrack (good: 150%, normal: 125%, and bad: 80%).

4.2.2.2 Locomotive Power Loss Function

A locomotive wastes part of its mechanical effort in its very operation. In OpenTrack, for each locomotive and each diagram of tractive force vs. speed, users can define a power loss function. For each speed interval, the function should be entered as a constant in kilowatts (kW) and as a percentage of tractive effort. OpenTrack then adds these losses to the total power requirement for a train.

For electric locomotives, total power requirement means power consumption at the catenary or third rail. For diesel and other non-electric locomotives, total power requirement means total energy consumption. In all cases this includes losses both in the locomotive and its train.

4.3 Track Layout Management

In OpenTrack the track layout is created and edited using a file called a worksheet. A worksheet consists of a track layout section with all its elements such as route, signals, stations etc. A worksheet can also include additional information such as text, pictures, graphical elements (rectangles, circles, lines) to help users better visualize the layout. Figure 102 illustrates a typical worksheet.

The railway network in Opentrack is represented through a graph, characterized by vertices or nodes connected through arcs.

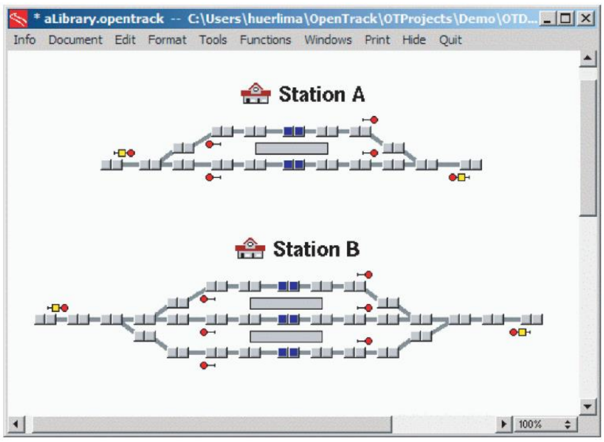


Figure 102 – OpenTrack Worksheet.

4.3.1. Vertex

Vertices mark the points in the railway network where at least one route attribute (gradient, radius, speed etc.) changes or where there is a signal. In OpenTrack vertices always appear in pairs (since OpenTrack represents the network using the double vertex graphing technique), but as single objects on the worksheet. Attributes such as names and reference points associated with a vertex can be entered and edited using the Inspector tool.

OpenTrack structures the track network using the double vertex graph technique (Montigel, 1994, 1992a, 1992b). In a double vertex graph the graph's vertices do not appear alone, but always together with a second vertex. Thus, contrary to classical (single vertex) graphs, double vertex graphs can provide information at each vertex about the edge via which the vertex has been reached.

The differences between classical graphs and double vertex graphs can be illustrated using the example of a switch represented in Figure 103 as a classical graph and double vertex graph. Double vertex graphs provide a simple and easily understood method for placing signals in OpenTrack so that they control only one direction of travel.

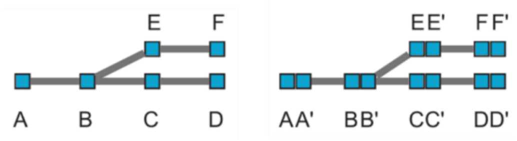


Figure 103 – Classical Graph (left) and Double Vertex Graph (right) representation.

Figure 104 illustrates the Vertex Inspector. When using the Vertex Inspector window is important to remember that Opentrack works with double vertices. For this reason, it is necessary to always check to which part of the top are attributing those specific characteristics.

Each vertex, through this interface, can therefore be characterized through:

- the name of the vertex;
- the kilometric distance;
- the station area to which it belongs.

In addition, depending on the specific characteristics of each vertex, the following attributes can be attributed by means of a flag in the corresponding box:

- station vertex;
- isolated joint;
- axle counter joint;
- switches.

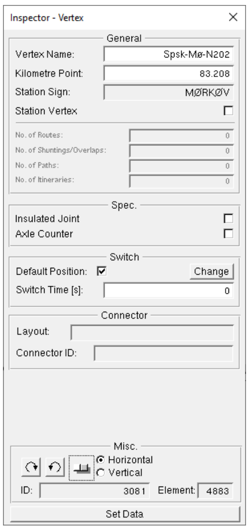


Figure 104 – Vertex Inspector.

4.3.2. Edges

In OpenTrack railroad track segments are symbolized by lines called "Edges". In a manner similar to vertices, edges can be drawn on the worksheet using the palette's Edge Tool and can be given attributes using an inspector.

Edge attributes include edge length (edges can be of any length), radius, and gradient. Additional information such as a description of the tunnel cross section (and/or a tunnel factor), provision of pilot line (loop), train speed per direction of travel, and membership of the edge in a safety margin after a signal (overlap) can also be attributed to an edge (Figure 105).

Edges have a direction which is set based on how the edge was drawn on the worksheet; the direction will be from the starting (first) vertex to the target (second) vertex. Edge direction is important because it is used to indicate gradient, radius, and line speed attributes; for example, a positive gradient on an edge indicates that the second vertex is at a higher position than the first.

The OpenTrack procedures for showing edge direction on the worksheet and changing edge direction are outlined below.

Edges can be linked together so that the edges are only occupied or allocated together. During the simulation reservations and occupations of edges (which train at what time) can be monitored and evaluated.

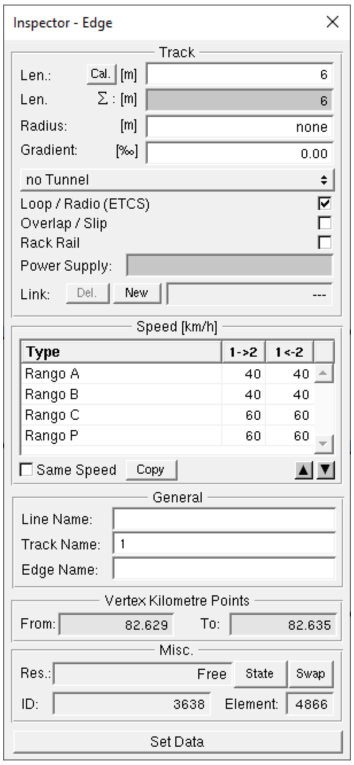


Figure 105 – Edges Inspector.

4.3.3. Signals

OpenTrack uses two different types of signals: signals with changing information (light signals, beacons) and halt position indicators. The light signals are subdivided into main signals (signals that can show stop), distant signals (signals without stop aspect), combined signals (combination of main and distant signal) and shunting signals. Main signals (including combined signals) can be further subdivided into home, exit and block signals.

Virtual signals do not have a corresponding installation on the route but are merely used to show the safety technology (for example discrete block division in case of the cab signaling).

The halt position indicators characterize a position in a station or at a stop, at which a train having a given length is to stop. OpenTrack allows the user to distinguish between many length graduations (10 m to 1000 m) and a general halt for all trains. During the simulation an entering train stops at the appropriate position given its length.

OpenTrack represents main and distant signals on the worksheet either by means of general, land independent icons or by means of the usual signal icons for so called Aspect Signaling (e.g. UK). All types of signals used in OpenTrack are illustrated and described in Figure 106.

OpenTrack treats signals similar to other track layout elements (e.g. vertices, edges) and allows the user to place signals on the worksheet using a graphical editor and to set signal attributes using the Inspector tool (Figure 107).

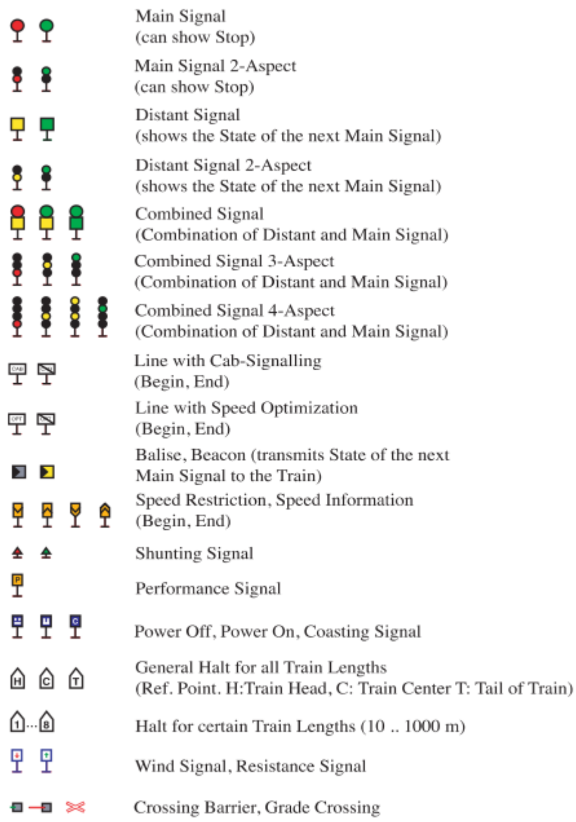


Figure 106 – Types of Signals.

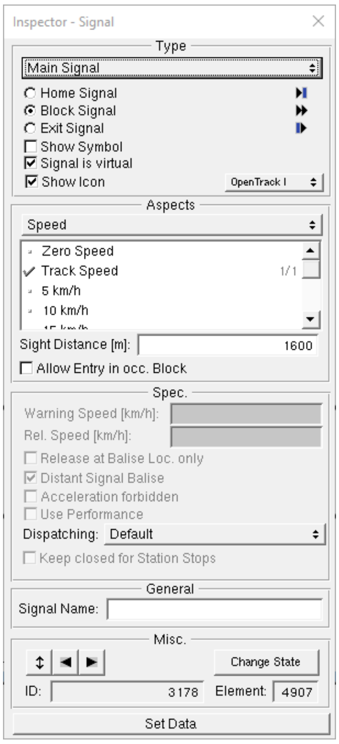
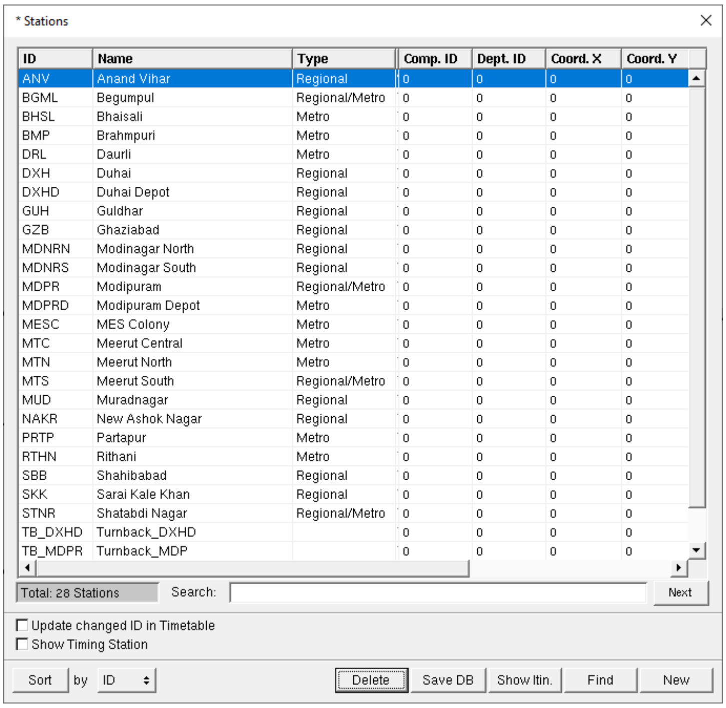


Figure 107 – Signals Inspector.

4.3.4. Stations

OpenTrack uses two methods to manage station data: a station database and as worksheet objects. The station database contains properties of as many stations as possible and is available to all users. Such information includes station name, abbreviation, rail administration data, height above sea level, territorial coordinates, etc (Figure 108).

When creating a track network, the user places stations on the worksheet using the palette's Station Tool. Then, using the inspector, the user sets station attributes including a linkage to the stations database. Station attributes assigned using the Inspector include such as kind of station (manned or unmanned, stop, service location) and type of signal box (Figure 109). A station cannot be placed on a worksheet until it has been first entered into the station database. Stations include passenger stations, train stops and service locations.



ID	Name	Type	Comp. ID	Dept. ID	Coord. X	Coord. Y
ANV	Anand Vihar	Regional	0	0	0	0
BGML	Begumpul	Regional/Metro	0	0	0	0
BHSL	Bhaisali	Metro	0	0	0	0
BMP	Brahmpuri	Metro	0	0	0	0
DRL	Daurli	Metro	0	0	0	0
DXH	Duhai	Regional	0	0	0	0
DXHD	Duhai Depot	Regional	0	0	0	0
GUH	Guldhar	Regional	0	0	0	0
GZB	Ghaziabad	Regional	0	0	0	0
MDNRN	Modinagar North	Regional	0	0	0	0
MDNRS	Modinagar South	Regional	0	0	0	0
MDPR	Modipuram	Regional/Metro	0	0	0	0
MDPRD	Modipuram Depot	Metro	0	0	0	0
MESC	MES Colony	Metro	0	0	0	0
MTC	Meerut Central	Metro	0	0	0	0
MTN	Meerut North	Metro	0	0	0	0
MTS	Meerut South	Regional/Metro	0	0	0	0
MUD	Muradnagar	Regional	0	0	0	0
NAKR	New Ashok Nagar	Regional	0	0	0	0
PRTP	Partapur	Metro	0	0	0	0
RTHN	Rithani	Metro	0	0	0	0
SBB	Shahibabad	Regional	0	0	0	0
SKK	Sarai Kale Khan	Regional	0	0	0	0
STNR	Shatabdi Nagar	Regional/Metro	0	0	0	0
TB_DXHD	Turnback_DXHD		0	0	0	0
TB_MDPR	Turnback_MDP		0	0	0	0

Figure 108 – Stations Database.

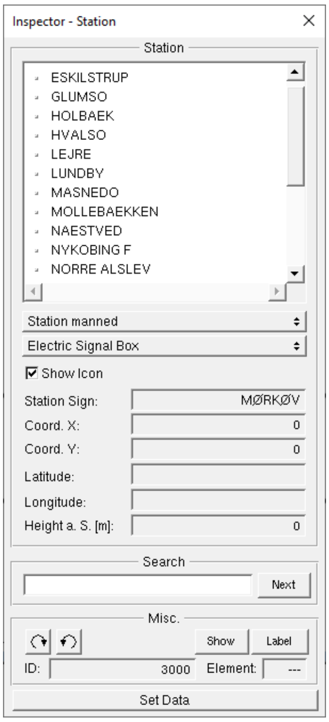


Figure 109 – Stations Inspector.

4.3.5. Measuring Instrument

Measuring instrument windows show data on trains passing a vertex during the simulation process. Figure 110 illustrates a measuring instrument window. Users can place measuring instruments on the worksheet at any vertex. The measuring instrument window shows course number, actual speed and the headway of trains passing through the vertex.

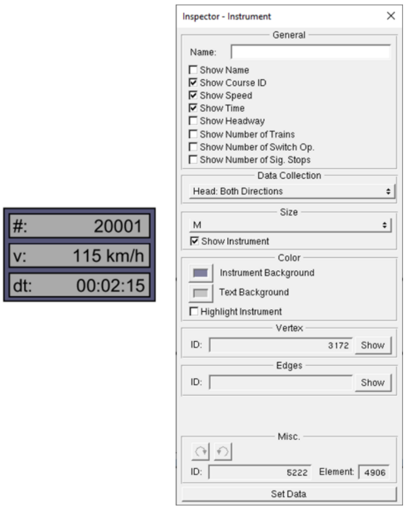


Figure 110 – Instrument Inspector.

4.4 Train Operations Management

OpenTrack uses several types of data structure to describe the track used by a train in its operation. These data structures are differentiated by level and by the type of information included in the particular data structure (Figure 111).

The first level of train path is called a route. Routes consist of an order of vertices of one direction of travel. Routes and shuntings do not, however, only serve to describe the track, but also form part of the safety apparatus of the track system.

The second level is called a path. Paths consist of multiple routes in one direction of travel. Typically, a set of routes that are often used together (for example all the routes that make up the track infrastructure from the exit signal of one station to the exit signal of the next station) are concatenated to form paths.

The top level is called an itinerary. An itinerary consists of one or several successive paths. Setting backs can also be modelled here. For the simulation the train is given a list of itineraries with a priority for each itinerary. This list comprises all itineraries on which the train may move. The actual route is determined during the simulation in that the train always selects the available itinerary (track that is unoccupied or not reserved for another train) having the highest priority.

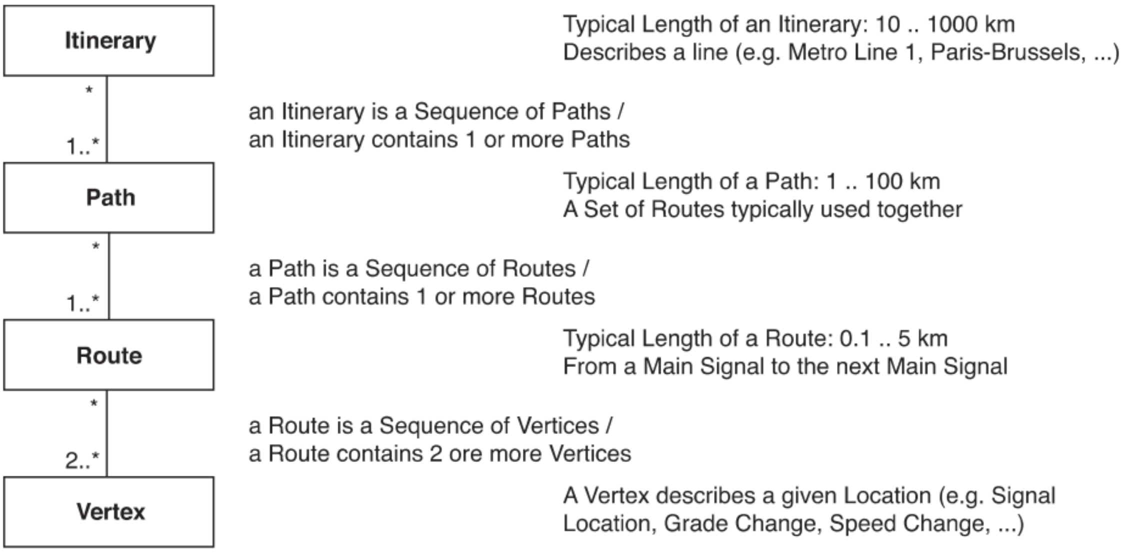


Figure 111 – Routes, paths and itineraries and their relations (Huerlimann and Nash, 2003).

4.4.1. Routes

A route consists of multiple vertices. Figure 112 illustrates a simple route. Routes always begin and end at main signals (home signal, exit signal or block signal). In OpenTrack routes belong to the vertex at which the main signal of the route begin is located. Route attributes such as release time, signal indications, release groups and slow speed zone can be allocated to a route using the Route Inspector (Figure 113).

Figure 112 – Route.

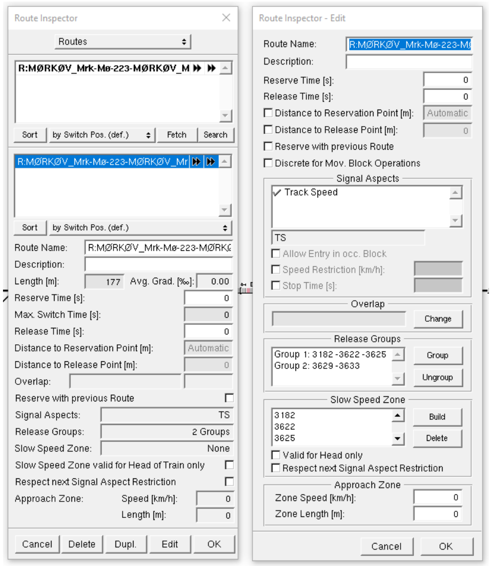


Figure 113 – Routes Inspector.

During the simulation process if a route is required by a train, the route will be reserved for the train only if it is not reserved for another train and if an edge belonging to the route is not reserved or occupied. Once the last part of a train has passed the release point of the route (or a route group), the reserved section is made available for another train after passage of the release time.

4.4.2. Paths

The second level of train operation definition in OpenTrack is called a path. Paths consist of a series of successive routes in one direction of travel. An unlimited number of routes can be included in a path. Paths are merely an organizational structure and do not correspond to any particular element of railway reality. As, however, train operations generally travel over several routes, route orders can be grouped into paths (Figure 114).

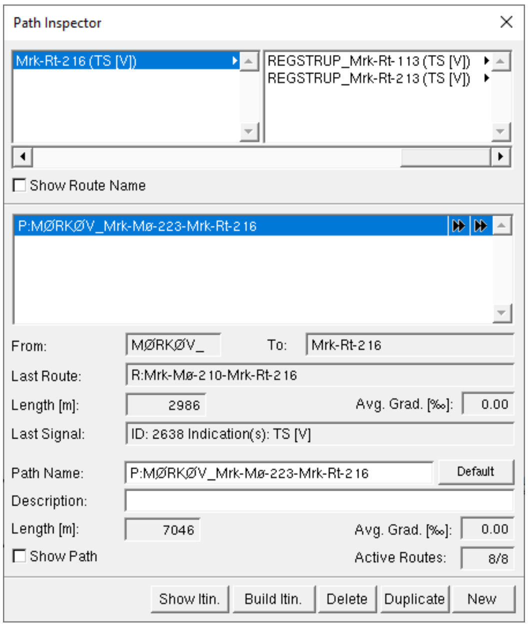


Figure 114 – Paths Inspector.

4.4.3. Itineraries

The top level of train operation infrastructure definition in OpenTrack is called an itinerary. An itinerary consists of one or several successive paths. Itineraries do not need to include paths that are all in the same direction; therefore, itineraries are used to model setting backs (Figure 115).

There are two types of itineraries: full and local. Full itineraries describe complete trip between two main points in the network (e.g. from Station A to Station D through a series of other stations). Local itineraries describe only a portion of the route (e.g. from intermediate B to intermediate Station C on the $A-D$ full itinerary). These local itineraries can be used as alternatives to the “main” route and can be assigned with priorities (e.g. priority 2 or priority 3). The priorities are used by OpenTrack in the simulation process to select the itinerary (i.e. track segments) that train will use.

In the simulation process a train is given a list of itineraries with a priority for each itinerary (Figure 115). This list comprises all itineraries on which the train may move. The actual itinerary used by the train is determined during the simulation in that the train always selects the available itinerary (track that is unoccupied or not reserved for another train) with the highest priority.

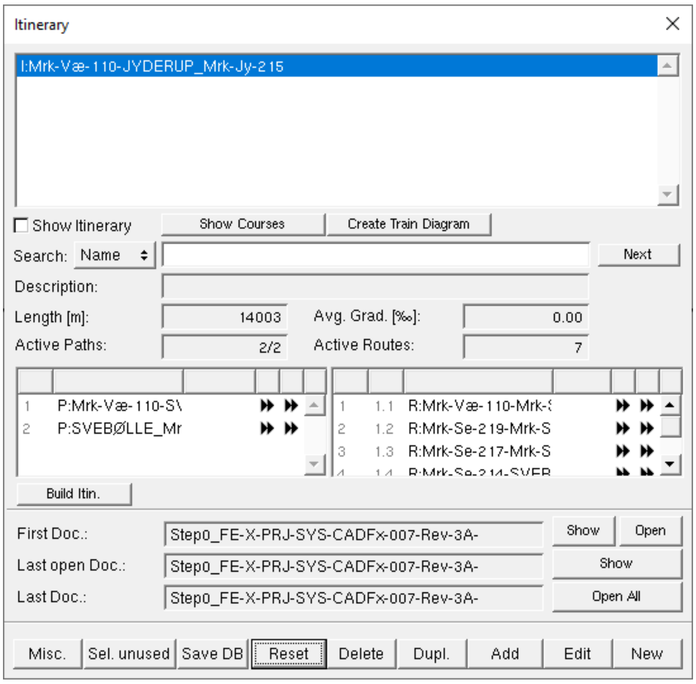


Figure 115 – Itineraries Window.

4.4.4. Courses and Timetables

4.4.4.1 Course Management

OpenTrack uses the term course to define a service operated by a train over a period of time (e.g. a day). In OpenTrack a course consists of a set of itineraries with an associated set of timetable entries, a train definition, a course number (each course must be unique), a train type (speed type), and an entry speed. Each course also specifies which train spacing philosophy should be used (i.e. discrete block, moving block). Another way to think of a course is as a particular "train."

The locomotive driver's behavior can also be defined and in the case that the train is on schedule or late. During the simulation at each train stop or station passage, the actual time is compared to the planned time (when defined in the timetable) and is used to determine which acceleration and speed behavior the train will use on the next section. For example, an acceleration value of 95% means that 95% of the technically possible acceleration rate will be used, but also, that only 95% of the travel speed on the section will be used.

Figure 116 illustrates the Courses/Services Window. Through this interface it is possible to insert countless data related to the travel in question, among which the main ones are: ID of the travel, itinerary, type of train, route reservation/release system.

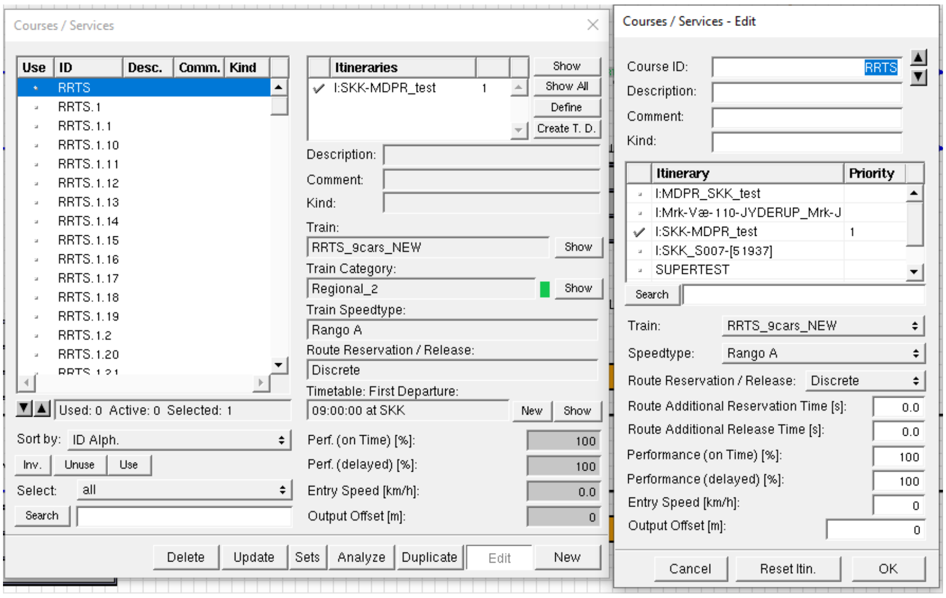


Figure 116 – Courses/Service Window.

4.4.4.2 Timetable Management

The timetable database manages the desired departure times, the minimum stop times at stations, connections, and other key data for the train movements being simulated in OpenTrack.

The timetable database works closely with the course management because the timetable database defines the single courses and their typification.

An entry of a course into the timetable consists of many entries into the timetable database (course number, station, arrival, departure, and minimum stop time) as well as entries per station in the table of connections (optional).

The general time format used in OpenTrack is $HH:MM:SS$ but the application also includes an optional day offset. The day offset enables users to run a simulation over multiple simulation days.

The same time format is used for all OpenTrack time inputs (e.g. timetable arrival and departure times, time values for incidents, plot values, simulation starting and end-time, etc.).

The timetable management window (Figure 117) also enables simple recording of interval trains. The user can define new trains modeled after the first train by simply inputting an interval and the modification value of the course ID number.

With the exception of the departure time (Departure) at the first station, all entries for arrival, departure and passing times are optional (if no time is defined, the cell shows $HH:MM:SS$).

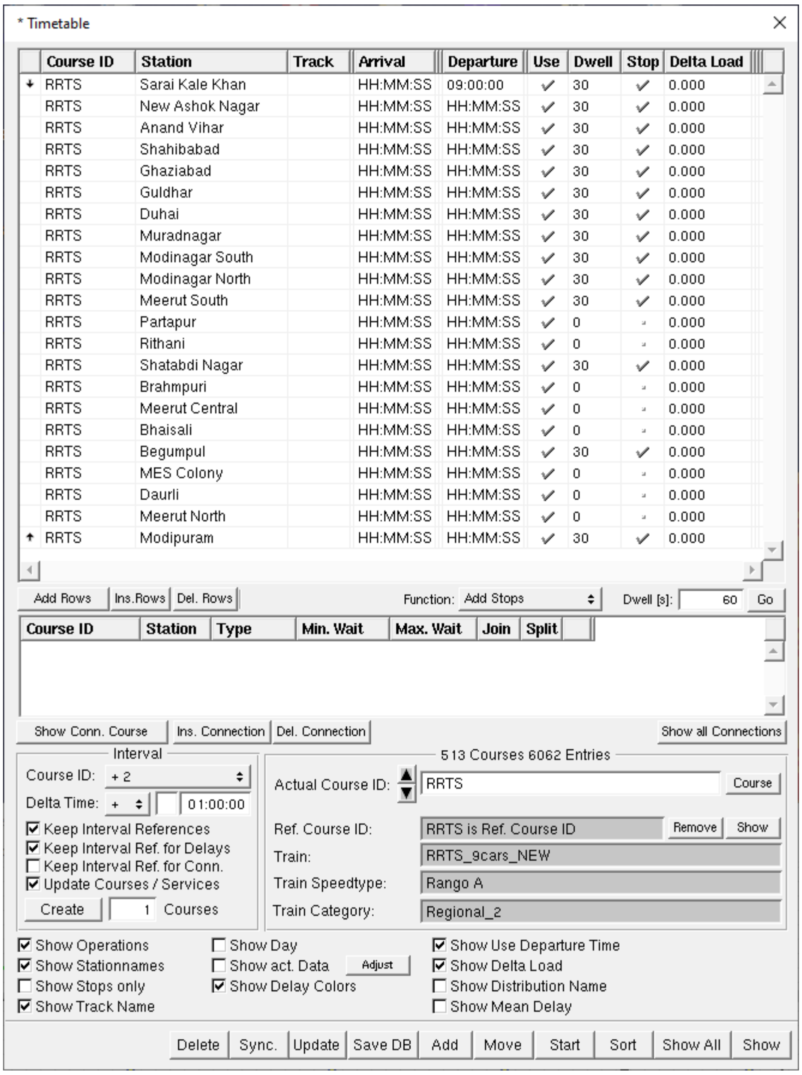


Figure 117 – Timetable Management Window.

4.5 Simulation in OpenTrack

Below is describes OpenTrack's simulation process. In the simulation OpenTrack models the behavior of all trains operating on the track network under user defined constraints including the infrastructure, the physical limitations of the rolling stock, and given timetable. The following paragraphs outline, respectively, the theoretical basis used by OpenTrack to simulate train motion, model protection systems and dispatch trains.

Following these three theoretical sections, three sections describe the procedures used in running a simulation, OpenTrack's animation features, and messages generated by the program during the simulation process. As these sections outline, OpenTrack permits users to define many parameters for the simulation including time interval, computation accuracy, climatic conditions, and delay characteristics. The user can also specify the amount of animation (e.g. train positions, signal settings, occupied and reserved track sections) to be displayed on-screen as the simulation is running. It is also possible to view the current simulation clock, the interactive messages, and the measuring instrument representations during the simulation.

4.5.1. Calculation Basis of the Simulation

The OpenTrack simulation is a mixed simulation. This means that it is a mixture of continuous and discrete simulation processes. The continuous process consists of train motion. OpenTrack simulates train motions using motion equations (differential equations) of the vehicles. The discrete processes include such things as changes in the state of safety installations (e.g. signal aspects) or delays.

A numerical method (Euler's Method) is used in order to solve the equations for train motion since it is not possible to find the solution of the differential motion equation in a self-contained, analytical form. Euler's method provides sufficiently exact approximate values for the simulation.

The basic equation of dynamics (Newton) serves as a basis for the calculation of the train motion:

$$F = m \cdot a$$

where:

- F is the tractive effort of the engine in N;
- m is the mass of the train in kg;
- a is the acceleration of the train in m/s^2.

In order for a train to accelerate, the traction vehicle must transfer a force to the rail which is larger than the traction resistance. The difference between tractive effort and traction resistance is called traction power surplus and is expressed in the following formula:

$$F_Z = Z(v) - R_F(v, s)$$

where:

- F_Z is the tractive effort surplus in N;
- Z is the tractive effort in N;
- R_F is the friction resistance in N;
- v is the speed in m/s;
- s is the distance covered in m.

The tractive effort is calculated using the tractive effort/speed diagram and depends upon the speed and environmental conditions (adhesion conditions). The traction resistance depends upon train speed and the track network's physical conditions.

The maximum technically possible acceleration rate is attained if the entire traction effort surplus is invested into accelerating the train; in this case the acceleration resistance is equal to the traction power surplus. From this follows:

$$a = F_Z / (m \cdot (1 + 0.01 + \rho))$$

where:

- F_Z is the tractive effort surplus in N;
- a is the acceleration in m/s²;
- m is the mass of the train in kg;
- ρ is the mass factor rotating masses.

The train's maximum possible acceleration rate at any point is also dependent on track speed limit, the locomotive's maximum speed, and the weight of trailing wagons.

Euler's Method works by calculating the change in a variable from a given starting point. It estimates each functional value using the preceding functional value (start value), the preceding derivative of the function, and a fixed time step. An example of Euler's Method for determining the speed at a time t is presented below and illustrated in Figure 118:

$$v(t) = v(t - \Delta t) + \Delta t \cdot \frac{dv}{dt}(t - \Delta t);\ v(t_0) = 0$$

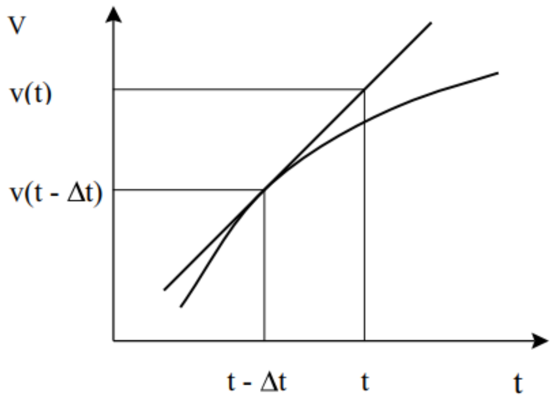


Figure 118 – Euler's Method (Huerlimann and Nash, 2003).

Using the motion equation, the actual speed of a train is calculated by integrating the formula below between the valid integration limits, as shown in the following equation:

$$v = v_0 + \int_{t1}^{t2} a\, dt$$

Similarly, the distance covered can be calculated by repeated integration of the following equation:

$$s = s_0 + \int_{t1}^{t2} v\, dt$$

A more comprehensive analysis of running dynamics and determination of journey times is described in Filipović (1989), Weidmann (1991) and Brunger and Dahlhaus (2014).

4.5.1.1 Modelling Braking Behaviour

It would be very complicated to simulate a train's braking behaviour completely. The model would need to simulate the braking behaviour of each locomotive and wagon in the train, as well as the behaviour of the locomotive driver. Therefore, OpenTrack uses a simplified computation model to simulate braking behaviour in the travel time computation algorithms which provides sufficiently accurate results. This method is based on the braking characteristics of each type of locomotive, it provides a braking rate for various speed intervals. Table 5 presents an example of a braking characteristic table for a particular locomotive.

v_{von} [km/h]	v_{bis} [km/h]	a [m/s²]
v_{max}	100	- 0,4
100	40	- 0,5
40	0	- 0,6

Table 5 – Example Locomotive Braking Rate Table.

The actual computation of the brake applications is calculated backwards from the target point (e.g. stopping point) and its target speed (i.e. its speed at the target point). Figure 119 illustrates a pre-calculated braking function for train T_1 approaching a closed signal MS_1. The marked points in the speed/distance diagram symbolize the values of the individual calculation steps. As soon as train T_1 crosses the brake employment point P_1, it brakes to a stop following the brake curve. Once the train reaches its target speed or if the brake action becomes void by a status change in the protection system (e.g. if a signal changes from a stop to a proceed aspect), then the current brake application is regarded as settled and the train is informed about the next brake employment which must be considered.

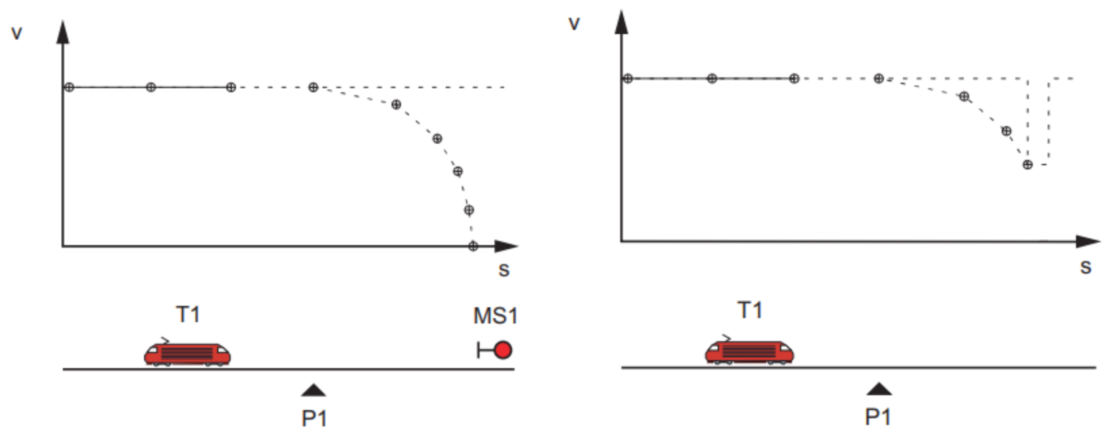


Figure 119 – Brake Application at Halt (left) and at Speed Reduction(right) (Huerlimann and Nash, 2003).

4.5.2. Behaviour of Protection Systems

OpenTrack uses a protection system to ensure collision-free train operations during the simulation process. The following two conditions guarantee safe operations:

- Each track section is reserved either for no trains or at most one train;
- Each train must be able to stop within the track section reserved for it.

The protection system and safety philosophy are used to define the effective distance ahead of and behind a train that lies in the train's protected zone. The method currently used by railroads is to release track sections in discrete units, or routes. Each route is protected by a main signal, which prevents movement of trains on the route when it is set on stop. A route can be reserved, and its main signal display the appropriate signal for proceeding only if:

- All safety elements belonging to the route are free or reserved for the applying train;
- The applying train must have a free continuing way at the end of the route;
- The free blocking is ensured, i.e. prevent the situation where two trains have the same track section available for occupation (deadlock).

The two following figures illustrate the behaviour of the protection systems following a request for track segment reservation by a given train for two examples.

Figure 120 illustrates the case of a successful route reservation. In this example Train T_1 is approaching the point (AP_1) of requesting the route from MS_1 to MS_2. As the figure shows, the train's brake curve has been precalculated for the possibility that Train T_1 will need to stop at Point MS_1. In the example Train T_1 receives permission to proceed on the route MS_1 to MS_2 and so the figure shows the train continuing at speed v_{T1} until it the point where it is necessary to brake to stop at point MS_2.

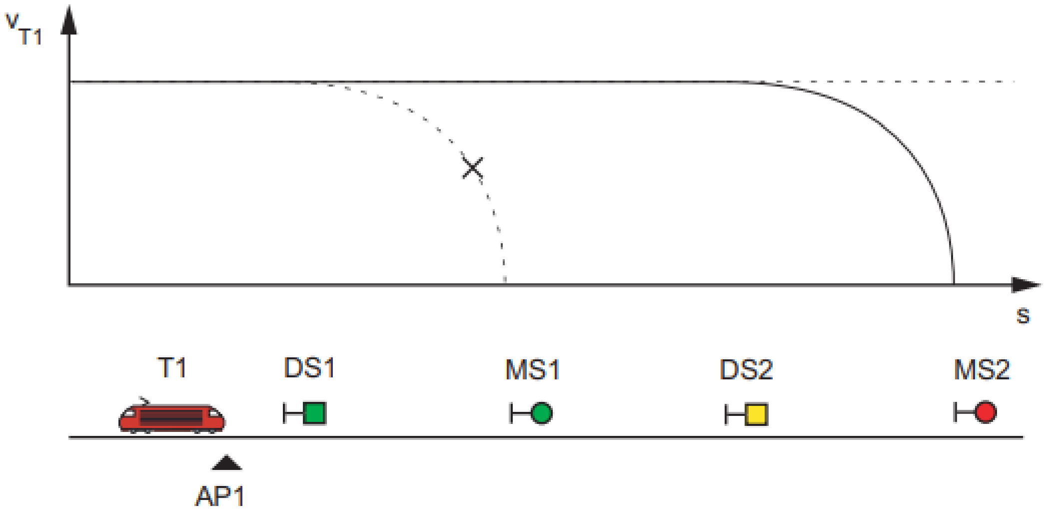


Figure 120 – Successful Track Segment Reservation (Huerlimann and Nash, 2003).

In contrast, Figure 121 illustrates the case of an unsuccessful route reservation. In this example Train T_1 request to enter the section behind Signal MS_1 fails despite free safety elements because a part (segment overlap in the figure) of the through route is being used to accommodate Train T_2. Thus Train T_1 must assume that it will need to stop at the beginning of the requested route (at MS_1) and can proceed past main signal MS_1 only when Train T_2 moves into the siding and can release the section of the through route requested by Train T_1.

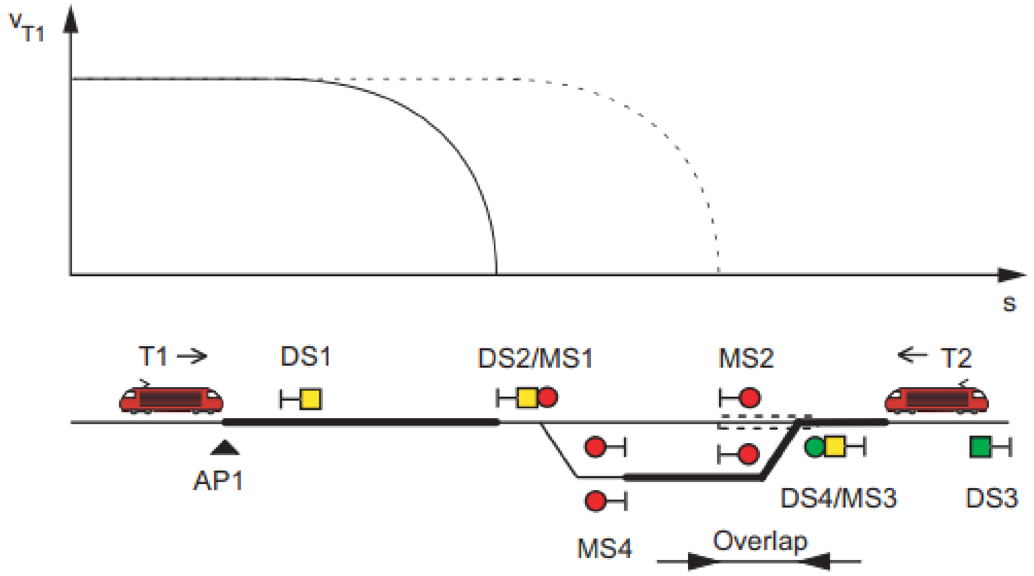


Figure 121 – Unsuccessful Track Segment Reservation (Huerlimann and Nash, 2003).

4.5.2.1 Discrete Block Signal System

Open Track calculates the optimal location for the route reservation so that the route is reserved once the train has reached the point within sight of the first distant signal for the start signal of the route. This means that the train driver should (almost) never see a "warning" indication on a distant signal or combined signal. If the line is equipped with loop or radio signalling, then the point is chosen based on the predicted braking point of the closed main signal, rather than the distant signal location.

The other conditions for successfully reserving a route are the same, the train must be located within sight distance of a distant signal or main signal, cross over a balise, be located on a loop antenna, or on a line equipped with cab signalling.

The automatic route reservation can be adjusted using a tool function called "*Distance To Reservation Point [m]*". This is especially helpful for railway systems in which automatic route reservation tends to be done too early.

Signal S_1 is a combined signal with a distant signal for Signal S_2. In the automatic route reservation method OpenTrack tries to complete the reservation of route R_2 once train T_1 reaches the point where it can see the distant signal (distance to signal $S_1 = s_{SIGHT(S_1)}$), i.e., the point marked $RP_{1(R_2)}$ on Figure 122. If the route R_2 has a specified Distance to Reservation Point ($s_{RES(S_1)}$), i.e., then

OpenTrack tries to complete the reservation process when the train reaches point $RP_{2(R_2)}$, in other words, the moment when the train is within the defined distance ($s_{RES(R_2)}$) from the starting signal for route R_2.

If the sight distance ($s_{SIGHT(S_2)}$), is less than the *Distance to Reservation Point* ($s_{RES(R_2)}$), the route segment is reserved when the train reaches the sight distance point.

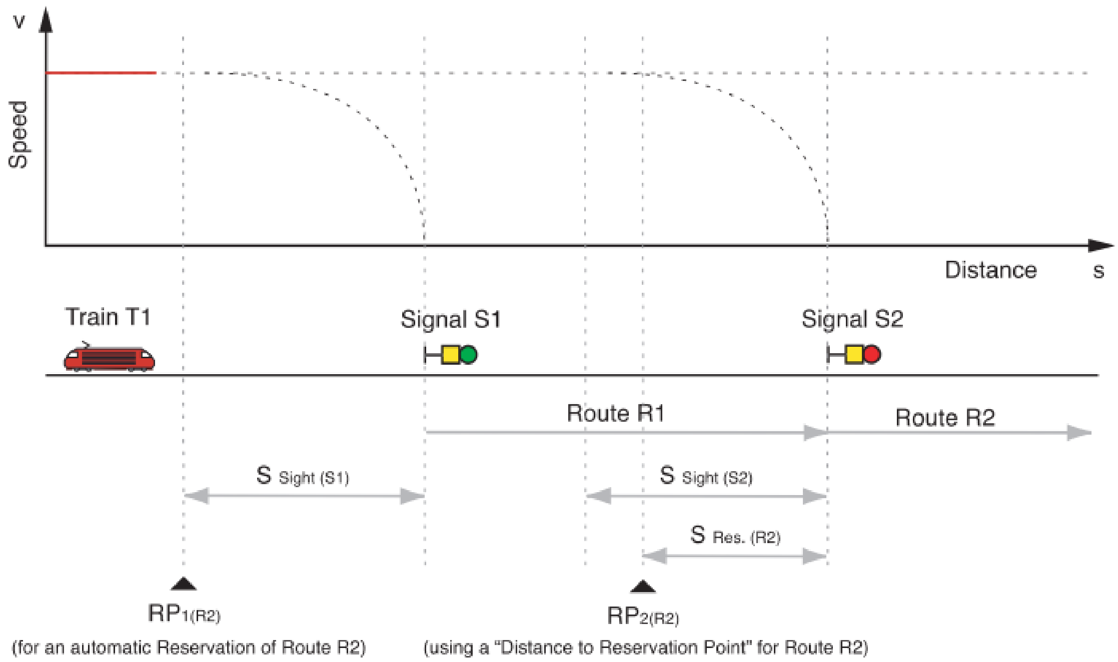


Figure 122 – Route Reservation (Huerlimann and Nash, 2003).

4.5.2.2 Moving Block Signal System

The second major type of signaling system is a moving block signal system. A moving block signal system is characterized by flexible block lengths; the block length is calculated based on train braking characteristics, train speeds and track layout. In contrast to fixed block systems, in a moving block system the flexible block is continuously examined to determine whether it is the appropriate length for the optimal progressive movement of the train while maintaining the necessary braking distance from other trains (i.e. track segments occupied or reserved for other trains). During acceleration or travel at constant speed the moving block system constantly checks that the train remains within its safe current braking distance. If the system recognizes a point of conflict, it moves into the next more restrictive speed condition.

Figure 123 illustrates the braking behaviour of Train T_2 as it approaches a stopped train (Train T_1) in a moving block signal system. In the figure Train T_2 has been accelerating up its maximum speed, but at time $(t - \Delta t)$ it receives a warning that further acceleration is impossible given the available braking distance. At the time t Train T_2 begins its effective brake applications, with the goal of stopping behind Train T_1. During each brake step the system examines whether Train T_2's speed can be increased, which would only be true if Train T_1 moved far enough to the right to shift Train T_2's danger point, thus permitting a termination of braking for Train T_2.

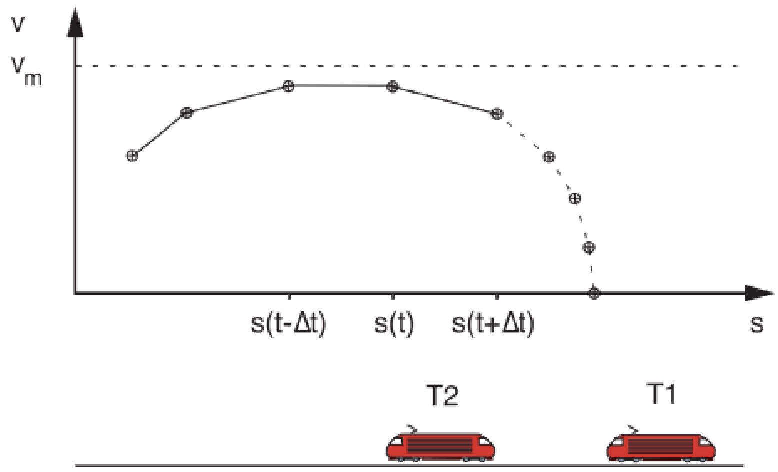


Figure 123 – Moving Block: Braking Behaviour (Huerlimann and Nash, 2003).

4.5.3. Dispatching Trains

OpenTrack's dispatching module performs the central task of time sensitive track segment reservation and providing appropriate the travel commands to individual trains during the simulation process. The dispatching module also controls the optimal progress of trains through pre-reservation of track segments and selecting alternative routes based on priority settings.

The dispatching system communicates to the safety system the starting point of the train and the number of track segments it wishes to reserve. Reasons for pre-reserving several routes include:

- train can travel at a higher speed on the route if the subsequent route is also reserved;
- reserving only one route segment could lead to deadlock.

The route request function of the safety system sorts route start positions according to ascending position for each requested route segment until either it encounters a route segment that cannot be reserved, or until all the route segments have been successfully reserved. The process is considered successful if at least one route segment can be reserved. The dispatching module is informed about the success and/or failure of each individual inquiry.

The tool dispatching module continuously examines possible route changes in the courses operating on the track network. The dispatching module assesses, with each route request inquiry, possible route changes, which could make the course's highest priority route available.

Figure 124 illustrates an example of OpenTrack's route selection process. In this example, Train T_1 tries to receive authorization for using its highest priority route R_1 (from Signal S_1 to Signal S_2) for entry into the station. Since Route R_1 is partially allocated to Train T_2 the safety system rejects Train T_1's request for the route. Train T_1 then tries to receive authorization for its second ranking route (Route R_2) which the safety system confirms is available and therefore the route is certified. The dispatching module attempts to move trains operating on low priority routes to high priority routes as quickly as possible.

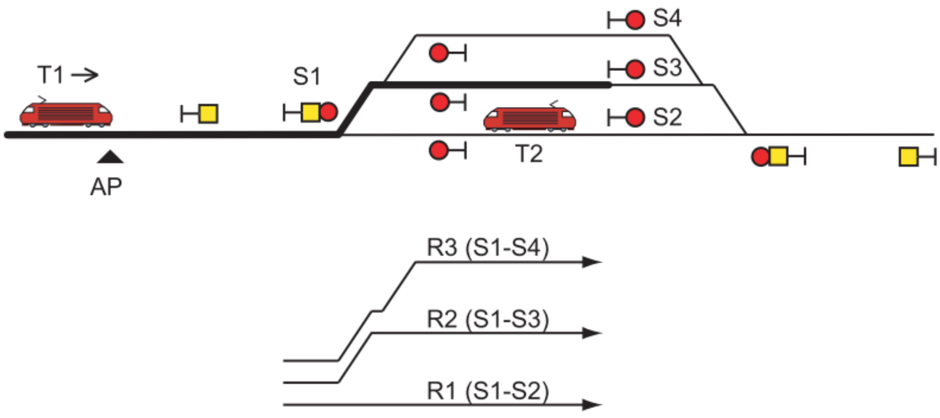


Figure 124 – Example: Choosing a Route (Huerlimann and Nash, 2003).

4.5.4. Running and Monitoring the Simulation

This section describes how the user can run a simulation using OpenTrack and how simulation progress can be monitored on screen. The following two sections describe OpenTrack's animation and monitoring message features respectively.

OpenTrack users set parameters regarding control and monitoring of the simulation using the Simulation Window. The Simulation Window is used to input information used to define the simulation and output information (Figure 125), including simulation input values (e.g. time window, scenarios, delays, etc) and the desired output quantities and diagram.

During the simulation process, the simulation is worked off step by step (dependent on the time step set by the user). At each time t the trains calculate their actual position, speed and acceleration. The necessary routes are requested automatically by the trains and reserved, if possible, and the appertaining signals are set on proceed. If a route cannot be reserved (e.g. if it is occupied by another train, or the route is blocked, etc.), the train brakes so that it comes to a standstill at the main signal before the route in question.

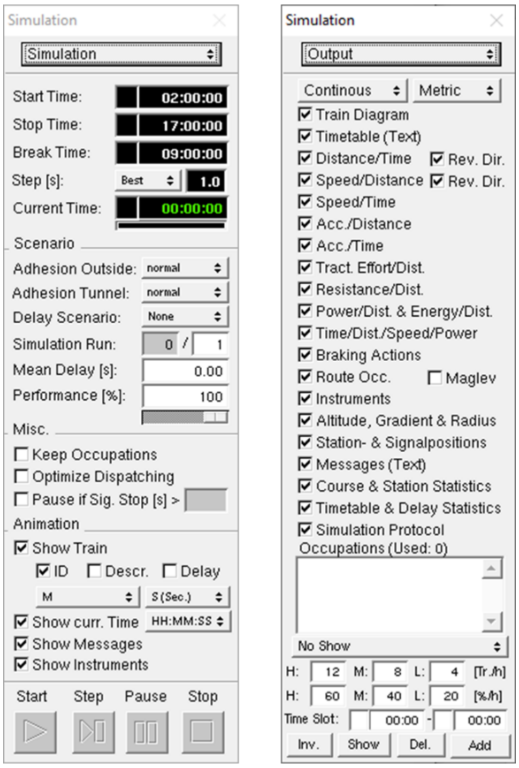


Figure 125 – Simulation Window (left) and Output Window (right).

4.6 Output Data

One of the key advantages of microscopic simulations is that it can log the virtual movements of trains on the infrastructure at each integration step. This huge quantity of data can be displayed and aggregated in several ways to obtain the statistics or diagrams.

4.6.1. Animation

The animation of trains running on the network is not only an impressive output for the decision makers; it also plays a key role for the users of the tool. In fact, it allows the planner to understand and show what happens in the virtual network, and in particular the routes each train takes, the aspect of signals it encounters, the reason of conflicts, etc (Figure 126).

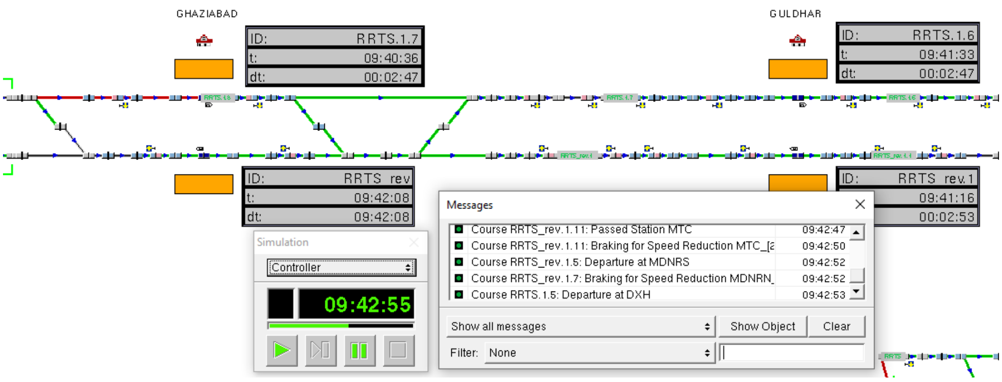


Figure 126 – Animation of Running Trains.

4.6.2. Timetable Graph

The timetable graph is a space-time diagram that represents the planned and/or actual movements of trains (Figure 127). A train moving along the line is represented by a line, whose inclination is proportional to the speed of the train. It is the most common technical diagram in railways and the most efficient to view operations along a line, identifying the conflicts and estimating their effect. A qualitative impression of the usage of a line is easily obtained by adding the blocking times to the timetable graph, giving one of the most easily-comprehensible outputs of deterministic capacity estimations. The graphic timetable can also be used in stochastic simulation, to show the effects on operations of an example delay scenario, obviously with no statistical meaning.

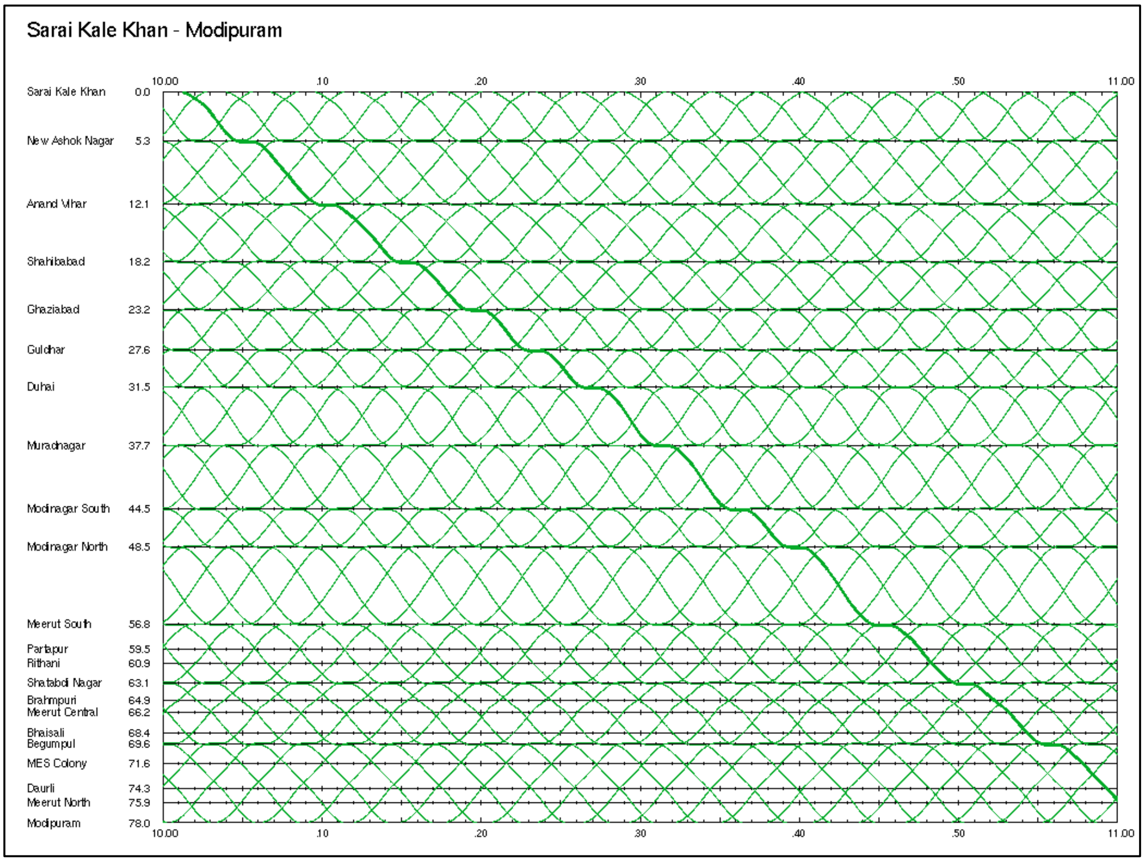


Figure 127 – Timetable Graph.

4.6.3. Diagrams

Diagrams such as speed vs. distance or time, acceleration, power consumption, etc. can be used to show how a train runs on its itinerary, also showing the effect of a different train set or speed profile.

The speed profile of a train on a given route is often visualized in a speed/diagram. It is usefull to add gradient/discance diagram to see how that influences the whole. An example of a typical speed profile as shown in Figure 128, where acceleration, constant movement, braking and coming to stop can be seen.

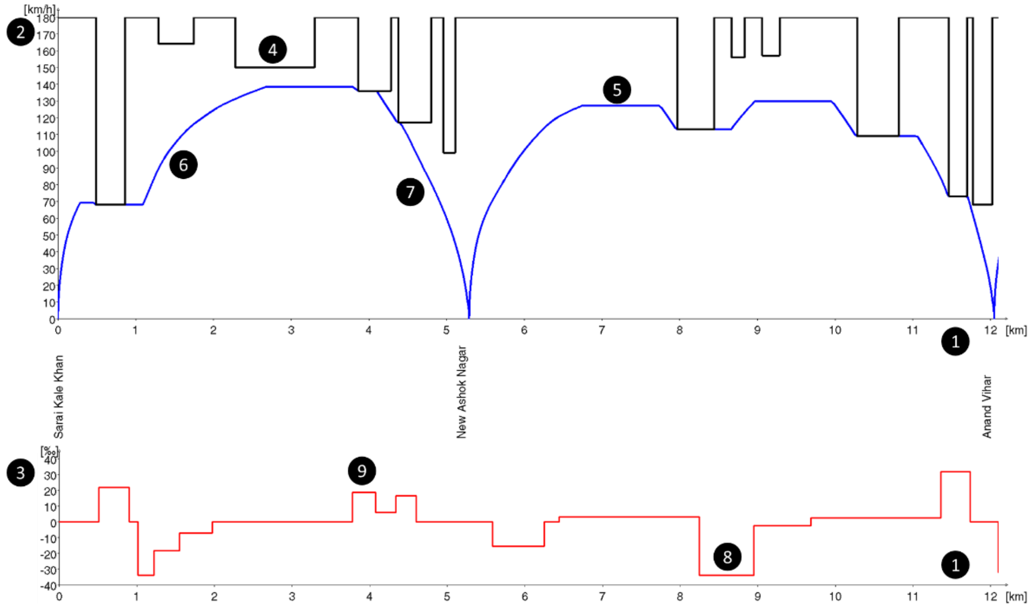


Figure 128 – Speed Profile.

1. The horizontal axis shows the route length measured in kilometers;
2. The vertical axis of the speed/distance diagram shows the velocity measured in km/h;
3. The vertical axis of second diagram shows the gradient of the line measured in ‰;
4. The speed limit given by infrastructure costrains changes several times on the route;
5. The speed of the train;
6. Acceleration phase;
7. Braking phase;
8. Downhill section;
9. Uphill section.

4.6.4. Statistics of Occupation

These statistics show the physical occupation or the blocking time of a certain interlocking element or block section. The blocking times represent the time in which the interlocking and signaling system keep the element blocked for a train; they are normally used as an output of deterministic simulation to identify the usage of critical sections in the peak hours or to show the theoretical headway time on it. The occupations represent the time in which an element is physically occupied by a train: they are useful when analyzing the usage of station tracks (Figure 129).

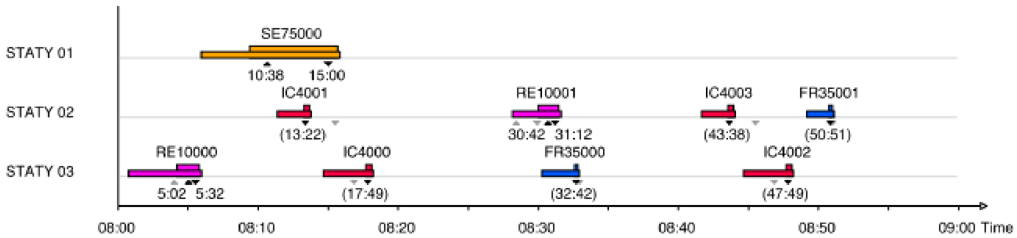


Figure 129 – Platform Occupation Chart.

4.6.5. Delay Statistics

All outputs listed previously mainly refer to deterministic simulations and do not allow aggregating the results of stochastic simulations. As a result, the most important output of stochastic simulations are the statistics of delays (Figure 130). An advantage of simulations is that reliability of operations can be measured using exactly the same indicators used in real operations. Since they can be measured for all trains and at all stations, the user can decide how to group the trains and where to measure them in order to limit the number of tables and graphs inserted in reports. Punctuality is normally measured as it is in reality, and thus at terminal or important stations, while the mean delay, which is not frequently used in official figures of operators and is more sensitive to slight timetable or infrastructure changes, can also be meaningful if measured at other locations. A classic example is the simulation of small infrastructure improvements whose effect might be negligible if it is measured only at the nearest large station.

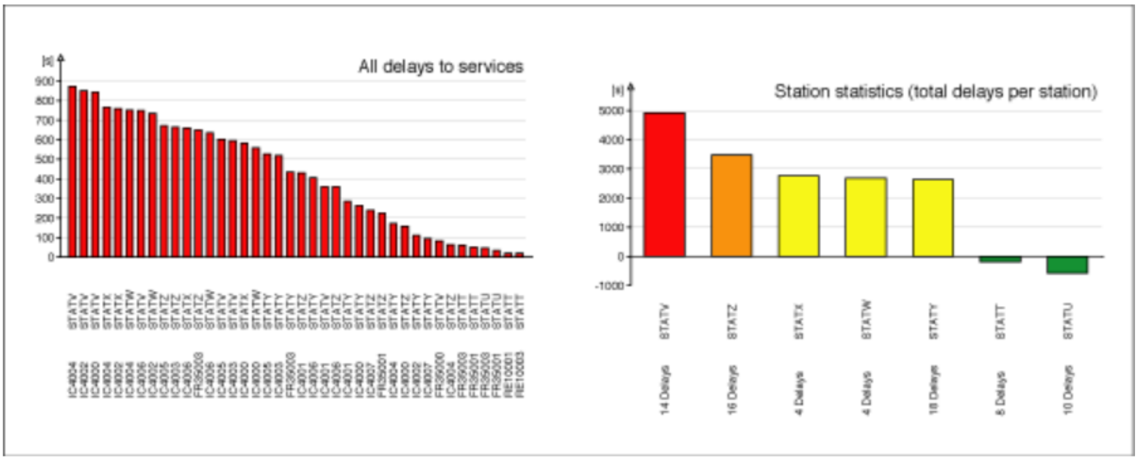


Figure 130 – Delay statistics.

5. CASE STUDIES

The railway signalling principles and the signalling systems have been described in the previous chapters. Then this thesis focused on the definition of the capacity and the techniques used to calculate it and after that, in chapter 4, a detailed description of the simulation activities has been done.

The fifth chapter was entirely dedicated to the presentation of the software used for simulations, Opentrack.

At the end of the bibliographic section, in the following chapter we proceed with the description of the various case studies performed during the doctoral period.

5.1 Projects Overview

The simulation activities involved several projects based on different signalling systems. The following paragraphs will describe in detail the various case studies and for each of them will be excluded:

- Scope of the simulation;
- Data used in the simulation;
- Type of simulation adopted;
- Results.

Figure 131 shows the different projects that have been simulated; specifically, the following lines are analyzed:

- Tvärbanan line: Solna – Sickla in Stockholm, Sweden;
- Næstved - Rødby Færge line, Denmark;
- Kalundborg – Roskilde line, Denmark;
- Metro Line 2 in Milan, Italy;
- Node of Rome, Italy.

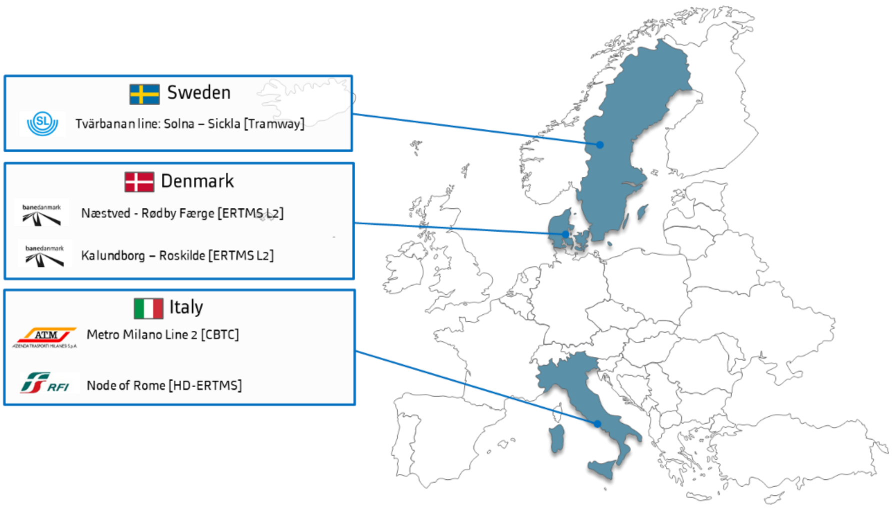


Figure 131 – Project Overview.

5.2 Fjernbane Infrastructure East (Denmark)

Banedanmark, the state-owned rail network infrastructure manager in Denmark has committed to an ambitious and radical planned upgrade of its total main line network. In a first ever decision by a national Infrastructure Manager to modernize its total network (currently amounting to more than 3245 route-km, 307 stations and 750 level crossings) the vision is to see this modernization completed by around 2024. This decision was facilitated by the Danish Parliament in January 2009.

Faced with huge challenges from many different systems, all of them very old, a situation of insufficient capacity and a lack of knowledgeable staff to maintain the existing systems topped with a monopolistic supply situation, the decision to install the state of the art European signalling system ERTMS level 2, made in January 2012, makes total sense. The decision to totally renew/replace the legacy, life expired and obsolete signalling systems deployed in danish soil, some of them dating back to the 1930s, and for which it has become progressively more difficult and expensive to find and acquire spares and to support and to maintain the danish ATC, was based on the urgent need to overcome network signalling problems which accounted for more than 50% of train delays. Indeed, with a system considered to life-expire by 2020, the urgency became evident and the choice was made to adopt a global, mature and interoperable, world-class system.

The introduction of ERTMS will facilitate the connectivity between major cities and capitals in Denmark. It will offer seamless travel within the Europe. With ERTMS, the danish network will be able to grasp the advantage of the inherent features of ERTMS, like increased and homogenous safety levels, allow high speed train movements, increased network capacity , improved punctuality as well as offering the basis for better information to passengers on the performance of the network and overall raising the attractiveness of rail transport. Overall, benefits include the adoption of European standards, fewer safety standards to comply with, fewer traffic management sites, fewer interfaces and less system integration concerns apart from, of course, achievable economies of scale and, in the tender phase, greater competition (UNIFE, 2017b).

5.2.1. Scope of the Simulation

The goal of the project is to design the signalling layout of the lines that will be able to guarantee the headway requirement, applying the lowest amount of signalling equipment.

To achieve this goal, an analytical-based methodology was built to define a robust signalling configuration which also provides a satisfying trade-off between total cost and railway operational performance (Vignali et al., 2020). It can be used for every signalling layout design process with ERTMS standards, with reference to ETCS Level 2, with the same initial inputs required (headway, layout topology, train's characteristics). It is based on Blocking Time Model, developed for ETCS Level 2.

Starting from track layout, rolling stock information and headway scenario, and knowing the trains features, an easy backward calculation, using OpenTrack tool, defines the first signalling equipment position (i.e. Marker Boards, Axle Counter) to fulfil the headway requirements. These outputs are afterwards used by Signalling Engineer to find the correct position of Stop locations considering also signalling engineering rules and operational requirements and constraints.

The purpose of the simulation is therefore to verify the correct design of the layout from the point of view of the capacity requirements.

5.2.2. Lines Overview

Figure 132 and Figure 133 shows the east Danish infrastructure fragmentation into several roll outs. Each of them is subject to a specific design in order to install the ERTMS system on the entire network. In the following paragraph will be analyzed only two rollouts relative to lines R07 and R08.

The R07 rollout extends from Lundby to Rødby Færge (Figure 134) while R08 starts from Roskilde up to Kalundborg (Figure 135). Both the lines have a first portion equipped with double track (Lundby – Nykøbing Falster in R07 and Lejre – Holæk in R08) and then continue with a single track.

The simulation activities have been performed only on the double track portion of both lines as requested by the Banedanmark.

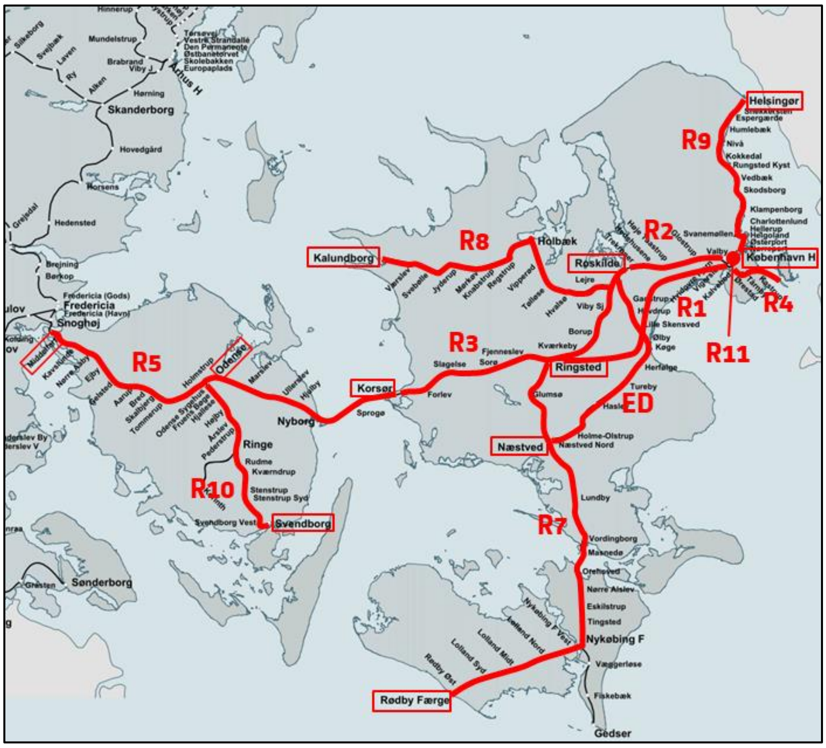


Figure 132 – Rollouts Overview.

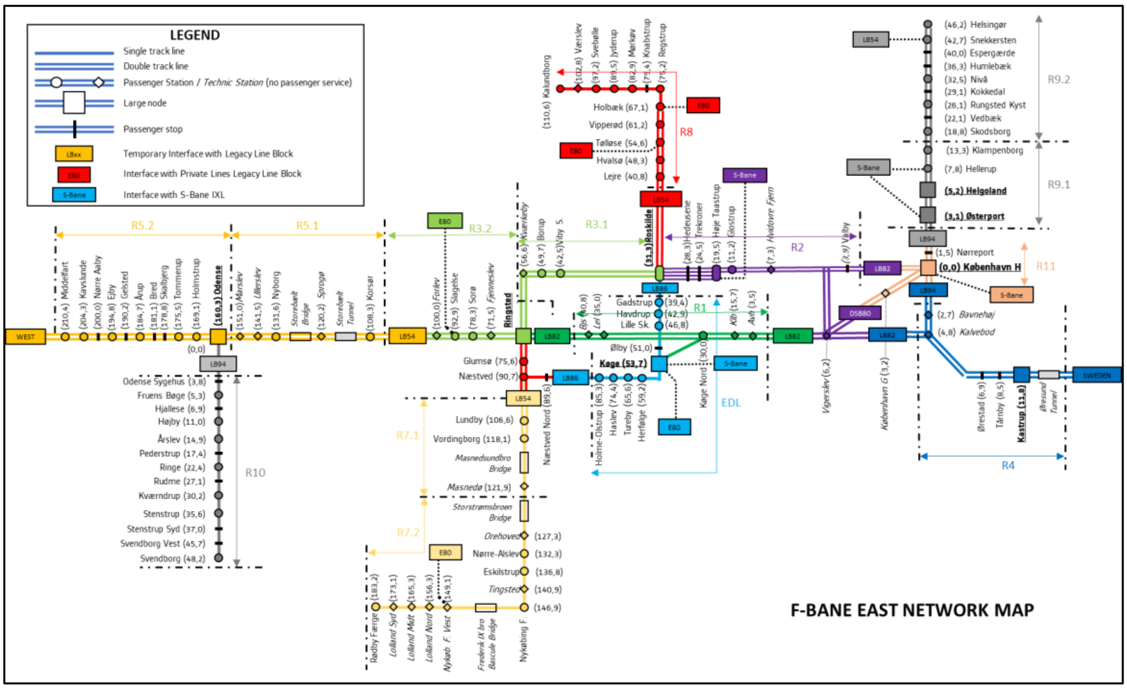


Figure 133 – Rollouts Fragmentation.

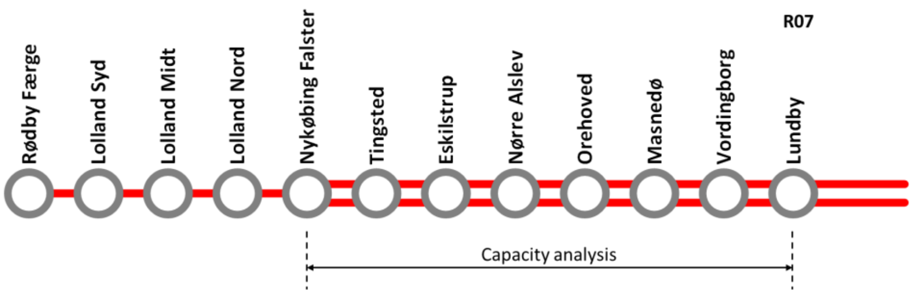


Figure 134 – R0llout 7: Lundby – Rødby Færge.

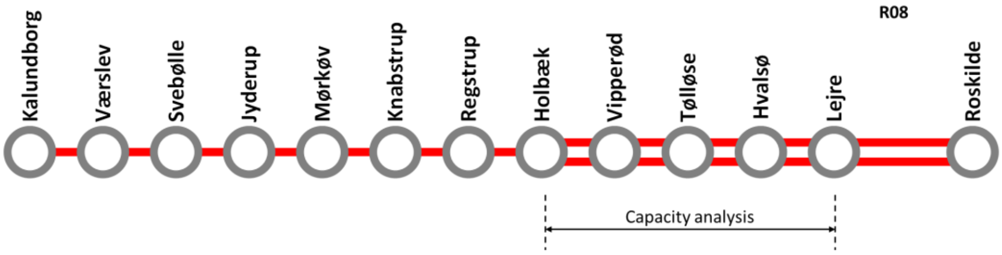


Figure 135 – R0llout 8: Roskilde – Kalundborg.

5.2.3. Fbane Methodology

The methodology is based on the backward calculation. Starting from few input data (rolling stock, operational plan and infrastructure), according to requirements (headway), the preliminary design of signalling block section length is carried out using an analytical calculation model.

Then the signalling layout is submitted to the headway assessment using OpenTrack tool. If the signalling layout fulfils each headway scenarios, it is considered a candidate final solution; otherwise it is re-designed based on Blocking Time Model and the headway assessment is carried out again up to the achievement of all headway scenarios required. When the signalling layout is assessed in OpenTrack tool, also the engineering and operational rules shall be considered, since they block the signal position with respect to safety and/or constraints by the owner of each railway's infrastructure.

The achievable headway, for every track layout, is strictly dependent on input data which therefore influence railway capacity; it's important to define these inputs clearly and on a general level so they can become the "defined step" necessary for the signalling design process.

5.2.4. Simulation Model Assumption

Here below the modelling assumptions related to the input used for the simulation are described.

5.4.2.1 Line Topology

The network layout is modelled in OpenTrack tool with a sequence of nodes and links.

Each edge is characterized by the following features:

- gradient (based on ATC Diagram gradient profile);
- no tunnel if is an outside edge;
- tunnel single smooth if is an inside tunnel edge;
- none information about curve radius;
- loop/ Radio ETCS (flagged for all edges, to allow a continue communication between track and train);
- overlap (flagged only for overlap edges);
- speed for train speed type and both directions, according to track speed profile, each edge contains two speed type "saerlig togset" or "others".

Marker Boards The signals types used in OpenTrack, are:

- Main Signal (home, block or exit signal for Marker Boards);
- Stopping position (stop head signal at platform for passenger train).

Each Marker Board, in OpenTrack, is set as track speed only (based on track speed profile).

No Cab Signal is used in the model, to indicates where ETCS area starts and finishes, because all the network is based on ETCS system. Moreover in OpenTrack model all the edges are flagged with loop/ Radio (ETCS), and the rolling stocks are flagged with loop/ Radio telegram; this means that there is a continuous communication between track and train, each train is modelled with ETCS Braking deceleration value, that is applied to all the network.

5.4.2.2 Overlap

Modelling ETCS, the End of Authority (EOA) is equal to the main signal. Overlaps for all ends of authority are modelled with a standard minimum value of 50 m (according to engineering rules

(Banedanmark, 2012) by placing track liberation equipment (i.e. axle counter) behind the infrastructure element (Figure 136).

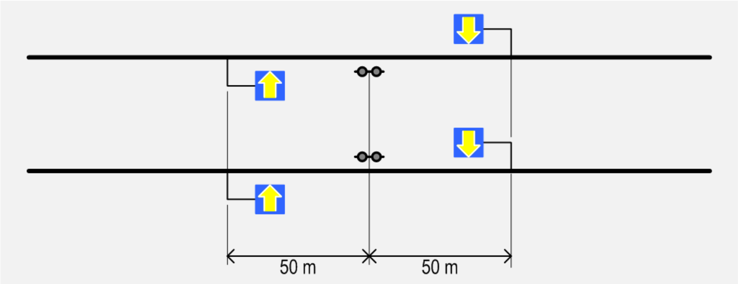


Figure 136 – Marker board and Axle Counter configuration, simple track example.

5.4.2.3 Speed Profile

The simulations will be carried out using the ETCS speed profile based on the train category, defined from the digital maps or ATC diagrams speed profiles (Table 6); where are not available will be used the TIB book (Table 7) given in (Banedanmark, 2013a).

In the ATC diagrams there are some cases with two speed restriction values for the same section, this difference depends by the train speed type ("saerlig togset" and "others"); in the simulation the highest value is applied to the "saerlig togset" train type, instead the lowest is applied to the "others" train type.

The following trains belong to "saerlig togset" train speed type:

- IC3;
- IR4;
- Desiro;
- Velaro.

The following trains belong to "others" train speed type:

- ME;
- EG.

The diverging speeds are taken from ATC Diagram; in some cases, where there are two diverging speeds for the same point, different on running direction base, the diverging lowest speed in both running direction is taken into account in the simulation.

Kalundborg - (Roskilde), main track 1						
Kilometer	Basic [km/h]	CD=100mm [km/h]	CD=130mm [km/h]	CD=150mm [km/h]	Other, Freight P, not replacing CD	Other, Freight G, not replacing CD
110+457	40	-	-	-	-	-
109+742	40	120	-	-	-	-
68+006	40	100	-	-	-	-
65+700	40	160	-	-	-	-
55+202	40	150	-	-	-	-
53+900	40	160	-	-	-	-
37+407	-	-	-	-	-	-

Table 6 – ATC Diagram Speed Profile.

	Line section		Required
TIB	from	to	Speed (Km/h)
1	København H	Vigerslev	120
1	Vigerslev	Hvidovre Fjern	100
1	København H	Hvidovre Fjern	180
1	Hvidovre Fjern	Roskilde	180
1	Roskilde	Ringsted	180
1	Ringsted	Korsør	200
1	Korsør	Nyborg	200
1	Nyborg	Odense	200
1	Odense	Middelfart	180
2	Ringsted	Næstved	160
2	Næstved	Vordingborg	160
2	Vordingborg	Masnedø	160
2	Masnedø	Orehoved	100
2	Orehoved	Nykøbing F	160
2	Nykøbing F	Rødby Færge	160
4	Roskilde	Køge	120
4	Køge	Næstved	120
5	Roskilde	Holbæk	160
5	Holbæk	Kalundborg	120
10	København H	Østerport	60
10	Østerport	Helgoland	90
10	Helgoland	Snekkersten	120
10	Snekkersten	Helsingør	100
11	København H	Kalvebod	120
11	Ny Ellebjerg	Kalvebod	100
11	Kalvebod	Kastrup	160
11	Kastrup	Peberholm	180
21	Odense	Svendborg	120

Table 7 – TIB Book for line speed profiles.

5.4.2.4 Interlocking Routes

In addition to the infrastructure elements, interlocking routes are needed to model train runs. An interlocking route is defined from one marker board to a following marker board. Each route is characterized by a setting time (reserve time) and a release time.

Route Setting time

Route Setting time has been estimated at nominal conditions considering the following contributions:

- TMS to issue the route set command;
- IXL to set the route;
- RBC to send the MA;
- GPRS to transmit the MA to the on-board.

We assumed the following values:

- 8 s for routes without need for point movement (e.g. routes sections without points or without need for point movement):
    - 1,5 s (TMS processing and transmission time);
    - 3 s (IXL processing and transmission time);
    - 1,5 s (RBC processing and transmission time);
    - 2 s (GPRS transmission delay, based on (UNISIG, 2005), is a reasonable representation for 95% of the messages).
- 15 s for routes with need for point movement (i.e. the route including the splitting point in detailed headway cases):
    - 1,5 s (TMS processing and transmission time);
    - 10 s (IXL processing and transmission time, including 4 s point movement time);
    - 1,5 s (RBC processing and transmission time);
    - 2 s (GPRS transmission delay).

Route Release Time

The section clearing (based on release groups, according to signalling characteristics) is assumed in 4 seconds.

5.4.2.5 Rolling stock

The rolling stock types required in the headway scenarios on R07 and R08 lines are:

- EG (freight train, 750 m length, braking weight percentage 80%, trailers weight 1600 t);
- IR4 (passenger train 228 m length, braking weight percentage 180%);
- ET (passenger train, 350 m length, braking weight percentage 180%, weight 680 t).

Some rolling stock values, required in OpenTrack tool, are set to default value in case of missing information provided by the customer.

The technical data for the following trains have been derived from (Banedanmark, 2013b, 2013c)

EG Freight Train

The freight train is composed by EG loco (engine) plus trailers and is available in 3 different configuration size: 750 m, 835 m and 1000 m length. Figure 137 shows the EG loco while in Table 8 the technical data are reported.

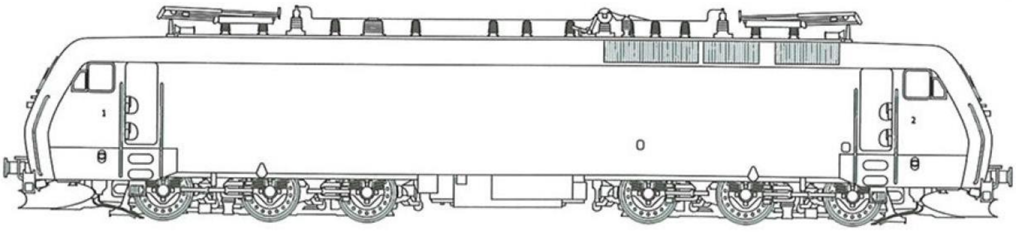


Figure 137 – EG Loco.

Parameter	Value
Load	87 t
Adherence load (Not influence, covered by tractive effort / speed diagram)	87 t (100% of total weight)
Length	21 m
Max. Speed	140 km/h
Max. Tractive Effort	400 KN
Max. Acceleration (OT default value)	3 m/s^2 (No influence)
Resistance Factor (OT default value)	3,2999
Rotating Mass Factor (OT default value)	1,10
Adhesion (OT default value)	Normal (125%)
Engine	Electric Engine

Table 8 – EG loco technical data.

In Figure 139 the EG traction force diagram is shown.

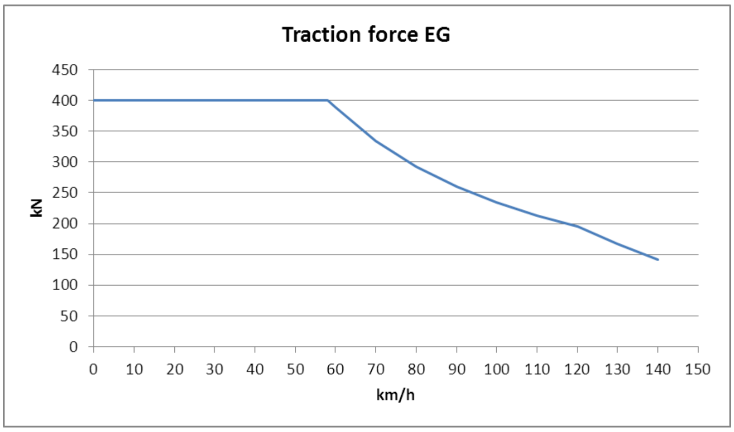


Figure 138 – EG Traction Force.

Considering also the trailers attached to the EG loco (Figure 139), Table 9 reports the freight train technical data.

Figure 139 – EG Freight Train.

Parameter	Value
Train Type	Freight
Load	1687 t (EG + 1600 t trailers)
Length	750 m / 835 m / 1000 m
Davis Formula (Air Resistance)	R= A + B*v+ C*v^2 (A= 3,300; B= 0,02422; C= 0,000552)
Curve Resistance (Roeckl Formula)	Not Applied
Braked Weight Percentage (BWP)	80% (Not Relevant for Deceleration function Default ETCS)
Max trailers speed	100 km/h
Deceleration function	Default (ETCS)
EB Deceleration Profile (EBD Curve)	<table><tr><td>Speed interval / km/h</td><td>Deceleration / m/s^2</td></tr><tr><td>0-100</td><td>0,54</td></tr></table>

Table 9 – Freight train technical data.

IR4 Passenger Train

The IR4 train, 228 m length, is composed by 3 trains sets coupled, each length 76 m. Figure 140 shows the single train set composition while in Table 10 the technical data are reported.

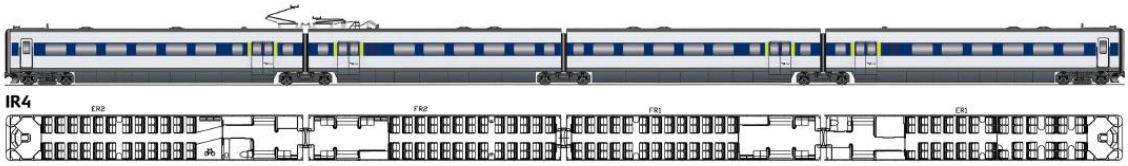


Figure 140 – IR4 Single Train Set.

Parameter	Value
Load	133 t
Adherence load (Not influence, covered by tractive effort / speed diagram)	66,5 t (50% of total weight)
Length	76 m
Max. Speed	180 Km/h
Max. Tractive Effort	417 KN
Max. Acceleration (OT default value)	3 m/s^2 (No influence)
Resistance Factor (OT default value)	3,2999
Rotating Mass Factor (OT default value)	1,0599
Adhesion (OT default value)	Normal (125%)
Engine	Electric Engine
Composition	ER-FR-FR-ER (Loco - Car - Car - Loco)

Table 10 – IR4 single set technical data.

In Figure 141 the IR4 traction force diagram is shown.

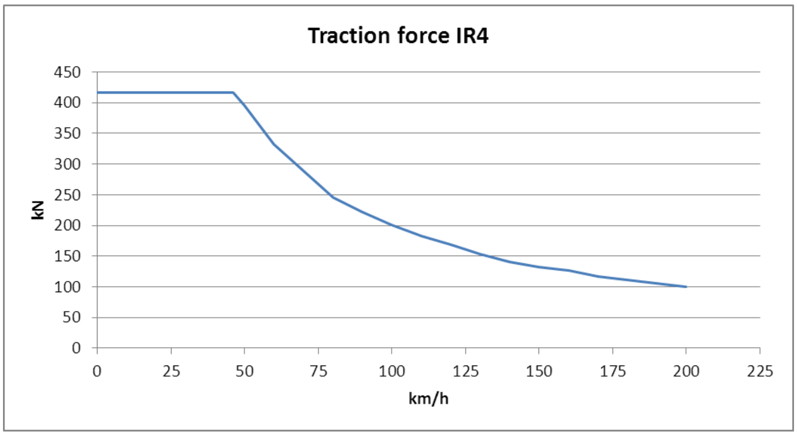


Figure 141 – IR4 Traction Force.

Considering the final composition of 3 train sets, Table 11 reports the IR4 train technical data.

<table>
<tr><th>Parameter</th><th>Value</th></tr>
<tr><td>Train Type</td><td>IC/ Fast Train</td></tr>
<tr><td>Load</td><td>399 t</td></tr>
<tr><td>Length</td><td>228 m</td></tr>
<tr><td>Davis Formula
(Air Resistance)</td><td>R= A + B*v+ C*v^2
(A= 3,300; B= 0,02422; C= 0,000552)</td></tr>
<tr><td>Curve Resistance
(Roeckl Formula)</td><td>Not Applied</td></tr>
<tr><td>Braked Weight Percentage (BWP)</td><td>180%
(Not Relevant for Deceleration function Default ETCS)</td></tr>
<tr><td>Deceleration function</td><td>Default (ETCS)</td></tr>
<tr><td>EB Deceleration Profile
(EBD Curve)</td><td><table><tr><th>Speed interval / km/h</th><th>Deceleration / m/s^2</th></tr><tr><td>0-100</td><td>1,31</td></tr><tr><td>100-120</td><td>1,11</td></tr><tr><td>120-150</td><td>0,91</td></tr><tr><td>150-155,55</td><td>1,14</td></tr><tr><td>155,55-180</td><td>0,87</td></tr></table></td></tr>
</table>

Table 11 – Passenger IR4 technical data.

ET Passenger Train

The train called "ET" is a theoretical train having the maximum allowed length of passenger trains with dynamic characteristics of one multiple units. Figure 142 shows the single train set composition while in Table 12 the engine technical data are reported.

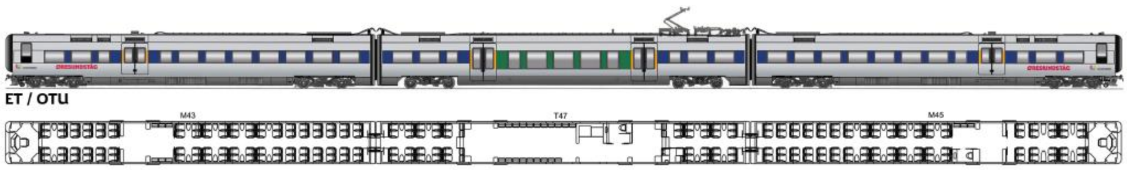


Figure 142 – ET Single Train Set.

Parameter	Value
Load	136 t
Adherence load (Not influence, covered by tractive effort / speed diagram)	50% of total weight
Length	70 m
Max. Speed	200 Km/h
Max. Tractive Effort	170 KN
Max. Acceleration	0,78 m/s2
Resistance Factor (OT default value)	3,2999
Rotating Mass Factor (OT default value)	1,0599
Adhesion (OT default value)	Normal (125%)
Engine	Electric Engine

Table 12 – ET single set technical data.

In Figure 143 the ET traction force diagram is shown.

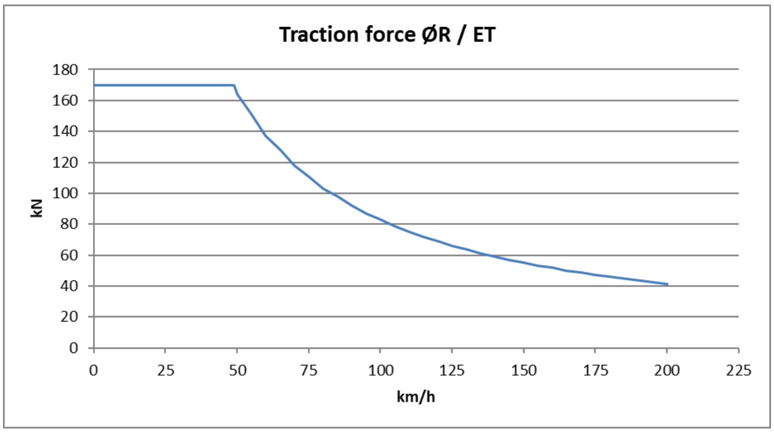


Figure 143 – ET Traction Force.

Considering the final composition of 5 train sets, Table 13 reports the ET train technical data.

<table>
<tr><th>Parameter</th><th>Value</th></tr>
<tr><td>Train Type</td><td>IC/ Fast Train</td></tr>
<tr><td>Load</td><td>680 t</td></tr>
<tr><td>Length</td><td>350 m
(5 trainsets)</td></tr>
<tr><td>Davis Formula
(Air Resistance)</td><td>R= A + B*v+ C*v^2
(A= 3,300; B= 0,02422; C= 0,000552)</td></tr>
<tr><td>Curve Resistance
(Roeckl Formula)</td><td>Not Applied</td></tr>
<tr><td>Braked Weight Percentage (BWP)</td><td>180%
(Not Relevant for Deceleration function Default ETCS)</td></tr>
<tr><td>Deceleration function</td><td>Default (ETCS)</td></tr>
<tr><td>EB Deceleration Profile
(EBD Curve)</td><td><table>
<tr><th>Speed interval / km/h</th><th>Deceleration / m/s^2</th></tr>
<tr><td>0-100</td><td>1,31</td></tr>
<tr><td>100-120</td><td>1,11</td></tr>
<tr><td>120-150</td><td>0,91</td></tr>
<tr><td>150-155,55</td><td>1,14</td></tr>
<tr><td>155,55-180</td><td>0,87</td></tr>
<tr><td>180-200</td><td>0,91</td></tr>
</table></td></tr>
</table>

Table 13 – Passenger ET technical data.

5.4.2.6 ETCS Braking Curve

In accordance to the Banedanmark requirements, if two trains are following each other at short headway (let's assume that train 2 follows train 1), it is acceptable that for train 1 an "Indication" (yellow) is repeatedly shown to the driver of train 1, and Normal Status (white) is repeatedly shown to the train 2 driver. These two colors appear as the current MA becomes shorter and shorter and disappear when the MA is extended. This is equivalent to the current way of driving on main lines with dense traffic under Danish ATC.

The terms "Indication" means that the DMI turns from white to yellow, indicating the driver that he must start braking using the service brake. The driver is then expected to brake according to the permitted speed curve.

The terms "Normal Status" means that the DMI turns from grey to white, indicating the driver that he is entering target speed monitoring. This reflects the situation where the train is approaching or has reached the indication point (from a braking curve perspective).

This has the consequence that all capacity simulations should be carried out using:

- the permitted braking curve (permitted point) for the first train (Train 1);
- the indication braking curve (indication point) for the second train (Train 2).

The signalling track plan is designed using the Indication Braking Curve, because this is the most conservative curve.

Banedanmark has provided for each train the following curves:

- Emergency Braking Deceleration Curve (EBD), calculated based on the trains EB deceleration profile;
- Permitted Braking Curve (P), calculated applying a time deceleration delay to the EBD (adding the EB build-up time and the SB build-up time and T_driver);
- Indication Braking Curve (I), calculated applying an additional delay between the P and I curves (depends from the SB build-up time of the train).

The braking curves and their assumptions are provided by Banedanmark.

Here below in Figure 144 is shown an example of EBD, P, I curves provided for each train.

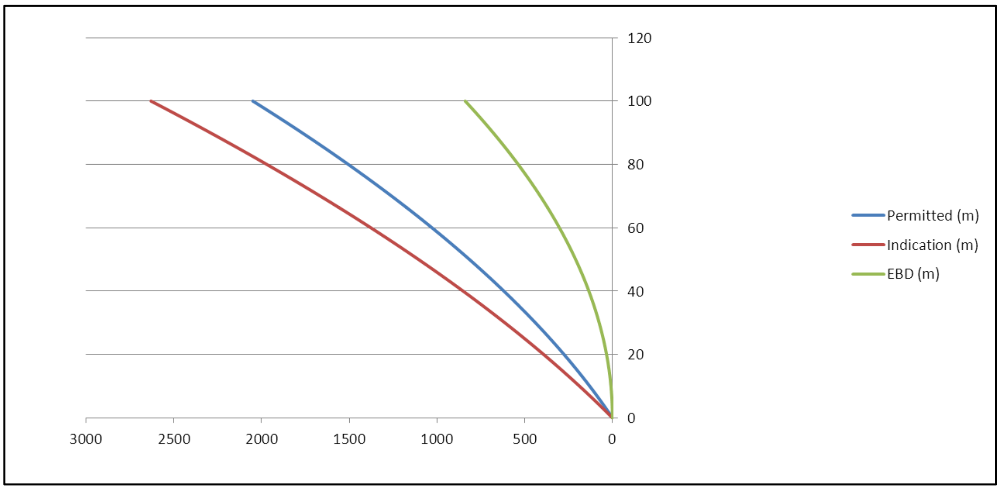


Figure 144 – ETCS Braking Curves.

In OpenTrack tool the EB deceleration profile is rounded down to the second decimal, therefore the braking curves using to carry out the simulations are a little more (about 1%) conservative than the input braking curves, so the customer has decide to improve the follower train braking behaviour, taking into account the Opentrack tool's constraints, applying the Permitted curve and increasing the route release time of each route of 5 seconds if the follower train is a passenger train.

The value of 5 seconds is the typical time difference between the P and I curve, then the release route time becomes 9 seconds when a passenger train is following another train; in this way it's possible to carry out a simulation closer to the reality, because both trains brake according to the P curve and the time distance between the trains is set to avoid an Indication (yellow display) on the follower train.

The braking curves and the braking distances provided by Banedanmark, based on normal adhesion condition and at level track (0% gradient), are used in the simulations also in case of a sloping track scenario (gradient profile different from 0).

However, the effect of the gradient profile on the ETCS Braking Curve, due to the strong slopes, is taken into account applying the "Correction deceleration in gradients in $m/s^2/$ ‰" in OpenTrack. This parameter value shall be 0.01 $m/s^2/$ ‰ in accordance to Banedanmark. This corresponds to the way that the ETCS specifications take gradient into account, please refer to UNISIG (2016).

For each train are defined the EBD deceleration values, the time delay from EBD to P and the time delay from P to I.

The service brake intervention in target speed monitoring is removed, to make up for the fact that there is no service brake intervention, there has to be a bigger delay from the point where the driver is indicated to brake (I curve) and to the preferred braking (P curve). This time includes the service brake build up time as well as some fixed delays, and for long freight trains the service brake build up time is very long.

EG Freight Train

The time delay from EBD to P (Target speed>0) and the time delay from P to I is shown in Table 14 for each freight train length:

Freight Train Length in meters	Time delay from EBD to P in seconds:	Time delay from P to I in seconds:
750	18,24	22,83
835	20,99	25,09
1000	26,32	30,44

Table 14 – EG decelerations delay.

The reason for the big delay difference from P to I has to do with the fact, that the service brake intervention in target speed monitoring is removed. To make up for the fact that there is no service brake intervention, there has to be a bigger delay from the point where the driver is indicated to brake (I curve) and to the preferred braking (P curve). This time includes the service brake build up time as well as some fixed delays, and for long freight trains the service brake build up time is very long.

Here below the EG train braking curves depending by the length are reported:

- Figure 145 and Table 15 are related to freight train 750 meters long;
- Figure 146 and Table 16 are related to freight train 835 meters long;
- Figure 147 and Table 17 are related to freight train 1000 meters long.

EG 750 m		
Speed (Km/h)	Permitted Braking Distance (m)	Indication Braking Distance (m)
100	1220	1854
90	1034	1605
80	845	1352
70	699	1143
60	554	935
50	417	734
40	305	559
30	208	398
20	118	245
10	45	108
0	0	0

Table 15 – EG 750 meters ETCS braking curves.

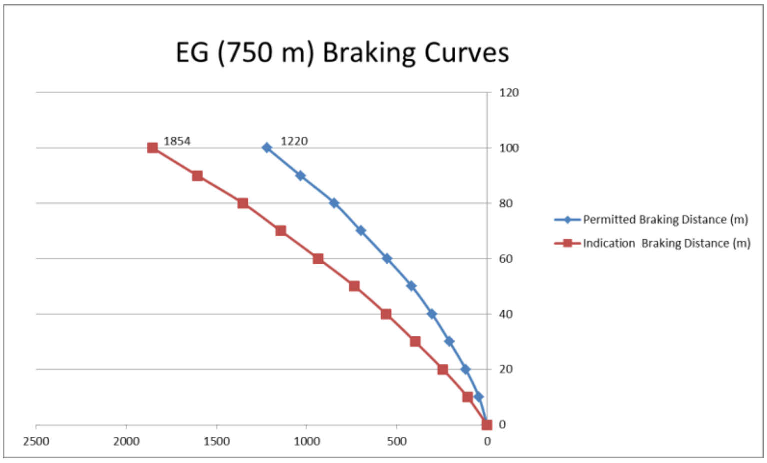


Figure 145 – EG 750 meters ETCS braking curves.

EG 835 m		
Speed (Km/h)	Permitted Braking Distance (m)	Indication Braking Distance (m)
100	1309	2006
90	1097	1724
80	908	1466
70	742	1230
60	598	1016
50	460	808
40	335	614
30	228	437
20	131	270
10	53	123
0	0	0

Table 16 – EG 835 meters ETCS braking curves.

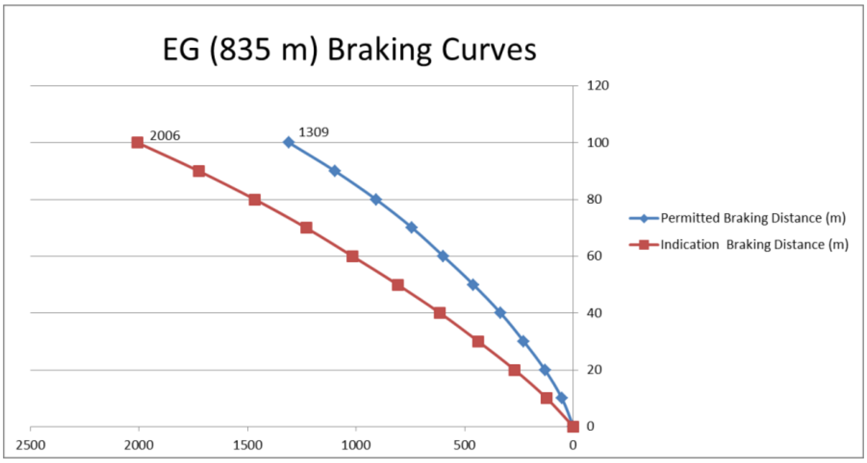


Figure 146 – EG 835 meters ETCS braking curves.

EG 1000 m		
Speed (Km/h)	Permitted Braking Distance (m)	Indication Braking Distance (m)
100	1429	2275
90	1218	1979
80	1029	1705
70	841	1433
60	679	1186
50	526	949
40	389	727
30	263	517
20	154	323
10	62	147
0	0	0

Table 17 – EG 1000 meters ETCS braking curves.

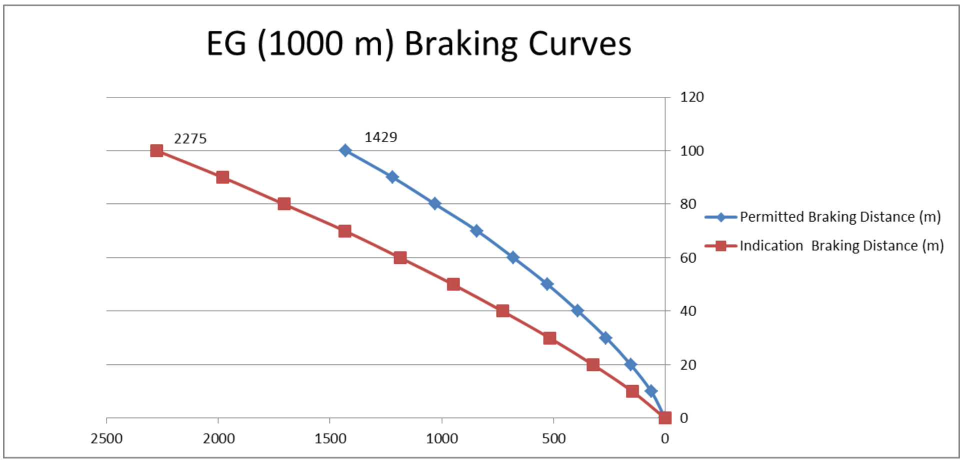


Figure 147 – EG 1000 meters Braking Curve.

IR4, ET Passenger Train

The time delay from EBD to P (Target speed>0) and the time delay from P to I is shown in Table 18 for both trains.

Time delay from EBD to P in seconds:	10,03
Time delay from P to I in seconds:	5

Table 18 – IR4, ET decelerations delay.

Here below the IR4 (Figure 148, Table 19) and ET (Figure 149, Table 20) train braking curves used in simulations are reported.

IC3/ IR4		
Speed (km/h)	Indication Braking Distance (m)	Permitted Braking Distance (m)
180	1976	1726
170	1767	1531
160	1569	1347
150	1425	1217
140	1249	1055
130	1086	905
120	933	766
110	823	670
100	721	582
90	601	476
80	517	406
70	439	342
60	352	269
50	276	207
40	200	144
30	138	96
20	83	55
10	32	18
0	0	0

Table 19 – IR4 Braking Curve.

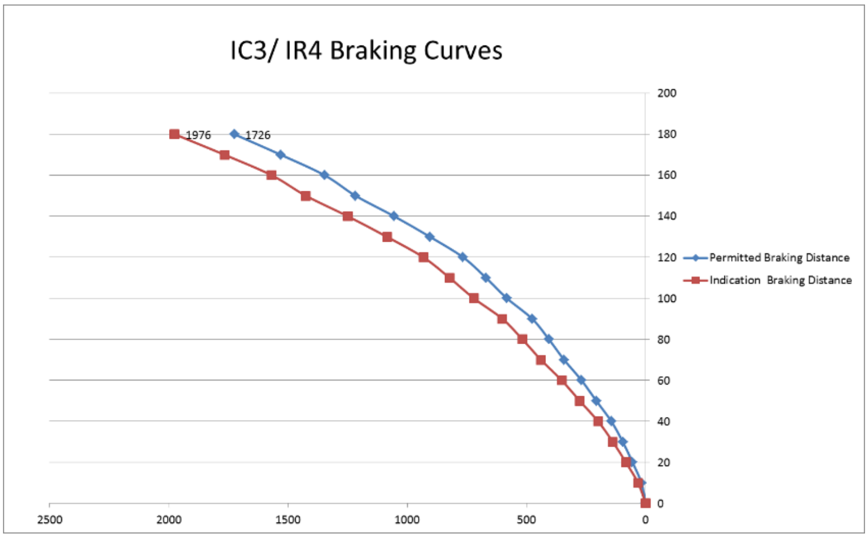


Figure 148 – IR4 Braking Curve.

ET		
Speed (km/h)	Indication Braking Distance (m)	Permitted Braking Distance (m)
200	2097	2370
180	1726	1976
170	1531	1767
160	1347	1569
150	1217	1425
140	1055	1249
130	905	1086
120	766	933
110	670	823
100	582	721
90	476	601
80	406	517
70	342	439
60	269	352
50	207	276
40	144	200
30	96	138
20	55	83
10	18	32
0	0	0

Table 20 – ET Braking Curve.

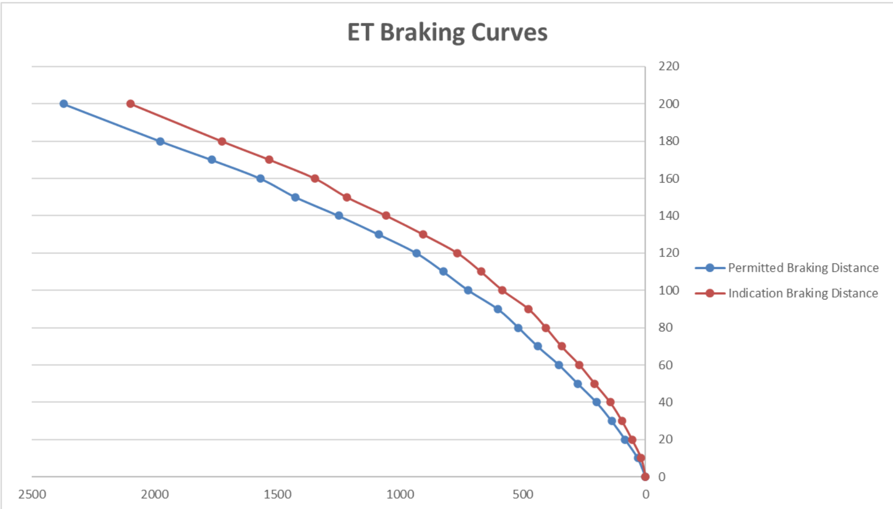


Figure 149 – ET Braking Curve.

5.4.3. Capacity Headway Requirements

For Fjernbane Infrastructure East, the scenarios with headway requirements (operational headway requirement means technical headway plus 15 seconds tolerance) are described in Table 21 and Table 22. The headway cases can be catalogued with letters from A to F based on the particular train sequence to be simulated as explained in paragraph 3.3.4.

The headway requirement that must be fulfilled is the Technical headway, as required by Banedanmark, that means each detailed operational headway scenario in the tables, must be considered reduced of the 15 seconds of tolerance.

The headway cases are fulfilled for each scenario, for each track in both directions, whereas the train sequence has changed (Figure 150).

Scenarios	Section	1st Train	2nd Train	Case	Headway [sec]	Separate Tracks in Station
1	Korsor - Sporgo	IC3, stop at Korsor	EG, stop at Korsor	C	min	Korsor

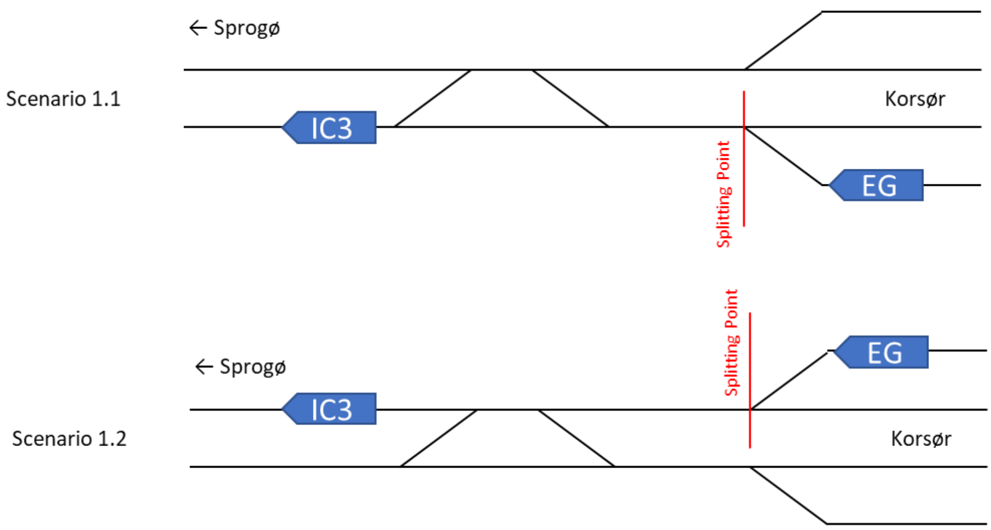


Figure 150 – Detailed headway scenarios "Case C".

Scenarios	Section	1st Train	2nd Train	Case	Headway [sec]	Separate Tracks in Station
1	(Ringsted) – Puttgarden	ET 350m, bp 180, stop at Ringsted	ET 350m, bp 180, stop at Ringsted	A	165	(Ringsted)
2	Puttgarden– (Ringsted)	ET 350m, bp 180, stop at Ringsted	ET 350m, bp 180, stop at Ringsted	A	165	(Ringsted)
3	(Næstved) – Lundby	EG 1000m, bp 80, stop at Lundby	ET 350m, bp 180 no stop	C	130 at end	Lundby
4	Lundby – (Næstved)	ET 350m, bp 180 no stop	EG 1000m, bp 80, stop at Lundby	C	25 at start	Lundby

Scenarios	Section	1st Train	2nd Train	Case	Headway [sec]	Separate Tracks in Station
5	Lundby – Vordingborg	ET 350m, bp 180 no stop	EG 1000m, bp 80, stop at Lundby	C	25 at start	Lundby
6	Vordingborg – Lundby	EG 1000m, bp 80, stop at Lundby	ET 350m, bp 180 no stop	C	130 at end	Lundby
7	Lundby – Vordingborg	EG 1000m, bp 80, stop at Vordingborg	ET 350m, stop at Vordingborg	C	130 at end	Vordingborg
8	Vordingborg – Lundby	ET 350m, bp 180 stop at Vordingborg	EG 1000m, bp 80, stop at Vordingborg	C	85 at start	Vordingborg
9	Vordingborg – Orehoved	ET 350m, bp 180, stop at Vordingborg	EG 1000m, bp 80, stop at Vordingborg	C	85 at start	Vordingborg
10	Orehoved - Vordingborg	EG 1000m, bp 80, stop at Vordingborg	ET 350m, bp 180, stop at Vordingborg	C	130 at end	Vordingborg
11	Vordingborg- Orehoved	EG 1000m, bp 80, stop at Orehoved	ET 350m, bp 180, no stop	C	130 at end	Orehoved
12	Orehoved - Vordingborg	ET 350m, bp 180, no stop	EG 1000m, bp 80, stop at Orehoved	C	25 at start	Orehoved
13	Orehoved – Nørre Alslev	ET 350m, bp 180, no stop	EG 1000m, bp 80, stop at Orehoved	C	25 at start	Orehoved
14	Nørre Alslev – Orehoved	EG 1000m, stop at Orehoved	ET 350m, bp 180, no stop	C	130 at end	Orehoved
15	Nørre Alslev– Nykøbing F	EG 1000m, bp 80, stop at Nykøbing F	ET 350m, stop at Nykøbing F	C	130 at end	Nykøbing F
16	Nykøbing F – Nørre Alslev	ET 350m, bp 180, stop at Nykøbing F	EG 1000m, bp 80, stop at Nykøbing F	C	85 at start	Nykøbing F
17	Nykøbing F – (Holeby)	ET 350m, bp 180, stop at Nykøbing F	EG 1000m, bp 80, stop at Nykøbing F	C	85 at start	Nykøbing F
18	(Holeby) – Nykøbing F	EG 1000m, bp 80, stop at Nykøbing F	ET 350m, bp 180, stop at Nykøbing F	C	130 at end	Nykøbing F

Table 21 – R07 Headway Scenario Requirements.

Scenarios	Section	1st Train	2nd Train	Case	Headway [sec]	Separate Tracks in Station
1	(Roskilde) – Tølløse	IR4 228m, bp 180, stop at Roskilde	IR4 228m, bp 180, stop at Roskilde	A	240	(Roskilde)
2	Tølløse – (Roskilde)	IR4 228m, bp 180, stop at Roskilde	IR4 228m, bp 180, stop at Roskilde	A	240	(Roskilde)
3	(Roskilde) – Tølløse	IR4 228m, bp 180 stop at Roskilde	IR4 228m, bp 180 stop at Roskilde, Lejre (15s), Hvalsø (15s)	B	120 at start	(Roskilde)
4	Tølløse – (Roskilde)	IR4 228m, bp 180 stop at Hvalsø (15s), Lejre (15s), Roskilde	IR4 228m, bp 180 stop at Roskilde	B	120 at end	(Roskilde)
5	Hvalsø – Holbaek	IR4 228m, bp 180, stop at Tølløse (15s), Vipperød (15s), Holbaek	IR4 228m, bp 180 stop at Holbaek	B	120 at end	Holbaek
6	Holbaek – Hvalsø	IR4 228m, bp 180 stop at Holbaek	IR4 228m, bp 180, stop at Holbaek, Vipperød (15s), Tølløse (15s)	B	120 at start	Holbaek

Table 22 – R08 Headway Scenario Requirements.

5.4.4. Design of Block Section Length

The preliminary design of signalling block section length is based on the blocking time model for ETCS L2 system that takes in input different parameters that are described in the previous paragraphs. It consists of the following parts (Figure 151, refer to Train 1):

- Route setting time (T_{RS}): that is the sum of Traffic Management System (TMS) command time, time of implementation of the route by IXL (Interlocking) and time of elaboration because dispatch of MA by RBC includes transmission delay (s). Route setting shall occur before the train reaches the Indication Point related to the EoA at the beginning of block section;
- Indication time (T_I) that is the time to travel the Indication braking distance (i.e. from the Indication Point to the stopping point at the beginning of block section) (s);
- Section length occupation ($T_{SECTION}$) that is the time to travel the block section (s);

- Overlap occupation (T_{OL}) that is the time to travel the overlap length at the end of block section (s);
- Train length occupation (T_{TL}) that is the time to travel the train length (s);
- Free track detection (T_{FTD}) that is the time to detect the track free within the block section (s).

The minimum headway is the minimum distance allowed between two consecutive trains with specified speed profiles and, comprising the blocking time sequences, is defined by Blocking Time Model in the critical section with hindrance free train running (i.e. usually the longest section of the others, or the section corresponding at the train stop because there is, also, the dwell time).

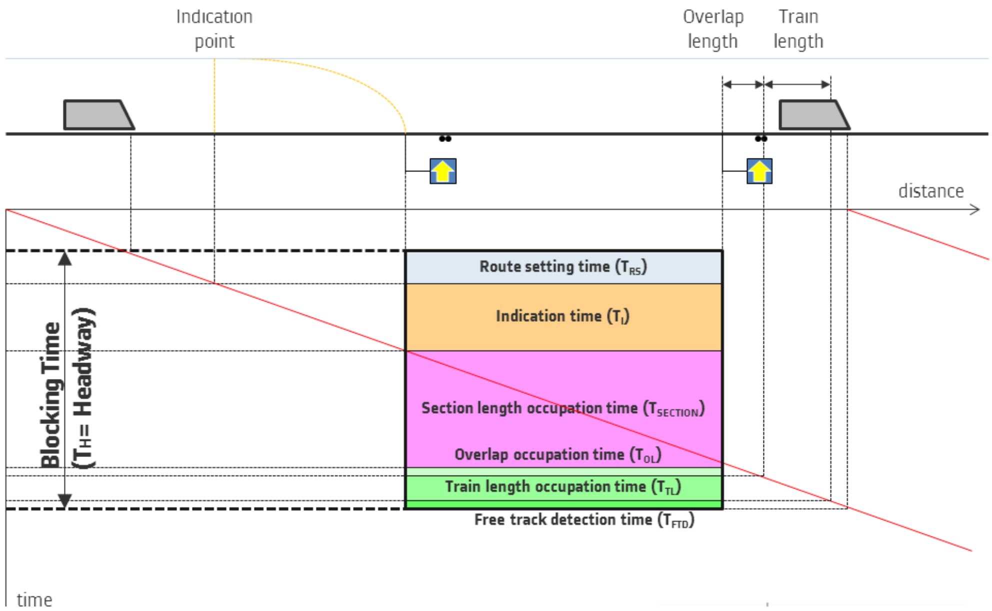


Figure 151 – ETCS L2 Blocking Time Model.

The block section length ($L_{SECTION}$) derives from the section occupation time ($T_{SECTION}$), calculated subtracting from the headway technical value (T_H) all the other Blocking Time components according to the following equations:

$$L_{SECTION} = T_{SECTION} \cdot V_{MAX}$$

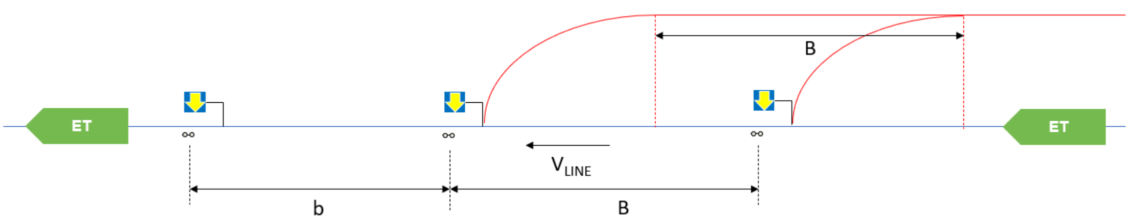
$$T_{SECTION} = T_H - T_{RS} - T_I - T_{OL} - T_{TL} - T_{FTD}$$

$$T_{SECTION} = T_H - T_{RS} - \left(\frac{D_I}{V_{MAX}}\right) - \left(\frac{D_{OL}}{V_{MAX}}\right) - \left(\frac{D_{TL}}{V_{MAX}}\right) - T_{FTD}$$

where D_I, D_{OL} and D_{TL} are respectively the Indication distance, the Overlap length and train length (m).

Due to the fact that different headway scenarios have to be verified with different kind of trains, it is important to identify and verify the worst-case scenario; usually the worst case is the "Case C" that affect the computation of block section length close to splitting point of the stations where a stopping freight train is followed by a non-stopping passenger train and vice versa.

Referring to the Case A, the maximum length of the section is calculated through a relation between the time required for the first passenger train to travel in the section "b" (Tb) and the time necessary for the second passenger train to travel in the section "B" (TB) (Figure 152).



$$T_b = \frac{b}{V_{ET}} \qquad T_B = \frac{B}{V_{ET}} \qquad V_{ET} = \min(V_{LINE}; V_{TRAIN}; V_{AVG})$$

$$T_B \le T_b \rightarrow \frac{B}{V_{ET}} \le \frac{b}{V_{ET}} \rightarrow B \le b$$

Figure 152 – Case A backward calculation.

Table 23 show an example of the output of the preliminary design of block length coming from the backward calculation related to a "Case A" of an IR4 train for different speed limits and headway requirements.

Input Data				
T_{RS} [s]	Route Setting Time			8
D_{OL} [m]	Overlap Lenght			50
D_{TL} [m]	Train Lenght			228
T_{FTD} [s]	Free Track Detection Time			4
T_{FTD} [s]	Free Track Detection Time			9

Speed / Headway Matrix								
Train: IR4		Indication Distance [m]	Headway requirement [s]					
			100	120	135	150	180	240
Speed [Km/h]	10	32	< 0	< 0	< 0	30 m	110 m	270 m
	20	83	< 0	150 m	230 m	310 m	470 m	800 m
	30	138	180 m	350 m	470 m	590 m	840 m	1330 m
	40	200	320 m	540 m	700 m	870 m	1190 m	1850 m
	50	276	450 m	720 m	920 m	1130 m	1530 m	2350 m
	60	352	570 m	900 m	1140 m	1390 m	1880 m	2860 m
	70	439	680 m	1060 m	1350 m	1640 m	2210 m	3350 m
	80	517	810 m	1240 m	1570 m	1890 m	2550 m	3850 m
	90	601	920 m	1410 m	1780 m	2150 m	2880 m	4350 m
	100	721	1000 m	1550 m	1960 m	2360 m	3180 m	4810 m
	110	823	1100 m	1700 m	2150 m	2600 m	3500 m	5290 m
	120	933	1190 m	1850 m	2340 m	2830 m	3810 m	5770 m
	130	1086	1240 m	1950 m	2480 m	3010 m	4070 m	6200 m
	140	1249	1280 m	2040 m	2610 m	3190 m	4330 m	6620 m
	150	1425	1310 m	2120 m	2740 m	3350 m	4570 m	7020 m
	160	1569	1360 m	2240 m	2890 m	3540 m	4850 m	7460 m
	170	1767	1370 m	2290 m	2990 m	3680 m	5070 m	7850 m
	180	1976	1360 m	2340 m	3080 m	3810 m	5280 m	8220 m

Maximum Section Lenght

Table 23 – IR4 Block Length Calculation Table.

Referring to the "Case C" scenario, it is possible to separate the backward calculation between arrival case and departure case; the more restrictive case between the two, that is that one that have more short sections, will be applied.

For "Case C" at arrival, in the first section before splitting point the maximum length of the section is calculated through a relation between the time required for the EG train to travel in the section "a" (Ta) and the time necessary for the ET train to travel in the section "A" (TA) (Figure 153).

Ta is evaluated as a function of the diverging track speed (VDIV), the route setting time of diverging track (Tset_div), the route setting time of straight track (Tset_straight) and the length of the section "a" (a).

TA is evaluated as a function of the length of the section "A" (A) and the ET train speed (VET), that is the minimum among the line speed (VLINE), the train speed (VTRAIN) and the train average speed (VAVG).

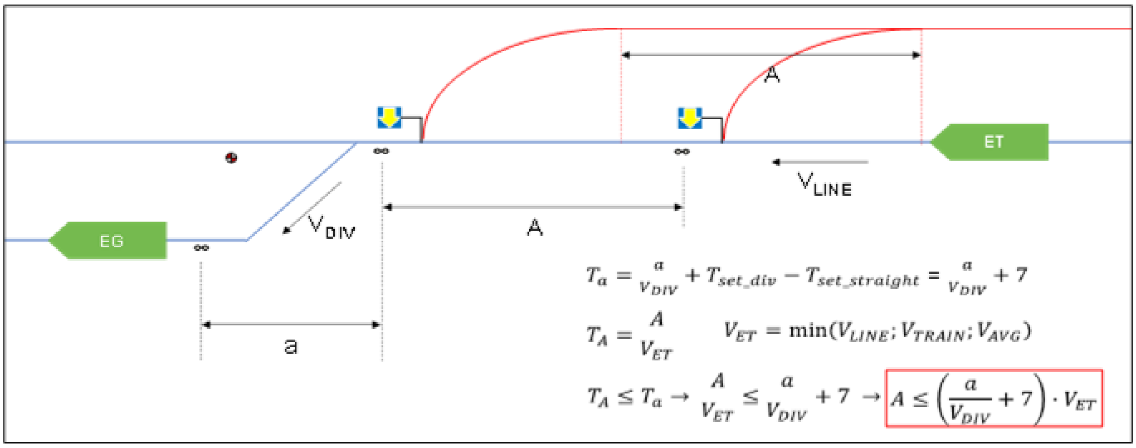


Figure 153 – Scenario "Case C at end", first section before splitting point.

In the section above the splitting point the maximum length of the section is calculated trough a relation between the time required for the EG train to travel in the section "b" (Tb) and the time necessary for the ET train to travel in the section "B" (TB) (Figure 154).

Tb is evaluated as a function of the length of the section "b" (b) and the diverging track speed (VDIV), which is assumed to be the freight train speed. TB is evaluated as a function of the length of the section "B" (B) and the ET train speed (VET), that is the minimum among the line speed (VLINE), the train speed (VTRAIN) and the train average speed (VAVG).

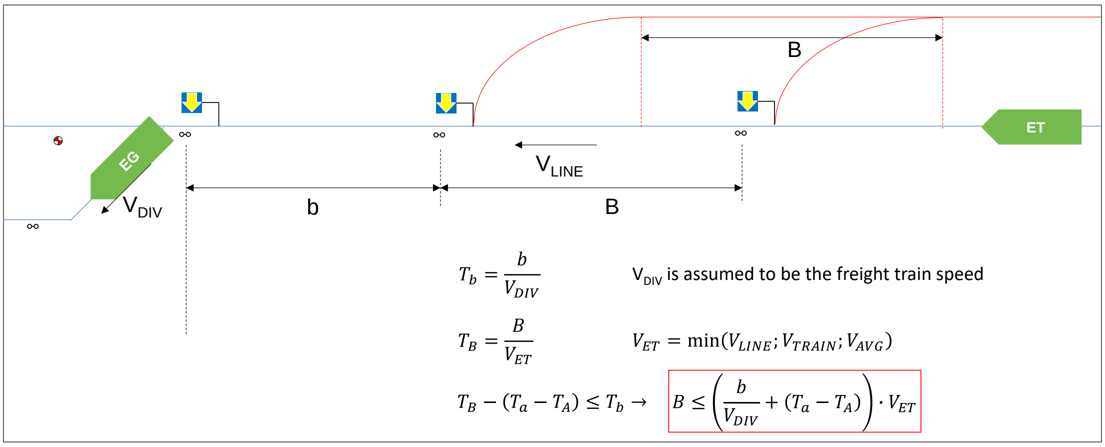


Figure 154 – Scenario "Case C at end", section above the splitting point.

Regarding the "Case C" at departure, in first section before splitting point the maximum length of the section "A" (A) depends on the ET train speed over "A" (VET) which can be a constant speed for a non-stopping train, or an accelerating speed (or at least partially) for a train starting from standstill.

In the first case, the maximum length of the section is evaluated as a function of the ET train speed over "A" (VET) and the time TA.

This last is the difference between the time t1, which is the time when section "A" shall be cleared by the ET train to be detected clear by signalling system at time t2, and the time t0, which is the time when ET train clears section "a" (signalling system can set the route for EG train after Trelease). t2 is the time when MA is available for EG train up to Mrk-B and signalling system can set the following route over "A" for EG train (the system sets the route up to Mrk-C as soon as the route is set up to Mrk-B) (Figure 155).

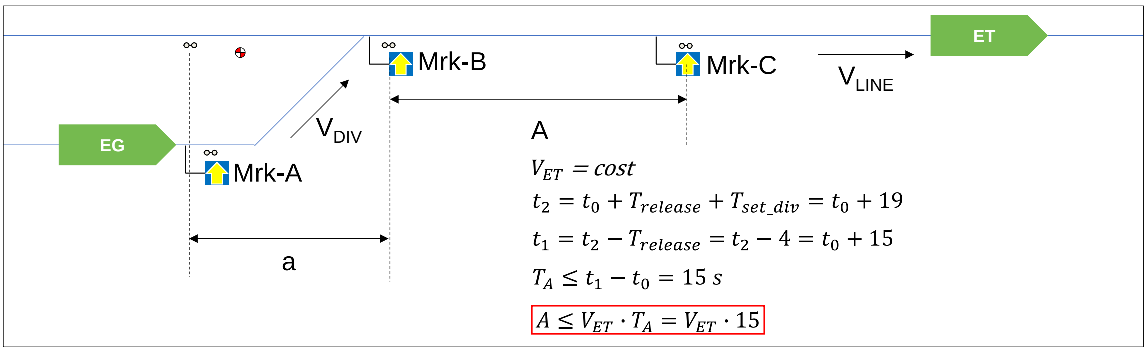


Figure 155 – Scenario "Case C at start", first section before splitting point, VET constant speed.

The second case, instead, is characterized by an ET train starting from standstill, which has a speed over "A" (VET) that can be (Figure 156):

- an accelerating speed over "A" (a): in this case the time related to the train acceleration phase (tACC) is longer than t1;

- a partially accelerating speed over "A", because the ET train partially accelerates and partially moves at constant speed. In this case the time related to the train acceleration phase (tACC) is included between time t0 and time t1. DACC is the distance related to the ET train acceleration phase.

If ET train is starting from standstill, time to travel over section "A" depends on the distance between starting point and beginning of section "A" (d0).

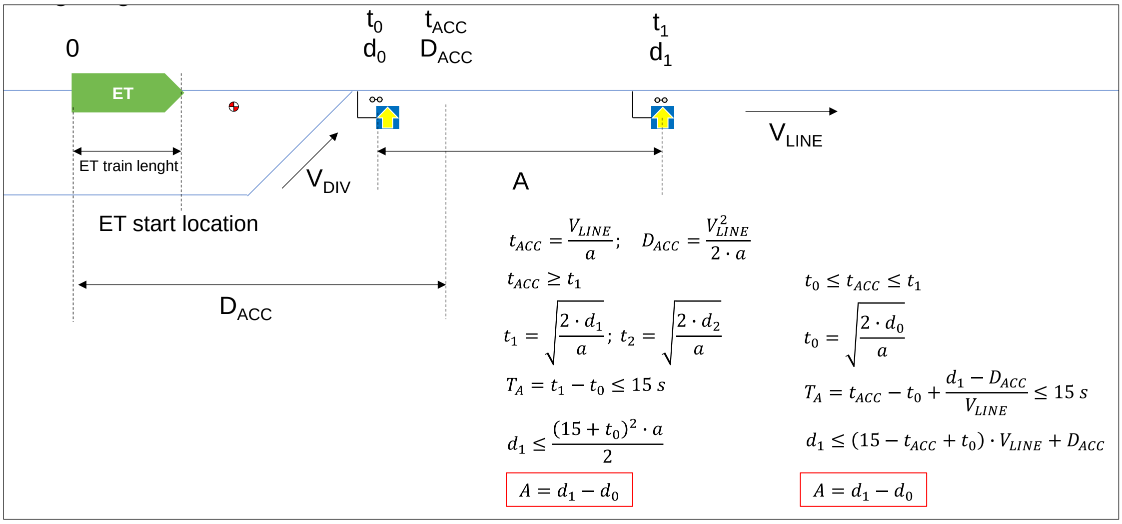


Figure 156 – Scenario "Case C at start", first section before splitting point, VET accelerating speed.

In the section above the splitting point the maximum length of the section is calculated as a function of the line speed (VLINE), the maximum acceleration of EG train (a) and the Indication distance (dIND) calculated for a speed double than the one at time t1 (worst case estimation). This last is the time when EG train gets the MA extension up to Mrk-C (Figure 157). Section B shall be less or equal than the distance travelled by ET train in tIND – t1.

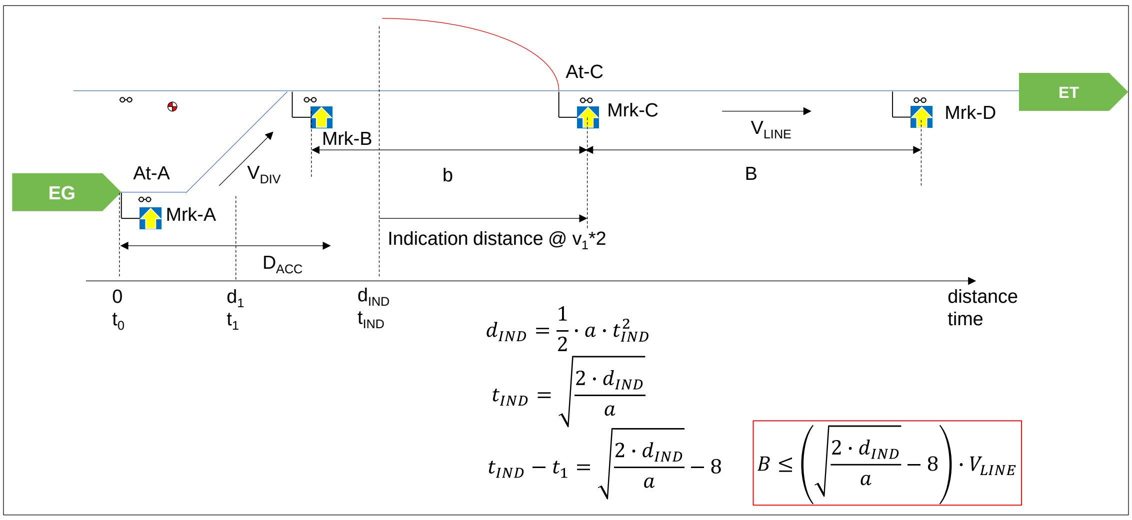


Figure 157 – Scenario "Case C at start", section above the splitting point.

With regard to case B and D, they may be treated as cases similar to Case A when dimensioning the length of sections in full line, while they may be treated as Case C when stop on different platforms at a station.

Once this preliminary design phase is done, the layout is ready to be submitted for the headway assessment carried out by OpenTrack tool. This is an iterative approach: starting from the input, the designer gets different topology output applying a trial and error procedure, which will stop when the obtained result is closed to the real traffic requirements given by Banedanmark.

5.4.5. RollOut 7 Simulation Results

In this paragraph will be reported the results for all the headway scenarios simulation of RollOut 7 from Lundby to Nykøbing F (Figure 158).

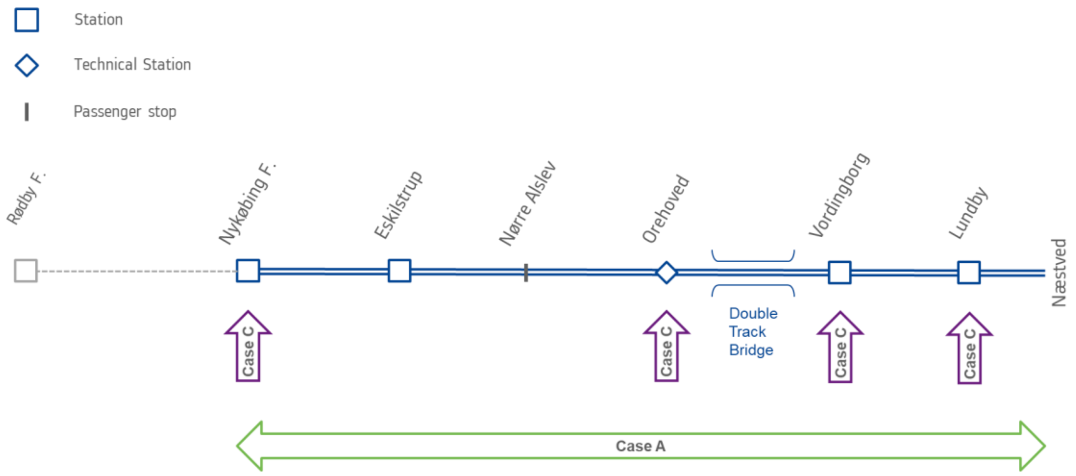


Figure 158 – R07: portion of line under capacity analysis

For each scenario will be showed the headway requirement, the usage of the track in case of stopping train, the train graph, the running profiles of both trains and eventually the explanation for the scenarios that doesn't meet the requirements.

5.4.5.1 Scenario 1

In this scenario the focus is on the line, the two non-stop ET trains are running at 200 Km/h from new rollout boundary at Mogenstrup to Nykøbing F.; the minimum achievable headway is 122 seconds (required headway 165 seconds) (Table 24).

The speed profile of each train is compliant with the track speed profile (Cant Deficiency 150 mm), the entry speed on the boundary at 95+203 km is 200 Km/h.

Scenarios	Track	Section	1st Train	2nd Train	Case	Technical Headway [sec]	Separate Tracks in Station	Headway Results [sec]
1	Left	(Ringsted) – Puttgarden	ET 350m, bp 180, stop at Ringsted	ET 350m, bp 180, stop at Ringsted	A	165	(Ringsted)	122/165
	Right	(Ringsted) – Puttgarden	ET 350m, bp 180, stop at Ringsted	ET 350m, bp 180, stop at Ringsted	A	165	(Ringsted)	122/165

Table 24 – R07: Headway Scenario 1 Results Overview

Here below is shown the train graph with the blocking time diagram of both ET trains at maximum speed at 122 seconds headway on both tracks (Figure 159).

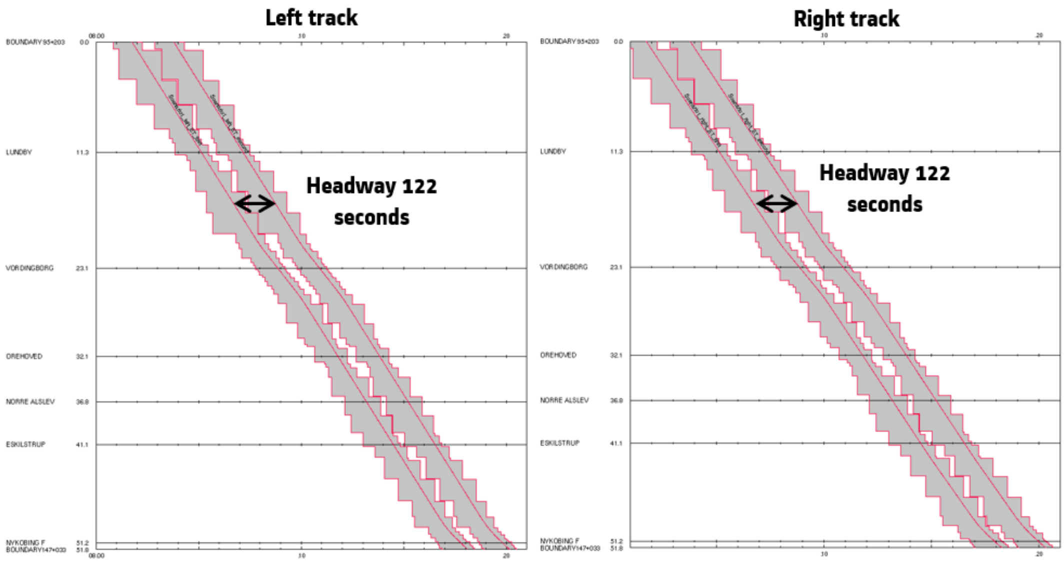


Figure 159 – Blocking time Case A (Ringsted) – (Puttgarden), ET train at 200 km/h

As shown in the speed profile below the 2nd train running at 122 second headway has no perturbations (Figure 160).

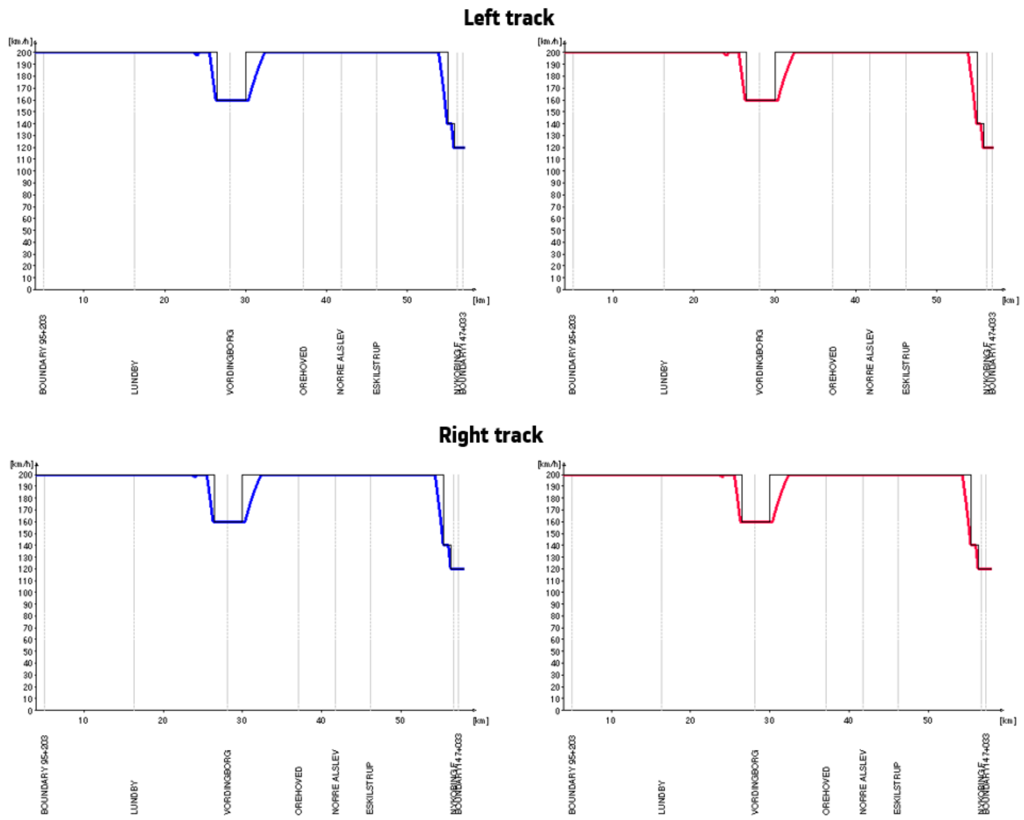


Figure 160 – Train Speed diagram Case A (Ringsted) – (Puttgarden), ET train at 200 km/h

5.4.5.2 Scenario 2

In this scenario the focus is on the line, the two no stops ET trains are running at 200 Km/h from Nykøbing F. to new rollout boundary at Mogenstrup; the minimum achievable headway is 121 seconds on the left track and 120 seconds on the right track (required headway 165 seconds on both track) (Table 25).

The speed profile of each train is compliant with the track speed profile (Cant Deficiency 150 mm).

Scenarios	Track	Section	1st Train	2nd Train	Case	Technical Headway [sec]	Separate Tracks in Station	Headway Results [sec]
2	Left	Puttgarden–(Ringsted)	ET 350m, bp 180, stop at Ringsted	ET 350m, bp 180, stop at Ringsted	A	165	(Ringsted)	121/165
	Right	Puttgarden–(Ringsted)	ET 350m, bp 180, stop at Ringsted	ET 350m, bp 180, stop at Ringsted	A	165	(Ringsted)	120/165

Table 25 – R07: Headway Scenario 2 Results Overview

Here below is shown the train graph with the blocking time diagram of both ET trains at maximum speed at 121 seconds headway on the left track and 120 seconds headway on the right track (Figure 161).

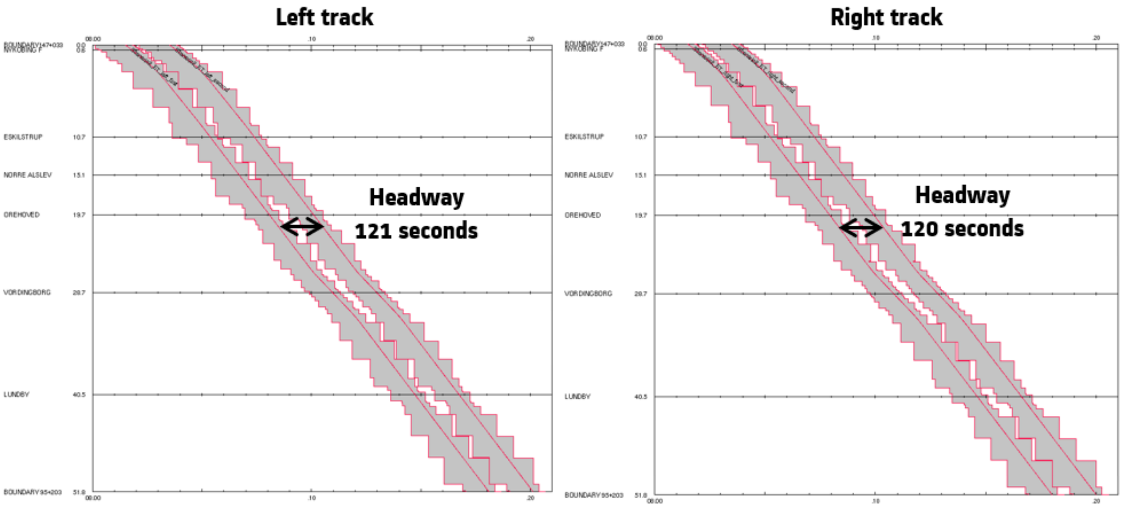


Figure 161 – Blocking time Case A (Puttgarden) – (Ringsted), ET train at 200 km/h

As shown in the speed profile below the 2nd train running at 121 second headway for the left track and at 120 second headway for the right track, has no perturbations (Figure 162).

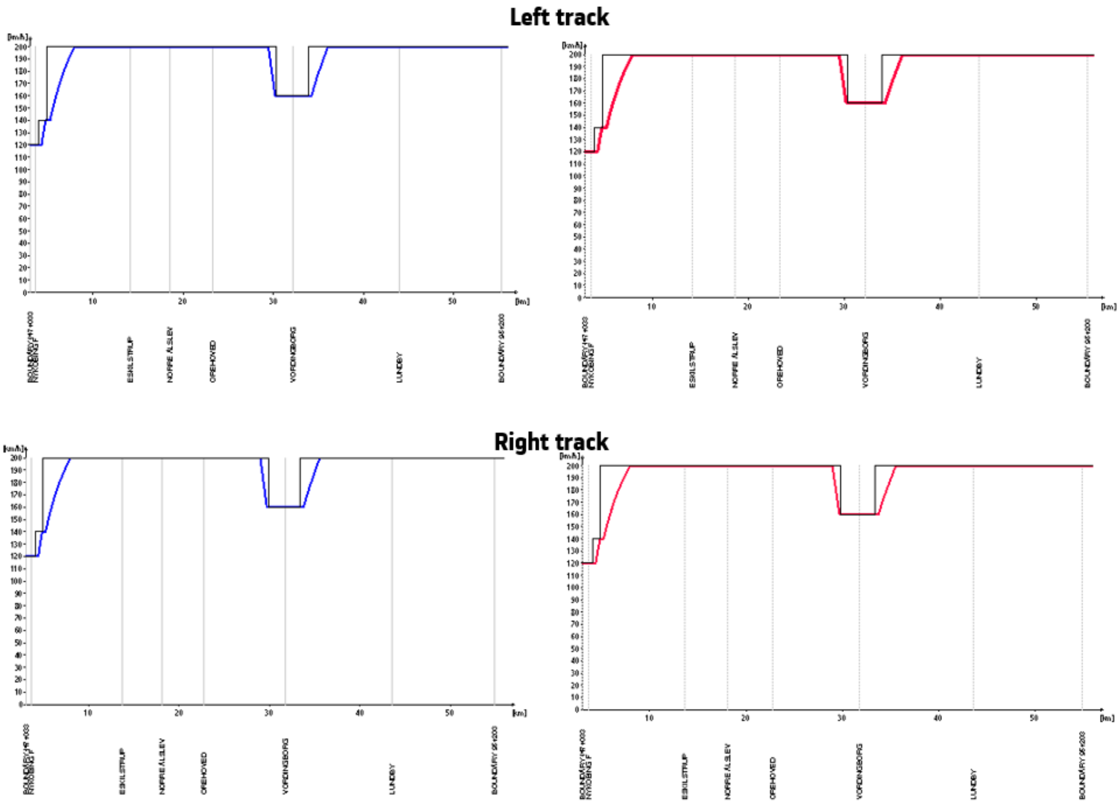


Figure 162 – Train Speed diagram Case A (Puttgarden) – (Ringsted), ET train at 200 km/h

5.4.5.3 Scenario 3

In this scenario the first train is freight train that is running from Næstved to Lundby direction, stops on the overtaking track in Lundby, followed by the ET passenger non-stop train (Table 26, Figure 163).

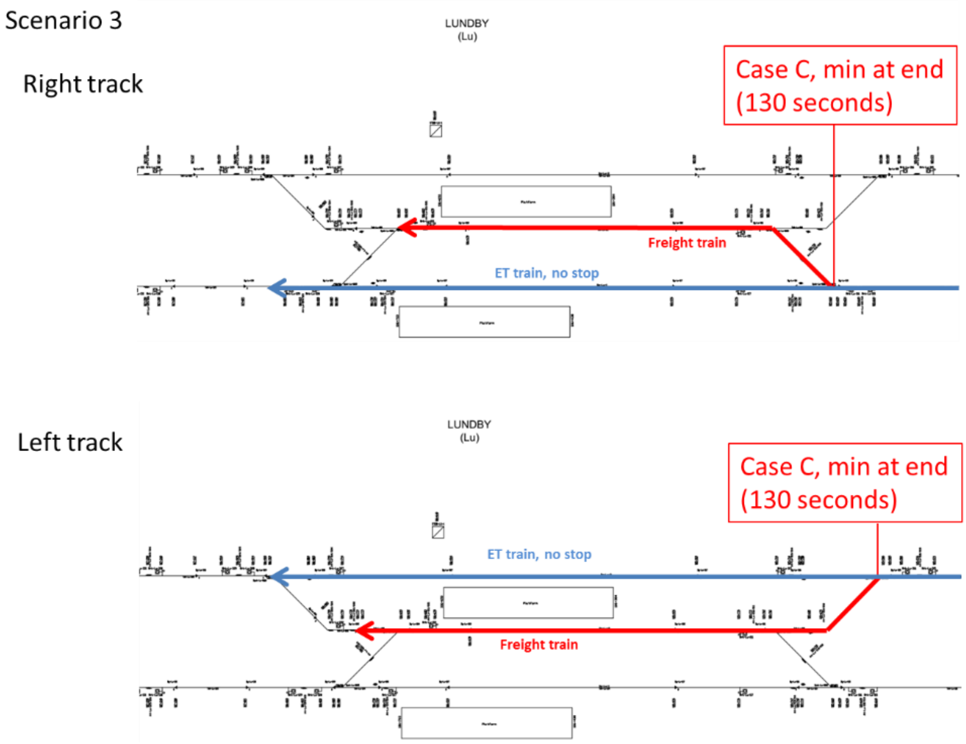


Figure 163 – R07: Scenario 3: Lundby use of track

Headway Case C detected at the splitting points Spsk-Lu-N001 (right track) and Spsk-Lu-N002 (left track) in Lundby.

Scenarios	Track	Section	1st Train	2nd Train	Case	Technical Headway [sec]	Separate Tracks in Station	Headway Results [sec]
3	Left	(Næstved) – Lundby	EG 860m, bp 80, stop at Lundby	ET 350m, bp 180 no stop	C	130 at end	Lundby	167/130
	Right	(Næstved) – Lundby	EG 1000m, bp 80, stop at Lundby	ET 350m, bp 180 no stop	C	130 at end	Lundby	167/130

Table 26 – R07: Headway Scenario 3 Results Overview

The bottleneck is the splitting point section for both tracks, due to the low diverging speed (60 Km/h) and reduced distance between splitting point and EOA for EG train. The longest freight train to respect the headway requirements is 700 m for the left track and 790 m for the right track.

Left Track

In this scenario the available overtaking track length in 907 m; the freight train length used for the simulation is 860 m.

The minimum achievable headway is 167 seconds (required headway 130 seconds) detected at the splitting point Spsk-Lu-N002 at 105+661 (Figure 164); to obtain the minimum headway the approach section to MB protecting the splitting point has been already optimized. The longest freight train to respect the headway requirements is 700 m.

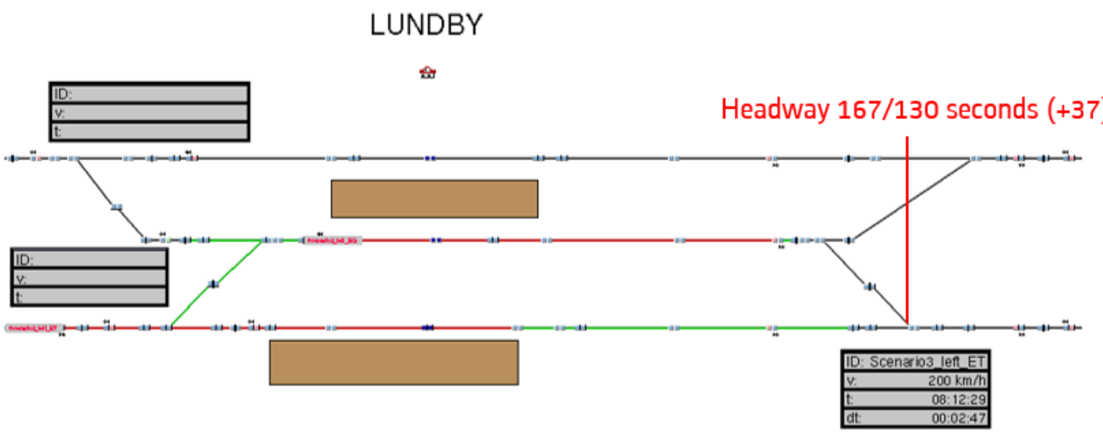


Figure 164 – Headway Case C (Næstved) – Lundby, Freight/ET left track, headway 167 seconds

Here below is shown the train graph with the blocking time diagram of both trains (Figure 165).

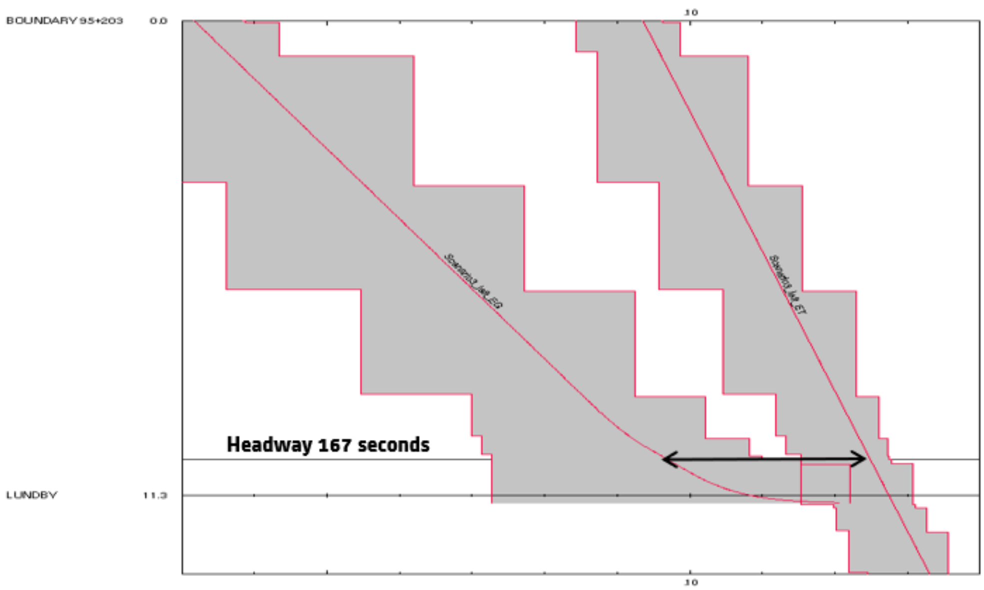


Figure 165 – Blocking time Case (Næstved) – Lundby, Freight/ET left track, headway 167 seconds

As shown in the speed profile below the 2nd train at 167 second headway has no perturbations (Figure 166).

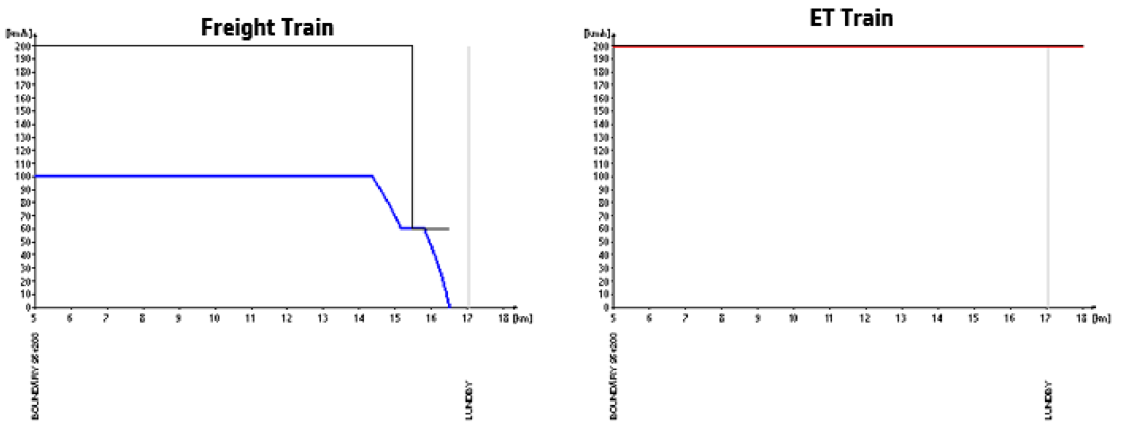


Figure 166 – Train Speed diagram Case C (Næstved) – Lundby, Freight/ET left track

Here below is shown the train graph with blocking time diagram of both trains at 166 seconds headway, to show that the bottleneck is the Mrk-Lu-115, that is as close as possible to the splitting point Spsk-Lu-N002 (Figure 167).

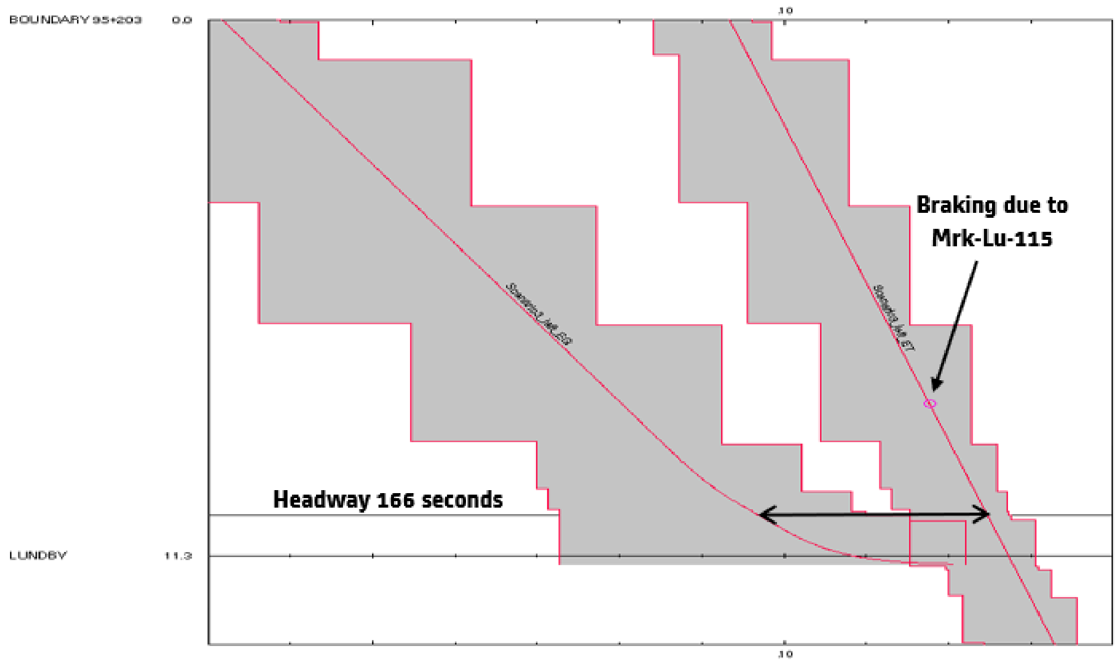


Figure 167 – Blocking time Case (Næstved) – Lundby, Freight/ET left track, headway 166 seconds

Right Track

In this scenario the minimum achievable headway is 167 seconds (required headway 130 seconds) detected at the splitting point Spsk-Lu-N001 at 105+587 (Figure 168); to obtain the minimum headway the approach section to MB protecting the splitting point has been already optimized. The longest freight train to respect the headway requirements is 790 m.

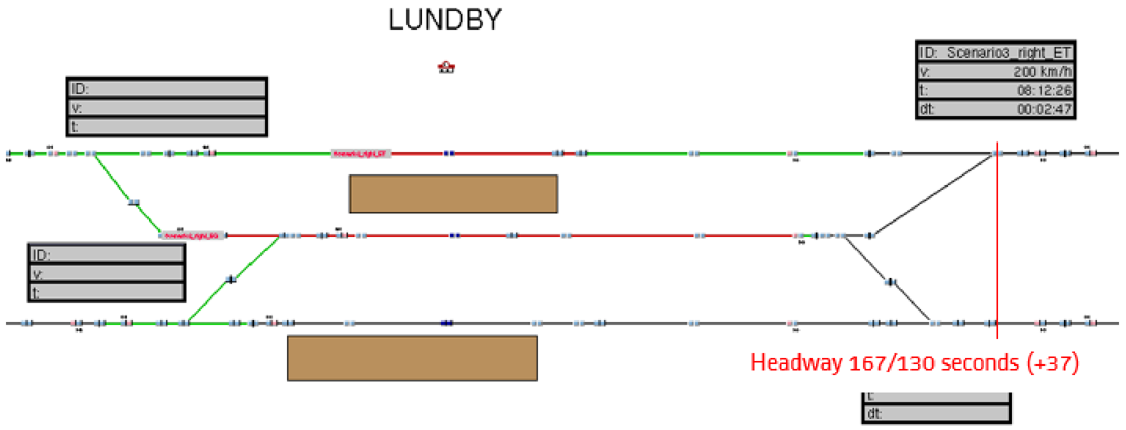


Figure 168 – Headway Case C (Næstved) – Lundby, Freight/ET right track, headway 167 seconds

Here below is shown the train graph with the blocking time diagram of both trains (Figure 169).

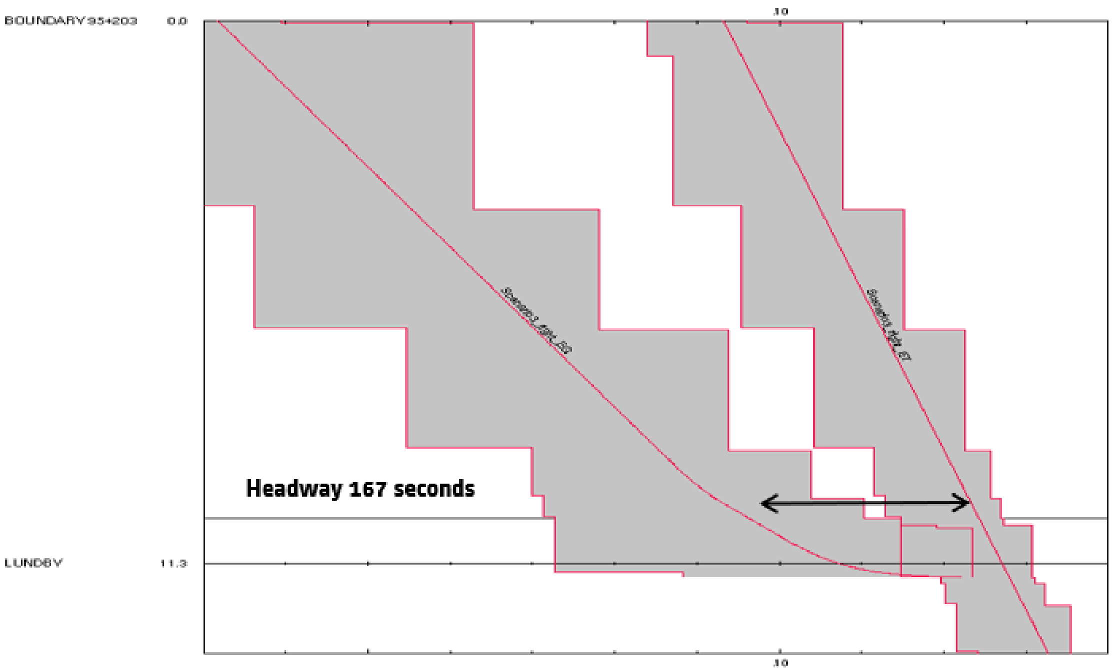


Figure 169 – Blocking time Case C (Næstved) – Lundby, Freight/ET right track, headway 167 seconds

As shown in the speed profile below the 2nd train at 167 second headway has no perturbations (Figure 170).

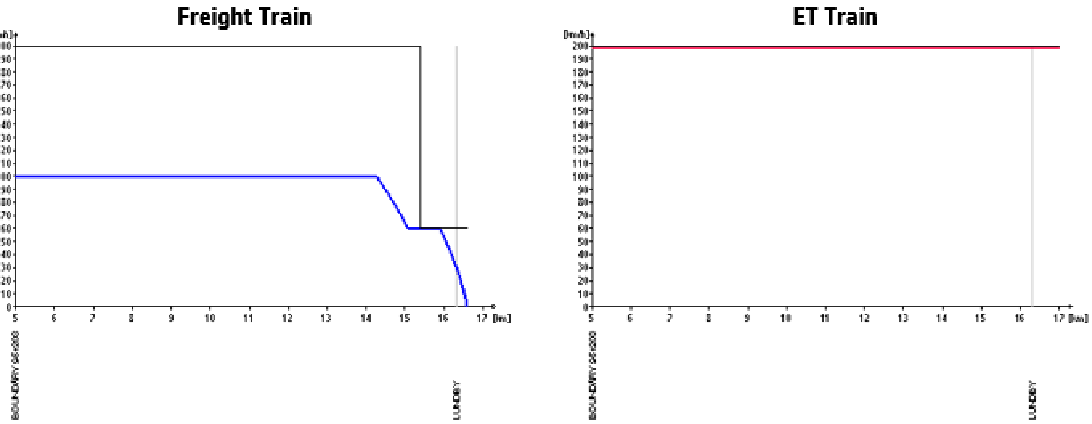


Figure 170 – Train Speed diagram Case C (Næstved) – Lundby, Freight/ET right track

Here below is shown the train graph with blocking time diagram of both trains at 166 seconds headway, to show that the bottleneck is the Mrk-Lu-315, that is as close as possible to the splitting point Spsk-Lu-N001 (Figure 171).

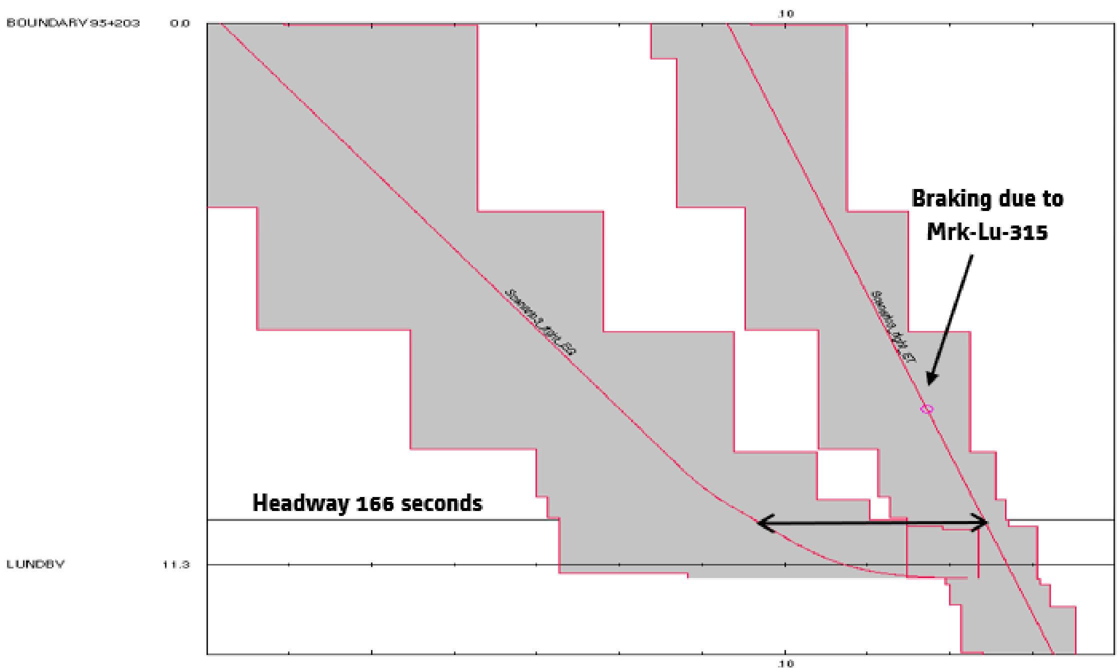


Figure 171 – Blocking time Case C (Næstved) – Lundby, Freight/ET right track, headway 116 seconds

5.4.5.4 Scenario 4

In this scenario the first train is the non-stopping ET train that runs at maximum speed (200 km/h) through Lundby in Næstved direction, the second train is the freight train that is starting from standstill in Lundby (Figure 172, Table 27).

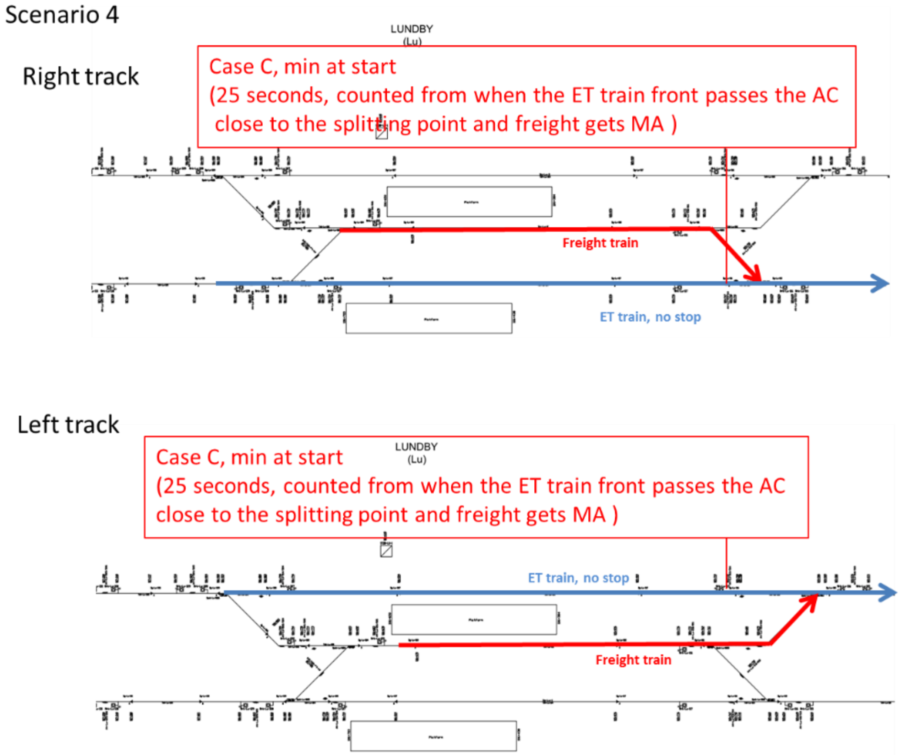


Figure 172 – Scenario 4: Lundby use of track

Headway Case C is detected from when the passenger train front passes the axle counter close to the splitting point to when the freight train gets a movements authority. This time is governed by the ET travel time along the splitting point section length plus train length.

Scenarios	Track	Section	1st Train	2nd Train	Case	Technical Headway [sec]	Separate Tracks in Station	Headway Results SL [sec]
4	Left	Lundby – (Næstved)	ET 350m, bp 180 no stop	EG 1000m, bp 80, stop at Lundby	C	25 at start	Lundby	29/25
	Right	Lundby – (Næstved)	ET 350m, bp 180 no stop	EG 1000m, bp 80, stop at Lundby	C	25 at start	Lundby	29/25

Table 27 – Headway Scenario 4 Results Overview

Left Track

In this scenario the minimum achievable headway is 29 seconds (required headway 25 seconds):

- from when the passenger train front passes the axle counter (At-Lu-313/314) close to the splitting point;
- to when the freight train gets a movements authority after;

to obtain the minimum headway the sectioning towards open line is optimized for EG train timely MA update. This is the minimum achievable headway in this scenario considering the route setting and release times (Figure 173).

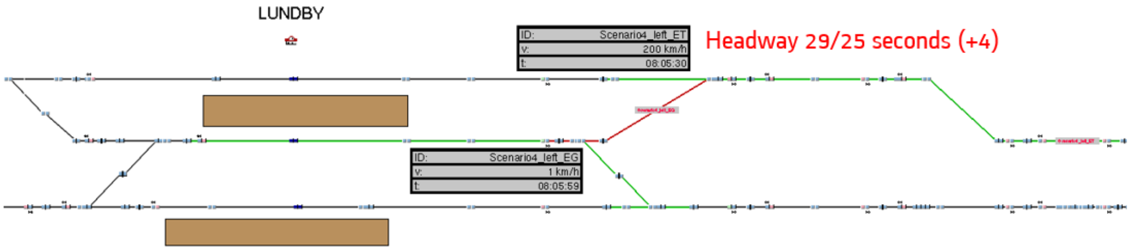


Figure 173 – Headway Case C Lundby – (Næstved), Freight/ET left track, headway 29 seconds

Here below is shown the train graph with the blocking time diagram of both trains (Figure 174).

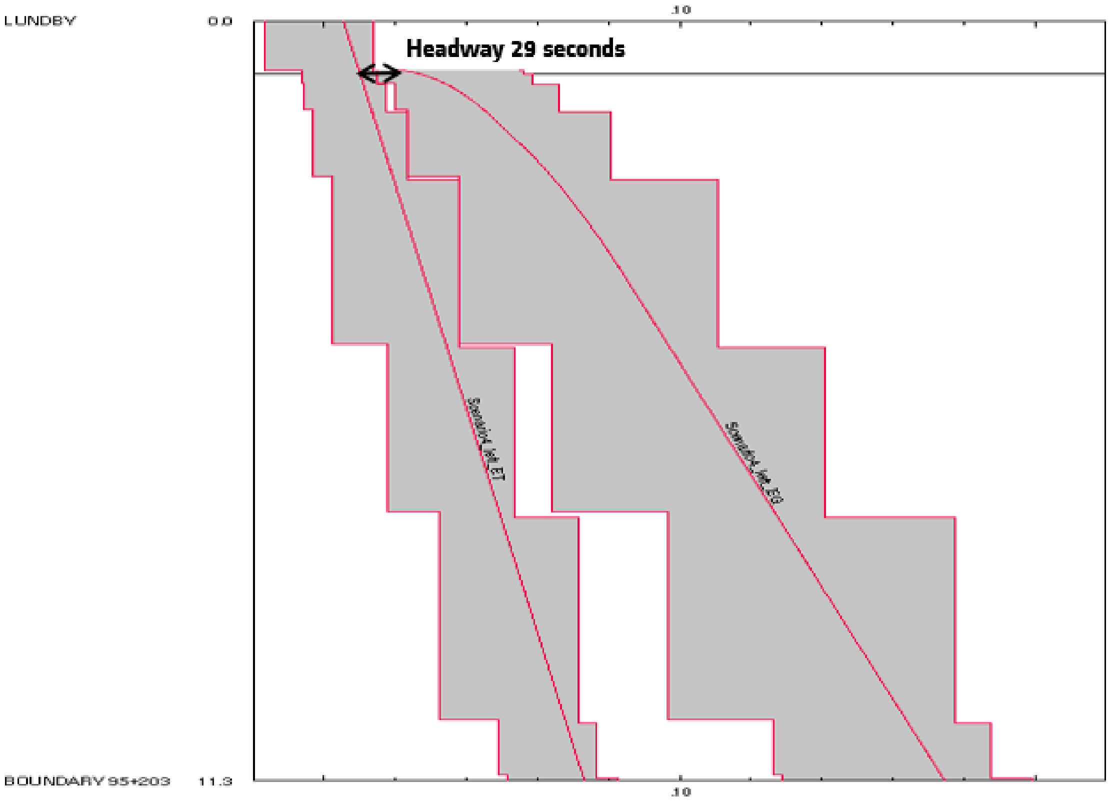


Figure 174 – Blocking time Case C Lundby – (Næstved), Freight/ET left track, headway 29 seconds

As shown in the speed profile below the 2nd train at 29 second headway has no perturbations (Figure 175).

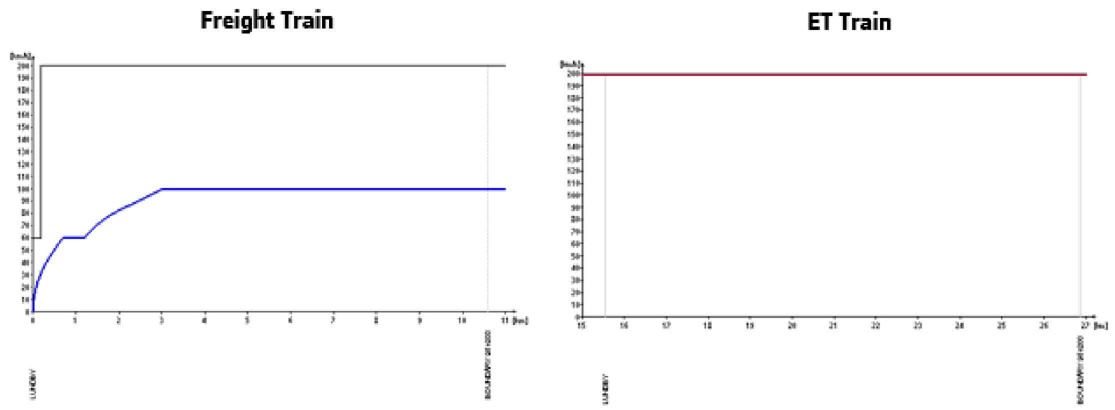


Figure 175 – Train Speed diagram Case C Lundby – (Næstved), Freight/ET left track

Right Track

In this scenario the minimum achievable headway is 29 seconds (required headway 25 seconds):

- from when the passenger train front passes the axle counter (At-Lu-114/115) close to the splitting point;
- to when the freight train gets a movements authority after;

to obtain the minimum headway the sectioning towards open line is optimized for EG train timely MA update. This is the minimum achievable headway in this scenario considering the route setting and release times (Figure 176).

Figure 176 – Headway Case C Lundby – (Næstved), Freight/ET right track, headway 29 seconds

Here below is shown the train graph with the blocking time diagram of both trains (Figure 177).

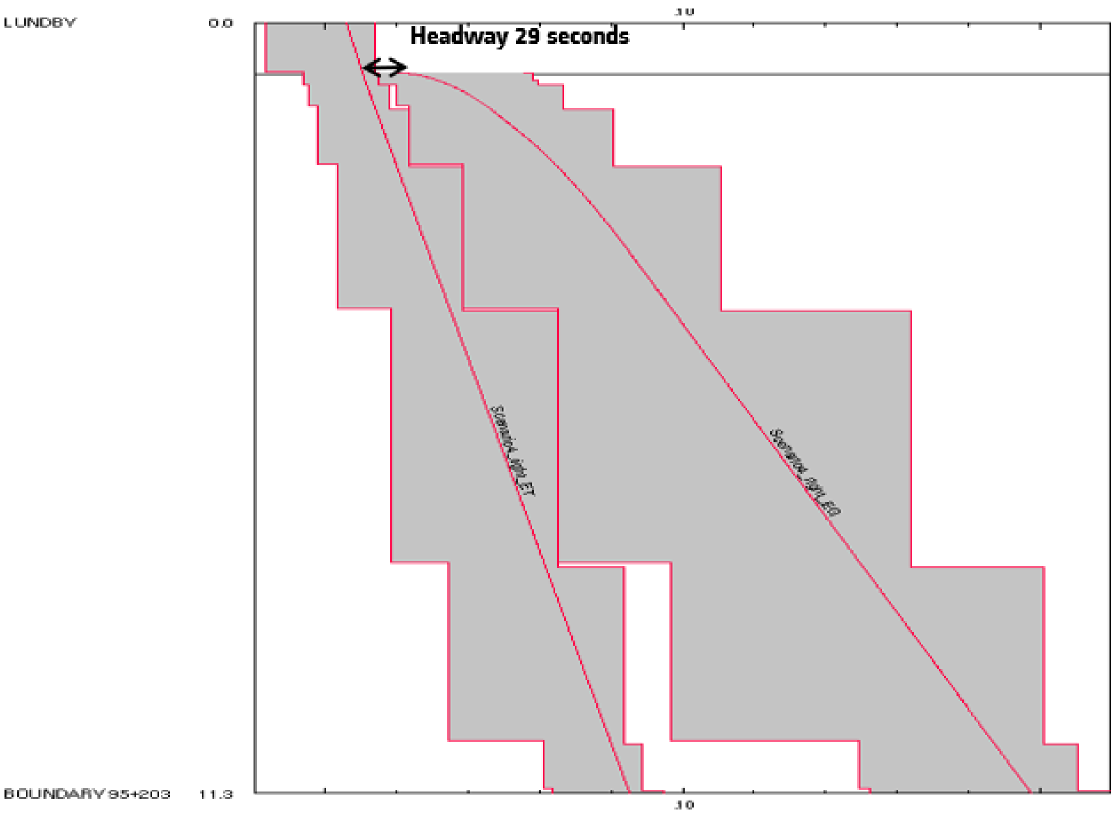


Figure 177 – Blocking time Case C Lundby – (Næstved), Freight/ET right track, headway 29 seconds

As shown in the speed profile below the 2nd train at 29 second headway has no perturbations (Figure 178).

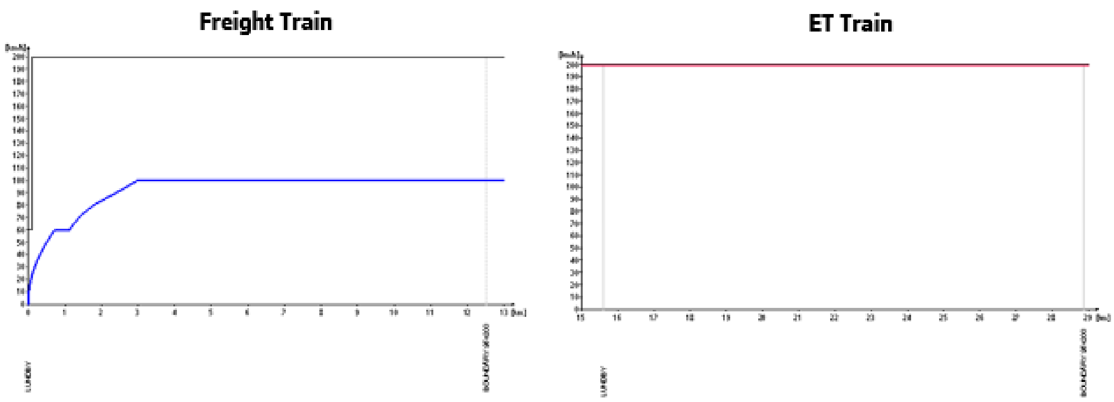


Figure 178 – Train Speed diagram Case C Lundby – (Næstved), Freight/ET right track

5.4.5.5 Scenario 5

In this scenario the first train is the non-stopping ET train that runs at maximum speed (200 km/h) through Lundby in Vordingborg direction, the second train is the freight train that is starting from standstill in Lundby (Figure 179, Table 28).

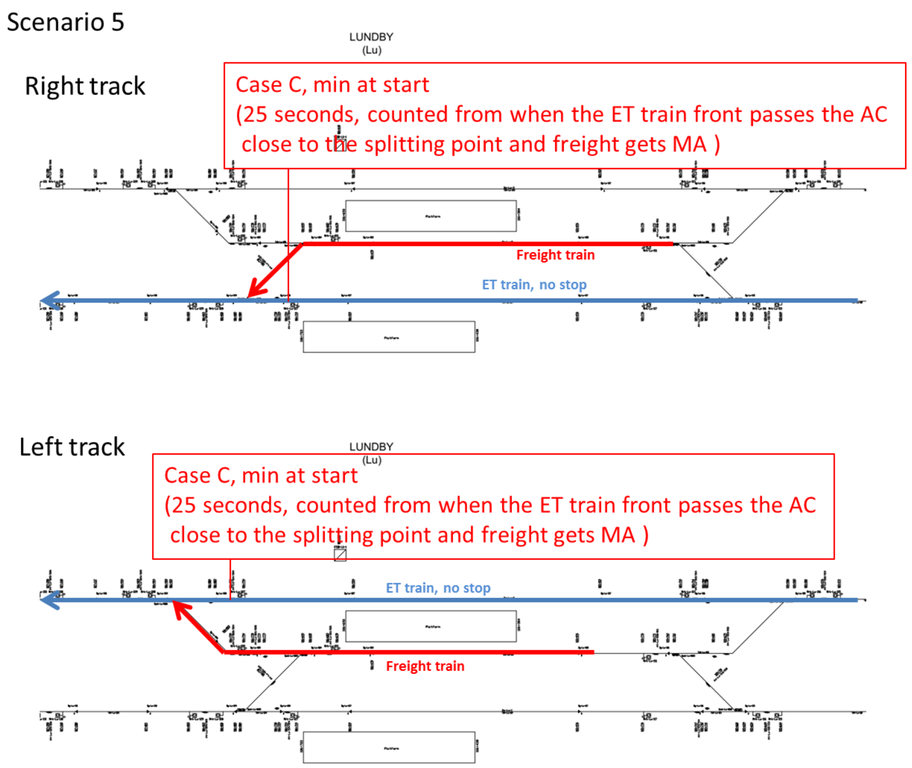


Figure 179 – Scenario 5: Lundby use of track

Headway Case C is detected from when the passenger train front passes the axle counter close to the splitting point to when the freight train gets a movements authority. This time is governed by the ET travel time along the splitting point section length plus train length.

Scenarios	Track	Section	1st Train	2nd Train	Case	Technical Headway [sec]	Separate Tracks in Station	Headway Results [sec]
5	Left	Lundby – Vordingborg	ET 350m, bp 180 no stop	EG 1000m, bp 80, stop at Lundby	C	25 at start	Lundby	28/25
	Right	Lundby – Vordingborg	ET 350m, bp 180 no stop	EG 1000m, bp 80, stop at Lundby	C	25 at start	Lundby	29/25

Table 28 – Headway Scenario 5 Results Overview

Left Track

In this scenario the minimum achievable headway is 28 seconds (required headway 25 seconds)

- from when the passenger train front passes the axle counter (At-Lu-115/124) close to the splitting point;
- to when the freight train gets a movements authority after;

to obtain the minimum headway the sectioning towards open line is optimized for EG train timely MA update. This is the minimum achievable headway in this scenario considering the route setting and release times (Figure 180).

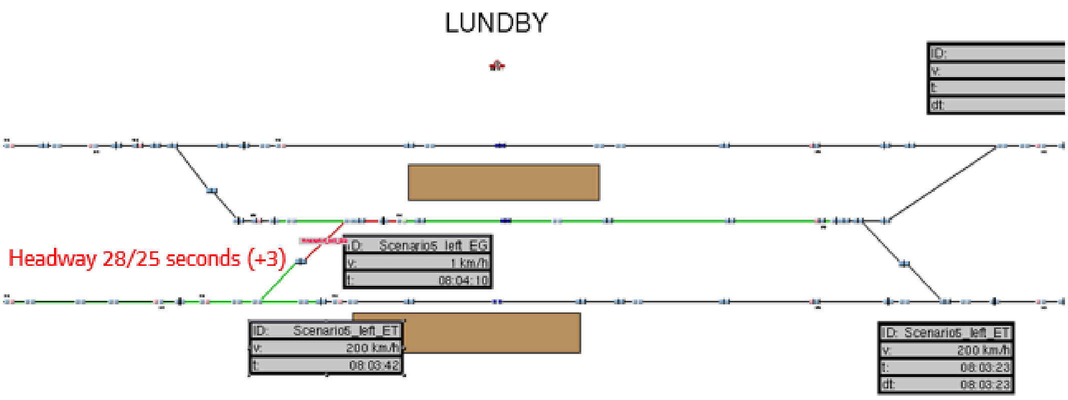


Figure 180 – Headway Case C Lundby –Vordingborg, Freight/ET left track, headway 28 seconds

Here below is shown the train graph with the blocking time diagram of both trains (Figure 181).

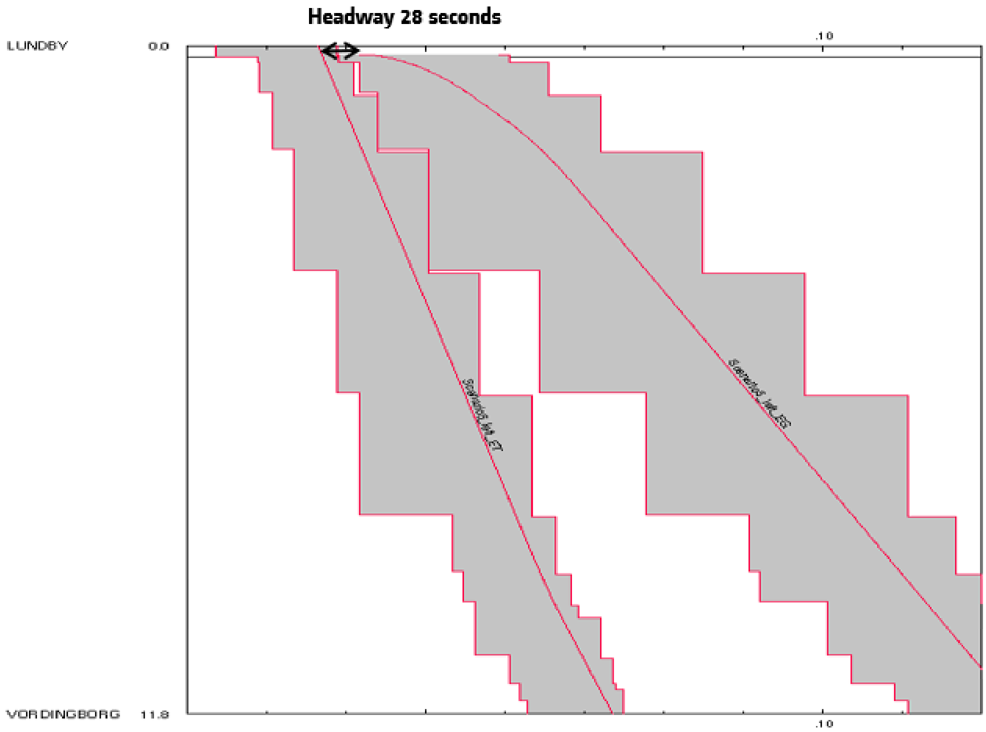


Figure 181 – Blocking time Case C Lundby –Vordingborg, Freight/ET left track, headway 28 seconds

As shown in the speed profile below the 2nd train at 28 second headway has no perturbations (Figure 182).

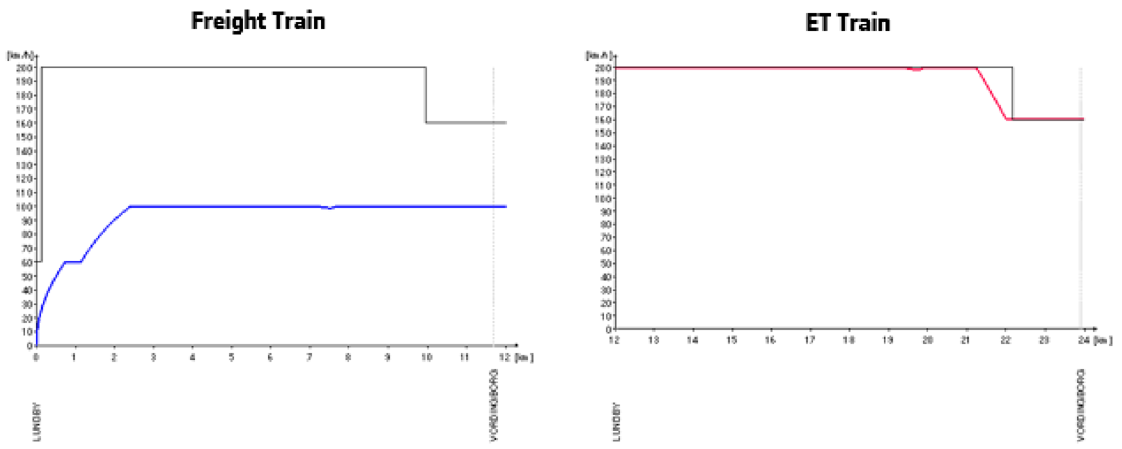


Figure 182 – Train Speed diagram Case C Lundby –Vordingborg, Freight/ET left track

Right Track

In this scenario the minimum achievable headway is 29 seconds (required headway 25 seconds):

- from when the passenger train front passes the axle counter (At-Lu-314/324) close to the splitting point;
- to when the freight train gets a movements authority after;

to obtain the minimum headway the sectioning towards open line is optimized for EG train timely MA update. This is the minimum achievable headway in this scenario considering the route setting and release times (Figure 183).

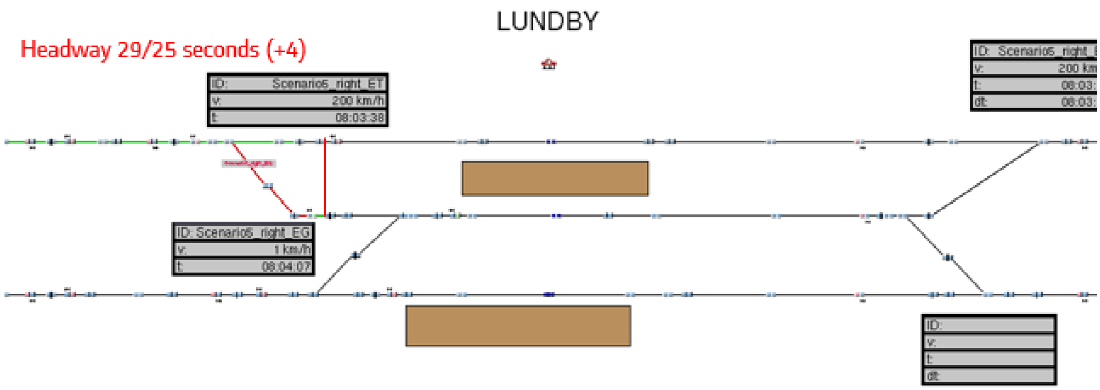


Figure 183 – Headway Case C Lundby –Vordingborg, Freight/ET right track, headway 29 seconds

Here below is shown the train graph with the blocking time diagram of both trains (Figure 184).

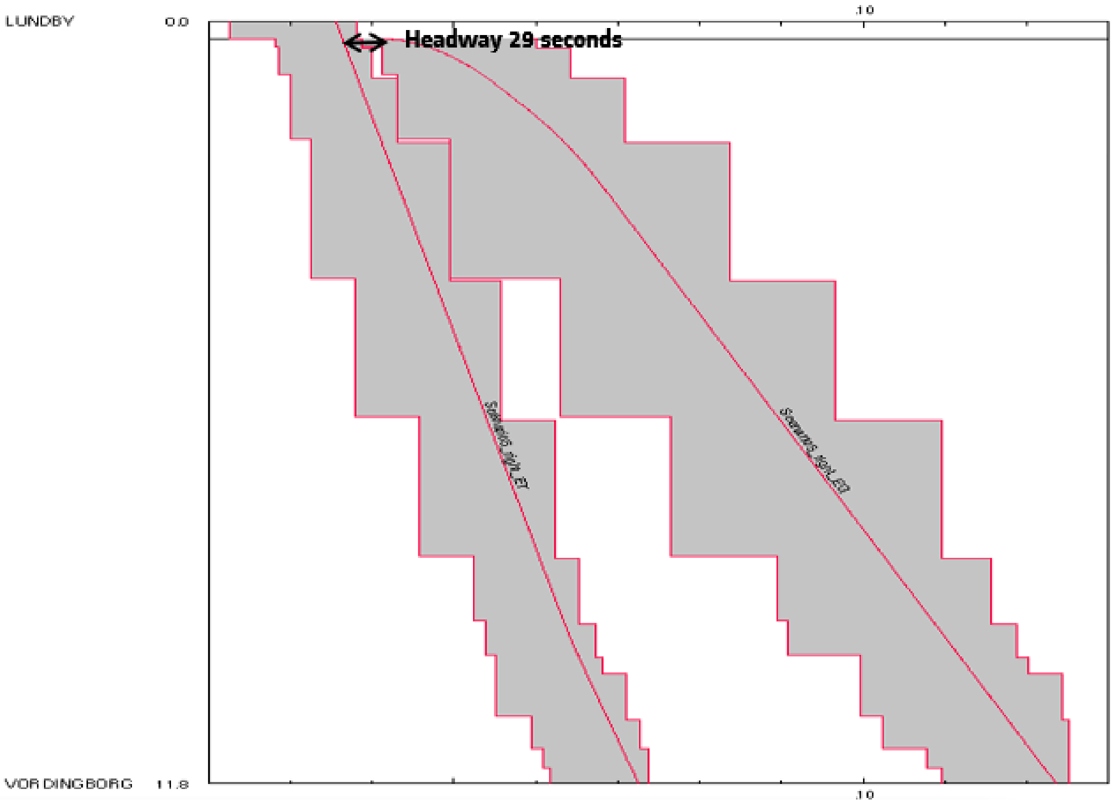


Figure 184 – Blocking time Case C Lundby –Vordingborg, Freight/ET right track, headway 29 seconds

As shown in the speed profile below the 2nd train at 29 second headway has no perturbations (Figure 185).

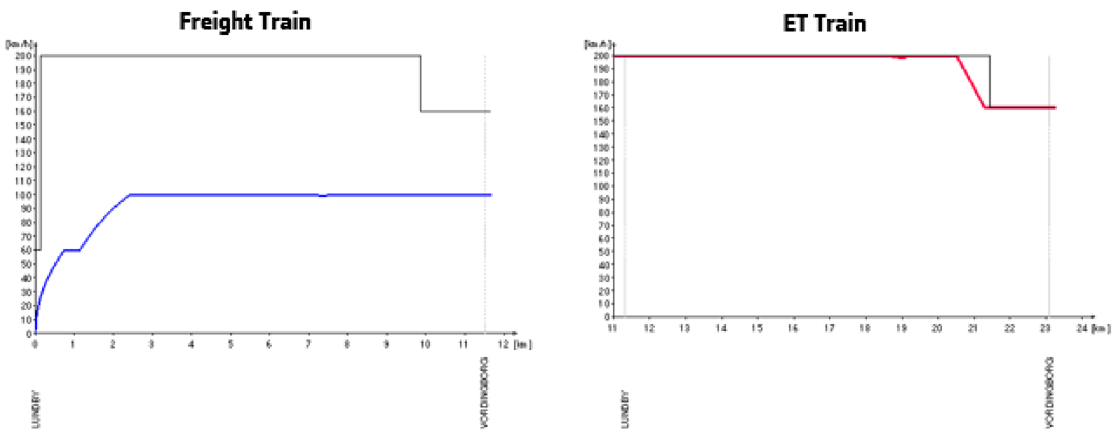


Figure 185 – Train Speed diagram Case C Lundby –Vordingborg, Freight/ET right track

5.4.5.6 Scenario 6

In this scenario the first train is freight train that is running from Vordingborg to Lundby direction, stops on the overtaking track in Lundby, followed by the ET passenger non-stop train (Figure 186, Table 29).

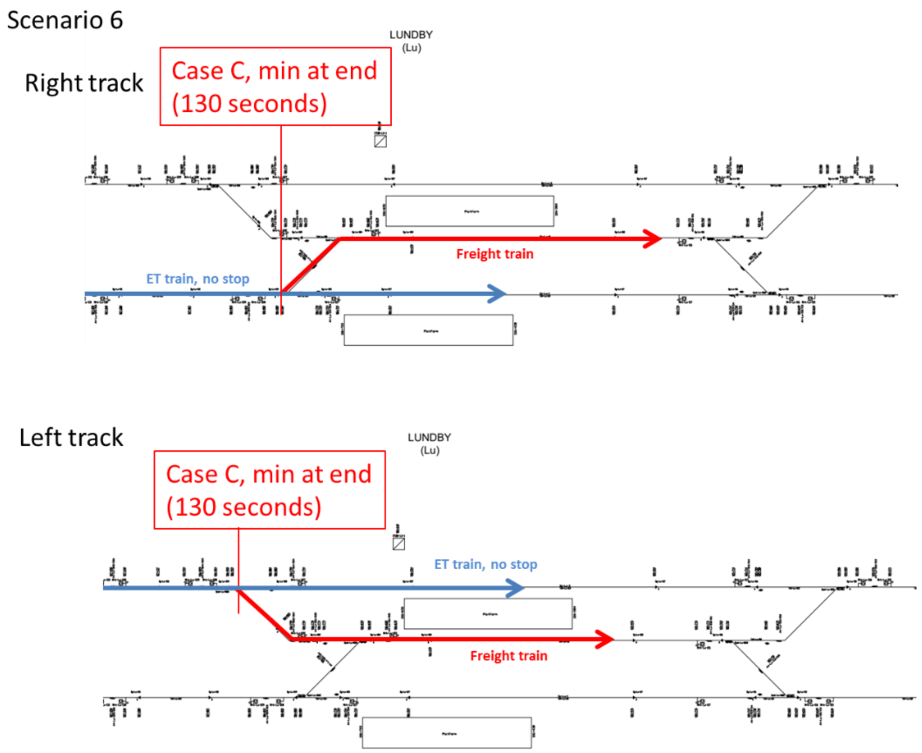


Figure 186 – Scenario 6: Lundby use of track

Headway Case C detected at the splitting points Spsk-Lu-N005 (right track) and Spsk-Lu-N006 (left track) in Lundby.

Scenarios	Track	Section	1st Train	2nd Train	Case	Technical Headway [sec]	Separate Tracks in Station	Headway Results [sec]
6	Left	Vordingborg – Lundby	EG 1000m, bp 80, stop at Lundby	ET 350m, bp 180 no stop	C	130 at end	Lundby	175/130
	Right	Vordingborg – Lundby	EG 1000m, bp 80, stop at Lundby	ET 350m, bp 180 no stop	C	130 at end	Lundby	167/130

Table 29 – Headway Scenario 6 Results Overview

The bottleneck is the splitting point section for both tracks, due to the low diverging speed (60 Km/h) and reduced distance between splitting point and EOA for EG train. The longest freight train to respect the headway requirements is 780 m for the left track and 710 m for the right track.

Left Track

In this scenario the available overtaking track length is 1023 m; the freight train length used for the simulation is 980 m.

The minimum achievable headway is 175 seconds (required headway 130 seconds) detected at the splitting point Spsk-Lu-N006 at 106+917 (Figure 187); to obtain the minimum headway the approach section to MB protecting the splitting point has been already optimized. The longest freight train to respect the headway requirements is 780 m.

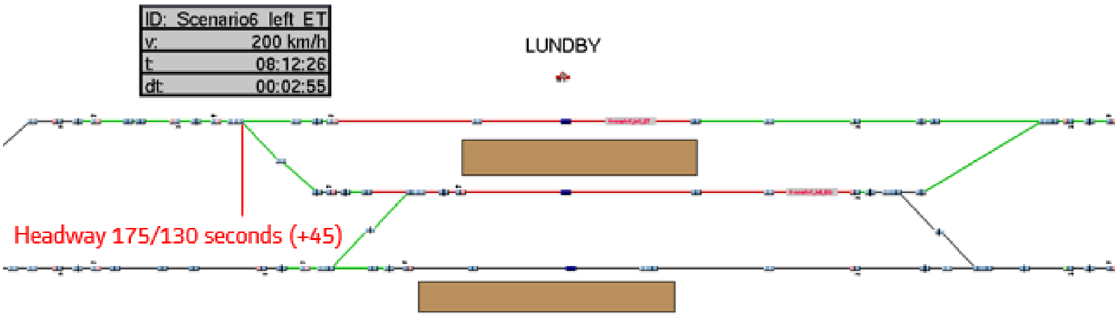


Figure 187 – Headway Case C Vordingborg – Lundby, Freight/ET left track, headway 175 seconds

Here below is shown the train graph with the blocking time diagram of both trains (Figure 188).

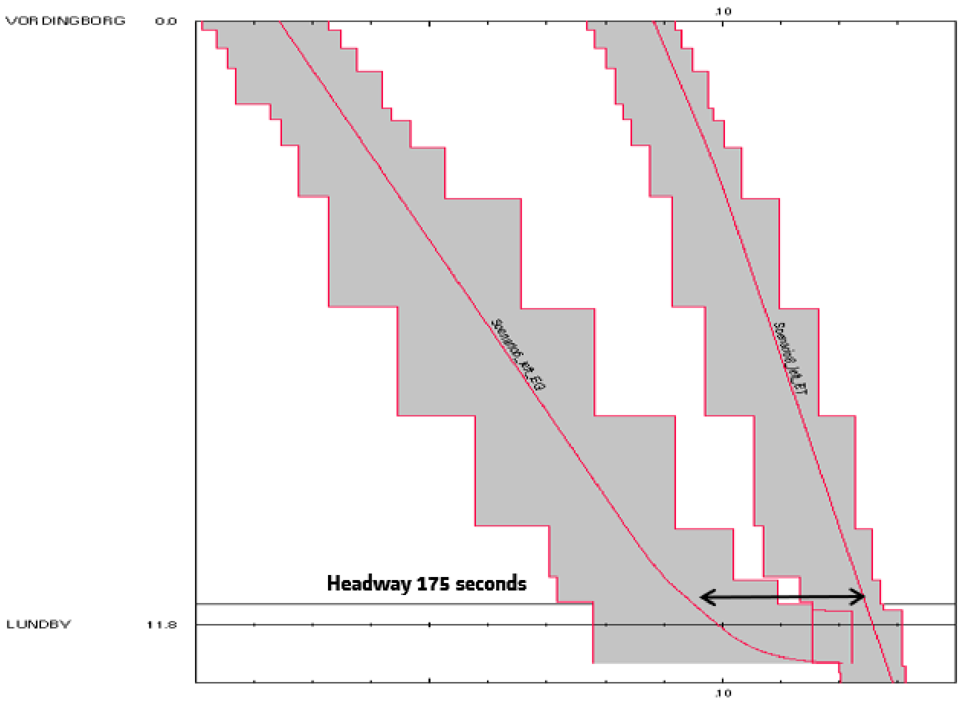


Figure 188 – Blocking time Case C Vordingborg – Lundby, Freight/ET left track, headway 175 seconds

As shown in the speed profile below the 2nd train at 175 second headway has no perturbations (Figure 189).

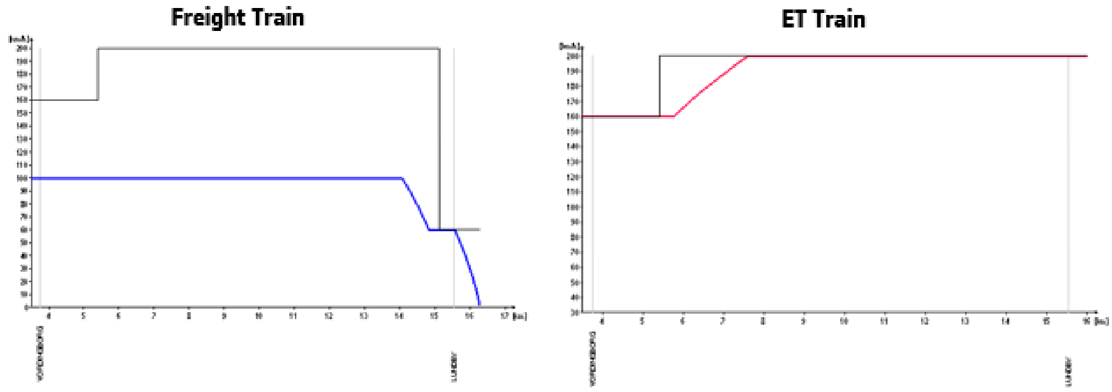


Figure 189 – Train Speed diagram Case C Vordingborg – Lundby, Freight/ET left track

Here below is shown the train graph with blocking time diagram of both trains at 174 seconds headway, to show that the bottleneck is the Mrk-Lu-329, that is as close as possible to the splitting point Spsk-Lu-N006 (Figure 190).

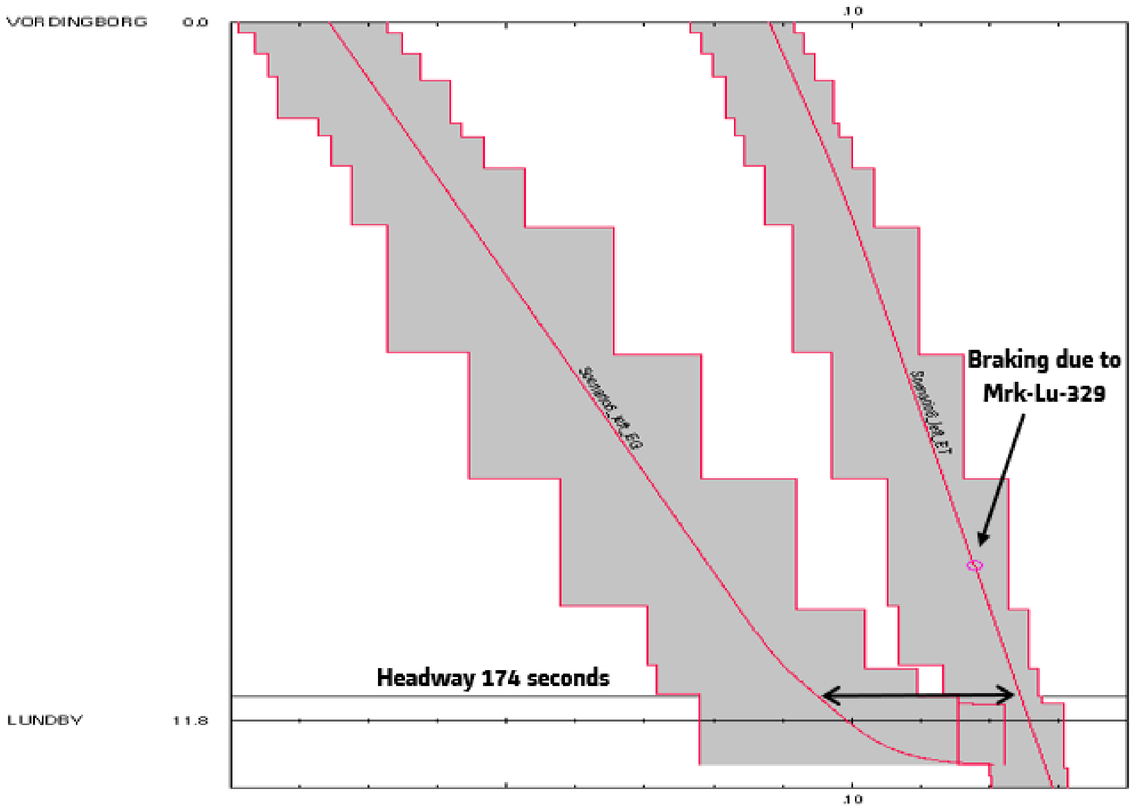


Figure 190 – Blocking time Case C Vordingborg – Lundby, Freight/ET left track, headway 174 seconds

Right Track

In this scenario the available overtaking track length in 907 m; the freight train length used for the simulation is 860 m.

The minimum achievable headway is 167 seconds (required headway 130 seconds) detected at the splitting point Spsk-Lu-N005 at 106+805 (Figure 191); to obtain the minimum headway the approach section to MB protecting the splitting point has been already optimized. The longest freight train to respect the headway requirements is 710 m.

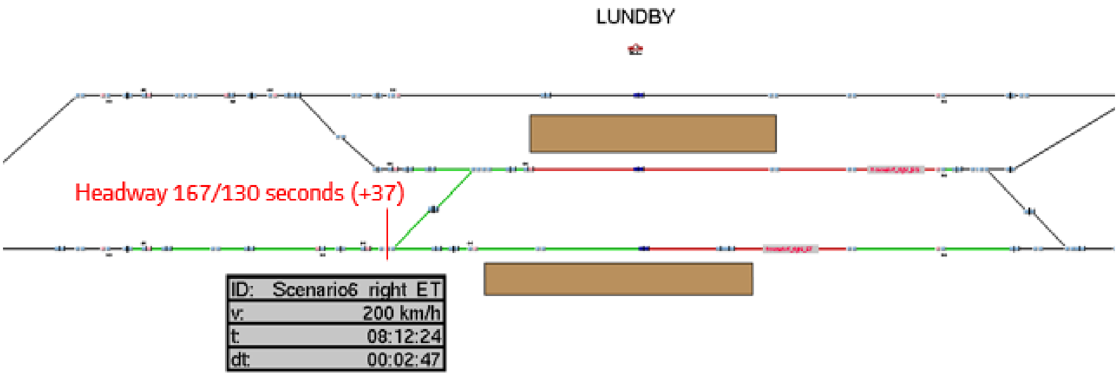


Figure 191 – Headway Case C Vordingborg – Lundby, Freight/ET right track, headway 167 seconds

Here below is shown the train graph with the blocking time diagram of both trains (Figure 192).

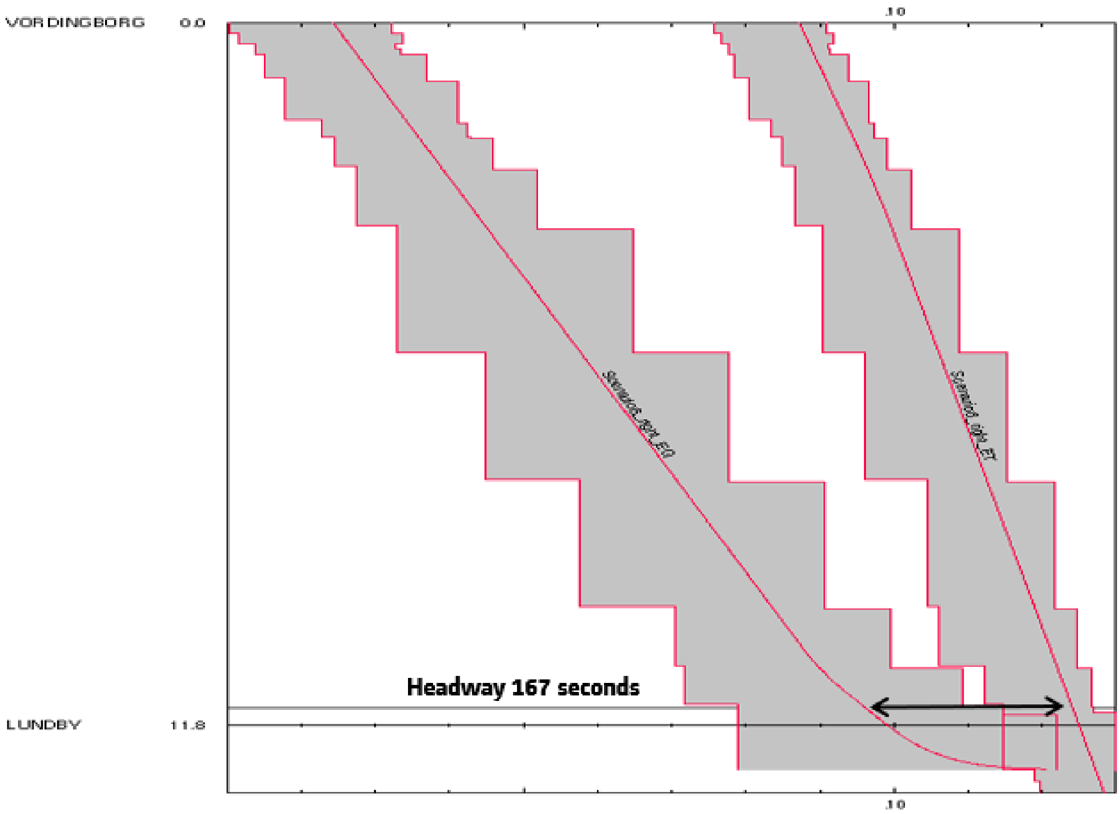


Figure 192 – Blocking time Case C Vordingborg – Lundby, Freight/ET right track, headway 167 seconds

As shown in the speed profile below the 2nd train at 167 second headway has no perturbations (Figure 193).

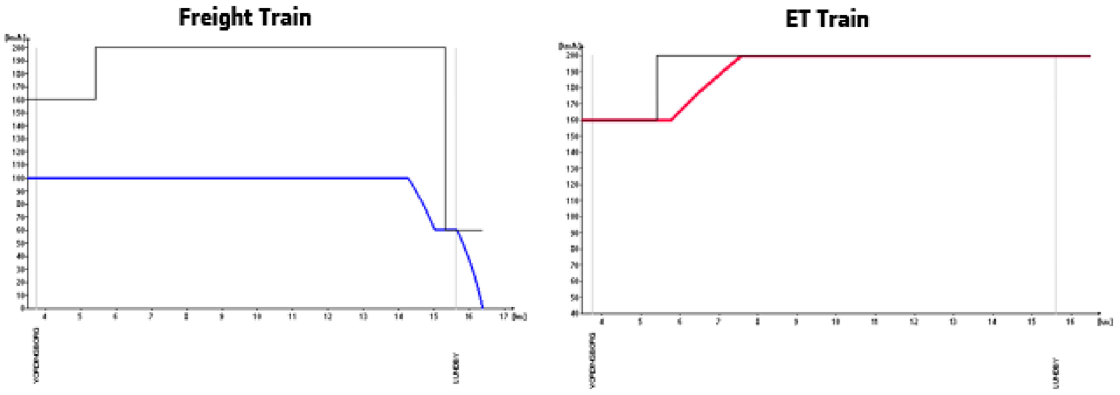


Figure 193 – Train Speed diagram Case C Vordingborg – Lundby, Freight/ET right track

Here below is shown the train graph with blocking time diagram of both trains at 166 seconds headway, to show that the bottleneck is the Mrk-Lu-129, that is as close as possible to the splitting point Spsk-Lu-N005 (Figure 194).

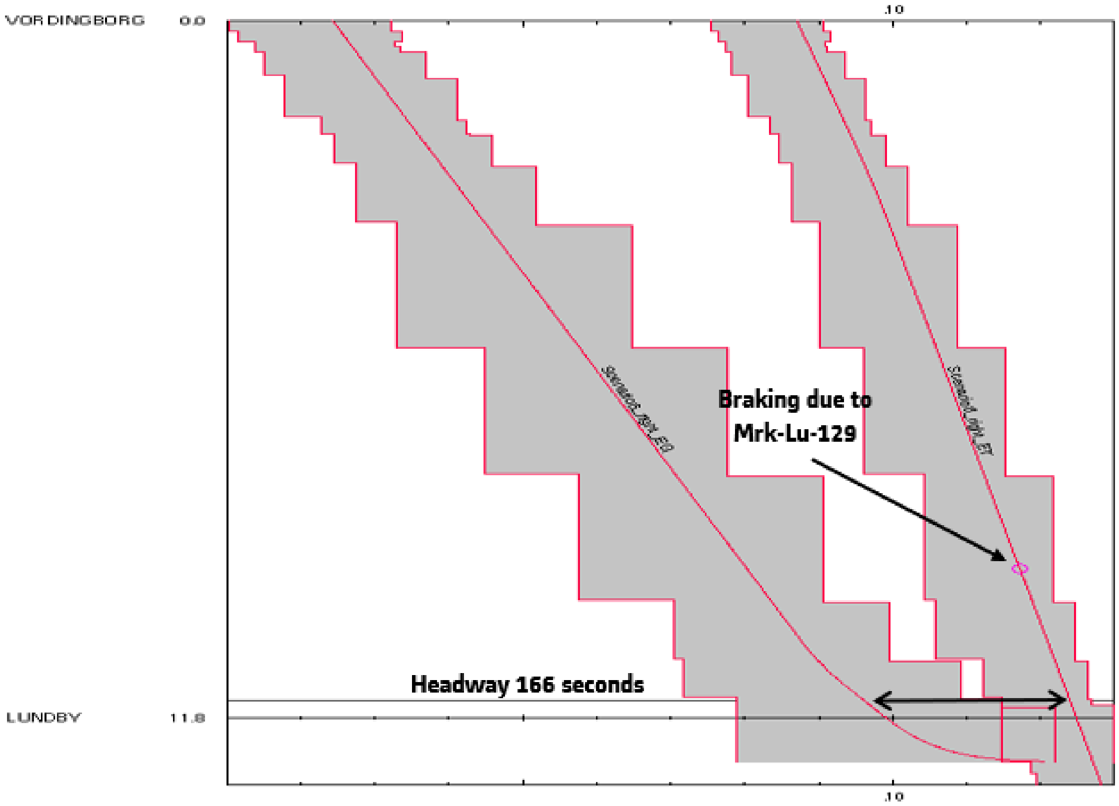


Figure 194 – Blocking time Case C Vordingborg – Lundby, Freight/ET right track, headway 166 seconds

5.4.5.7 Scenario 7

In this scenario the first train is freight train that is running from Lundby to Vordingborg direction, stops on the overtaking track in Vordingborg, followed by the ET passenger that stops at the end of the platform in the same station (Figure 195, Table 30).

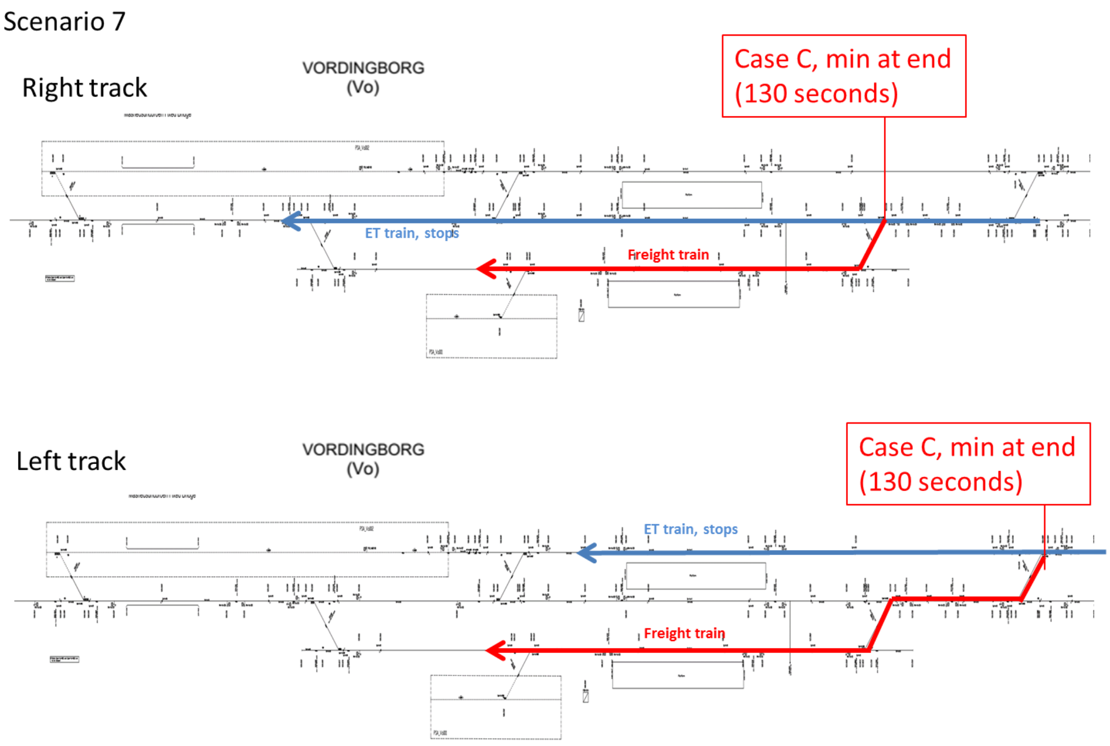


Figure 195 – Scenario 7: Vordingborg use of track

Headway Case C detected at the splitting points Spsk-Vo-N001 (right track) and Spsk-Lu-N003 (left track) in Vordingborg.

Scenarios	Track	Section	1st Train	2nd Train	Case	Technical Headway [sec]	Separate Tracks in Station	Headway Results [sec]
7	Left	Lundby – Vordingborg	EG 1000m, bp 80, stop at Vordingborg	ET 350m, stop at Vordingborg	C	130 at end	Vordingborg	165/130
	Right	Lundby – Vordingborg	EG 1000m, bp 80, stop at Vordingborg	ET 350m, stop at Vordingborg	C	130 at end	Vordingborg	120/130

Table 30 – Headway Scenario 7 Results Overview

The simulation has considered the presence of Neutral section, which has a negligible impact on the headway results.

The bottleneck is the splitting point section mainly for left track, due to the low diverging speed (60 Km/h). The longest freight train to respect the headway requirements is 820 m for the left track.

Left Track

In this scenario the available overtaking track length is higher than 1040 m, the freight train length used for the simulation is 1000 m.

The minimum achievable headway is 165 seconds (required headway 130 seconds) detected at the splitting point Spsk-Vo-N003 at 117+773 (Figure 196); to obtain the minimum headway the approach section to MB protecting the splitting point has been already optimized. The longest freight train to respect the headway requirements is 820 m.

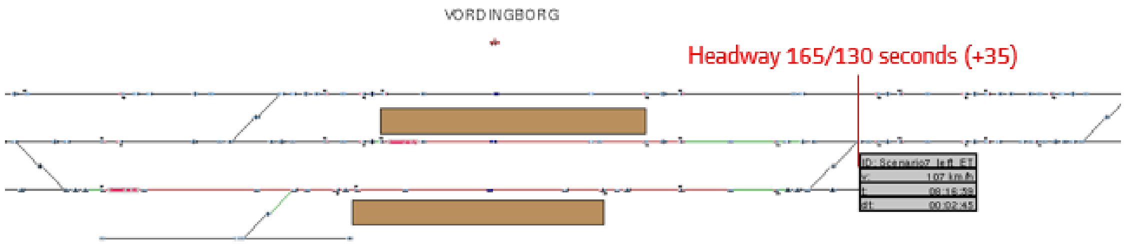


Figure 196 – Headway Case C Lundby – Vordingborg, Freight/ET left track, headway 165 seconds

Here below is shown the train graph with the blocking time diagram of both trains (Figure 197).

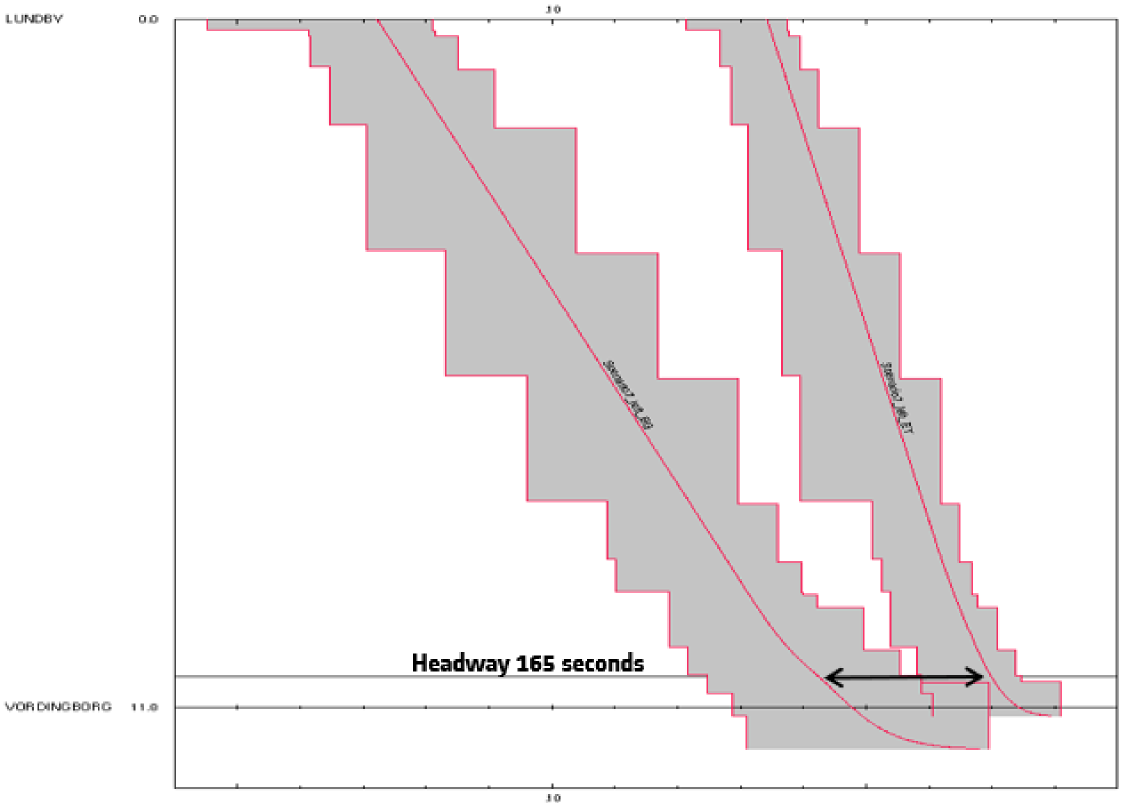


Figure 197 – Blocking time Case C Lundby – Vordingborg, Freight/ET left track, headway 165 seconds

As shown in the speed profile below the 2nd train at 165 second headway has no perturbations (Figure 198).

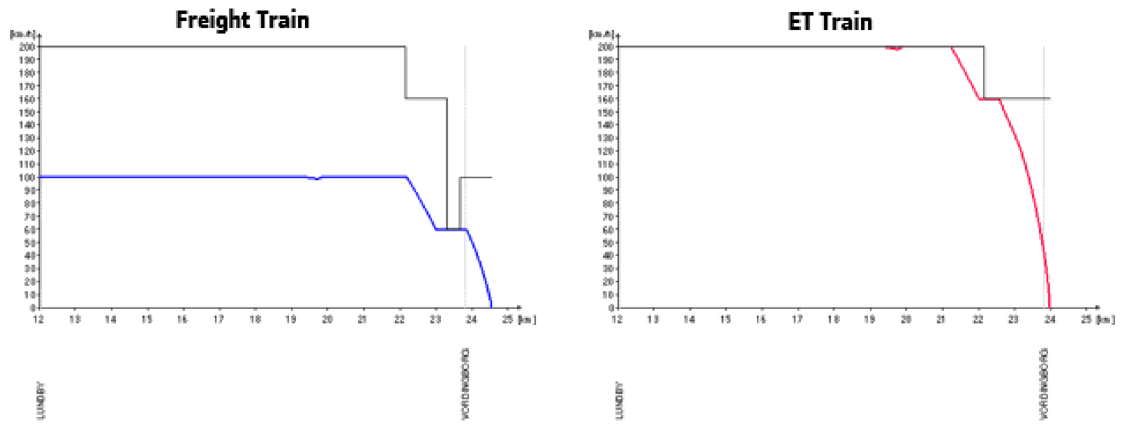


Figure 198 – Train Speed diagram Case C Lundby – Vordingborg, Freight/ET left track

Here below is shown the train graph with blocking time diagram of both trains at 164 seconds headway, to show that the bottleneck is the Mrk-Vo-214, that is as close as possible to the splitting point Spsk-Vo-N003 (Figure 199).

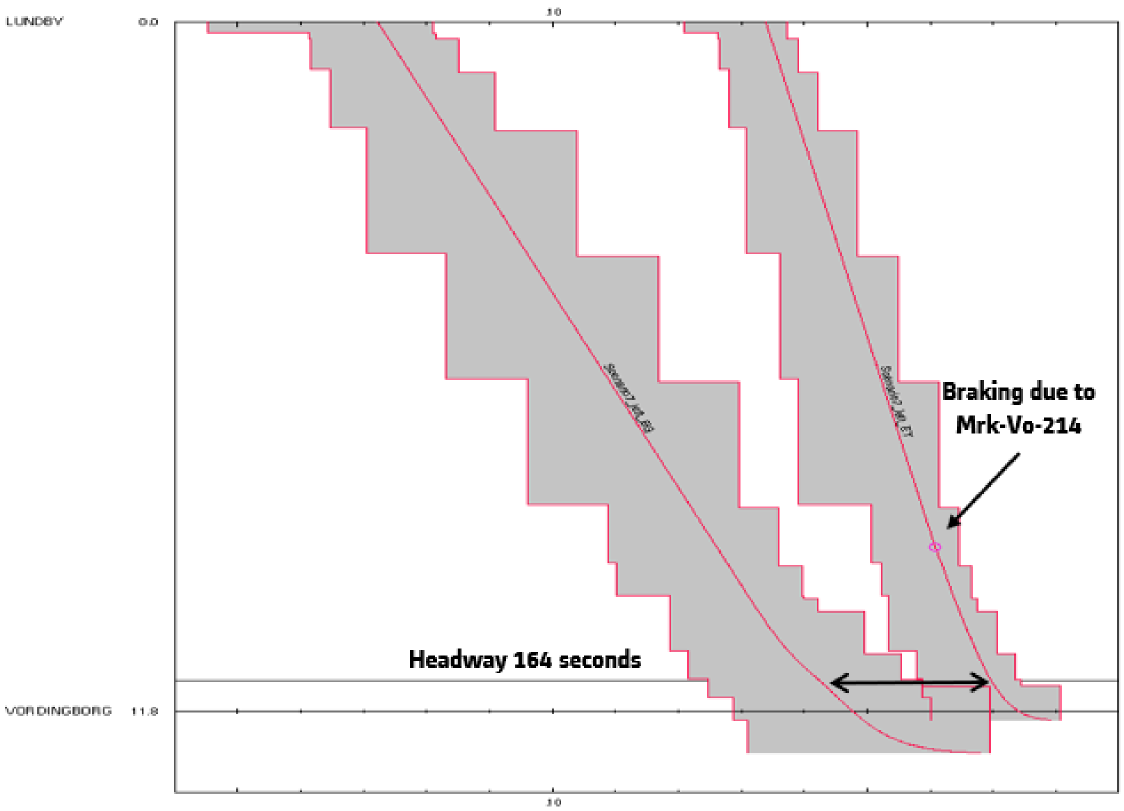


Figure 199 – Blocking time Case C Lundby – Vordingborg, Freight/ET left track, headway 164 seconds

Right Track

In this scenario the available overtaking track length is higher than 1040 m, the freight train length used for the simulation is 1000 m.

The minimum achievable headway is 120 seconds (required headway 130 seconds) detected at the splitting point Spsk-Vo-N001 at 116+392 (Figure 200); to obtain the minimum headway the approach section to MB protecting the splitting point has been already optimized.

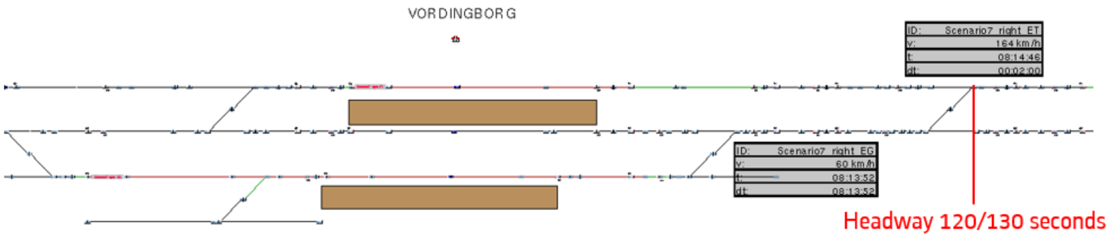


Figure 200 – Headway Case C Lundby – Vordingborg, Freight/ET right track, headway 120 seconds

Here below is shown the train graph with the blocking time diagram of both trains (Figure 201).

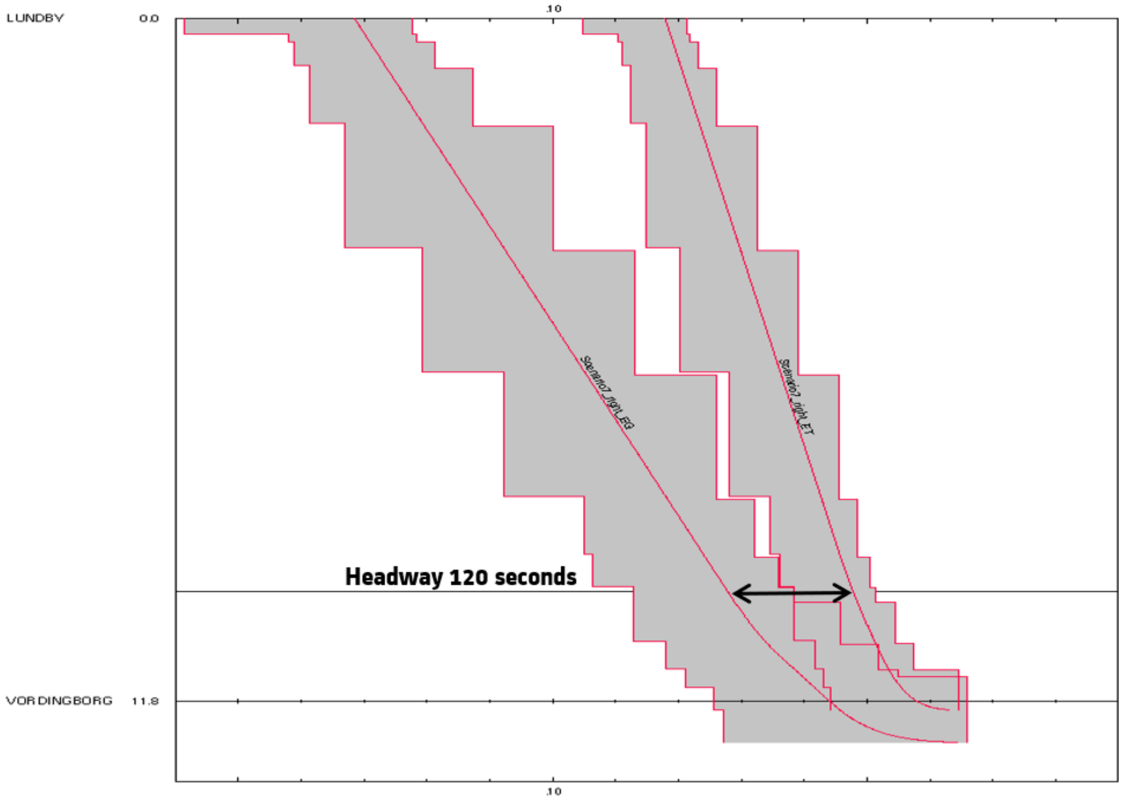


Figure 201 – Blocking time Case C Lundby – Vordingborg, Freight/ET right track, headway 120 seconds

As shown in the speed profile below the 2nd train at 120 second headway has no perturbations (Figure 202).

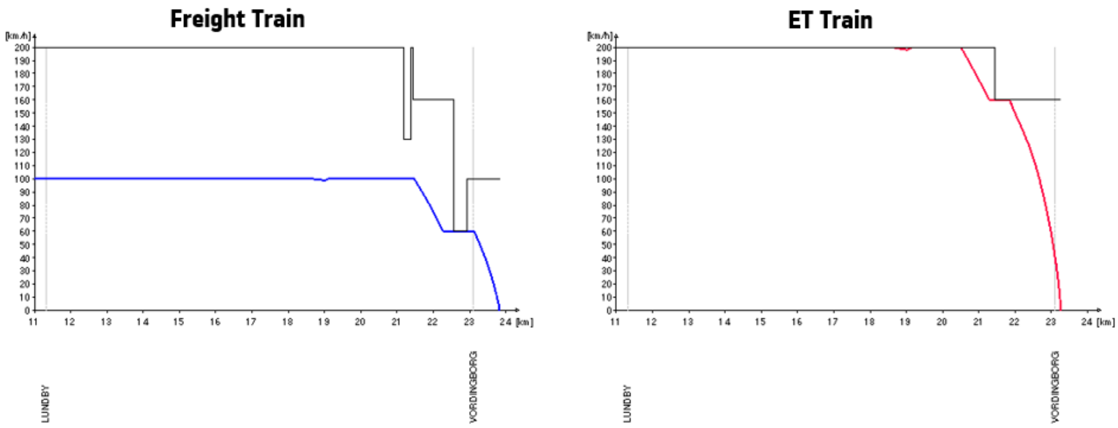


Figure 202 – Train Speed diagram Case C Lundby – Vordingborg, Freight/ET right track

Here below is shown the train graph with blocking time diagram of both trains at 119 seconds headway, to show that the bottleneck is the Mrk-Vo-310, that is as close as possible to the splitting point Spsk-Vo-N001 (Figure 203).

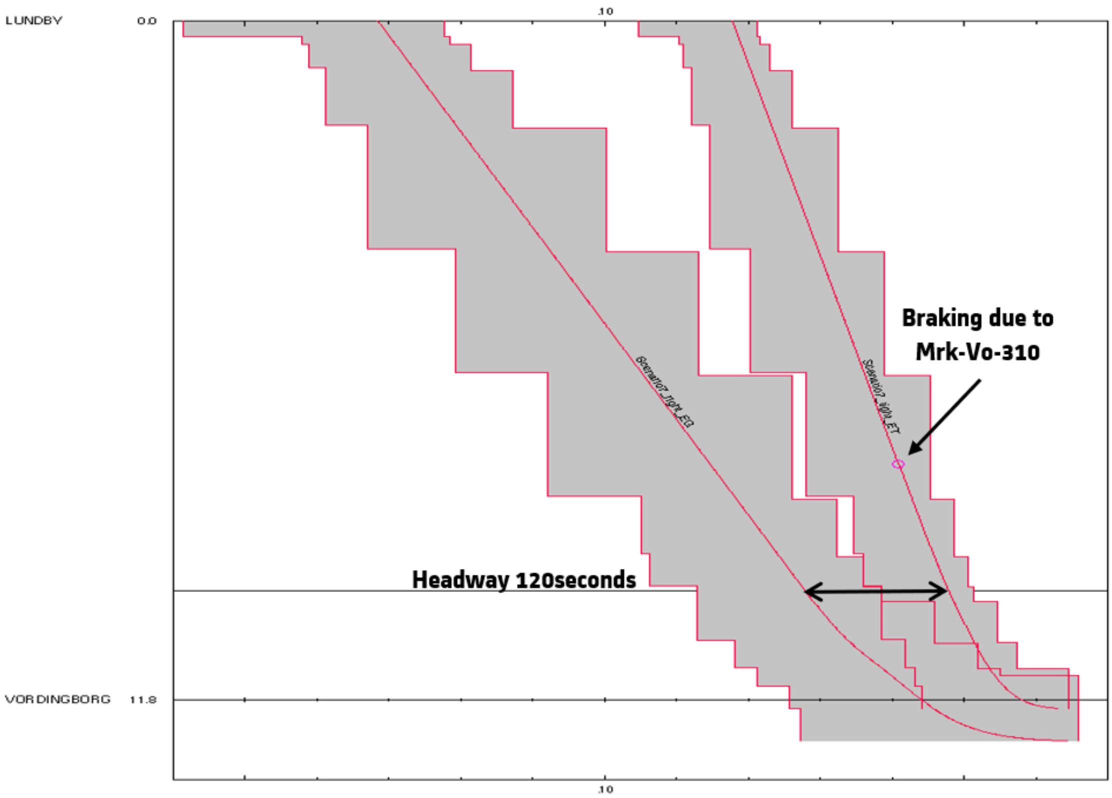


Figure 203 – Blocking time Case C Lundby – Vordingborg, Freight/ET right track, headway 119 seconds

5.4.5.8 Scenario 8

In this scenario the first train is the ET train, starting from standstill at the end of the platform in Vordingborg, the second train is the freight train that is starting from standstill from the same station on the overtaking track (Figure 204, Table 31).

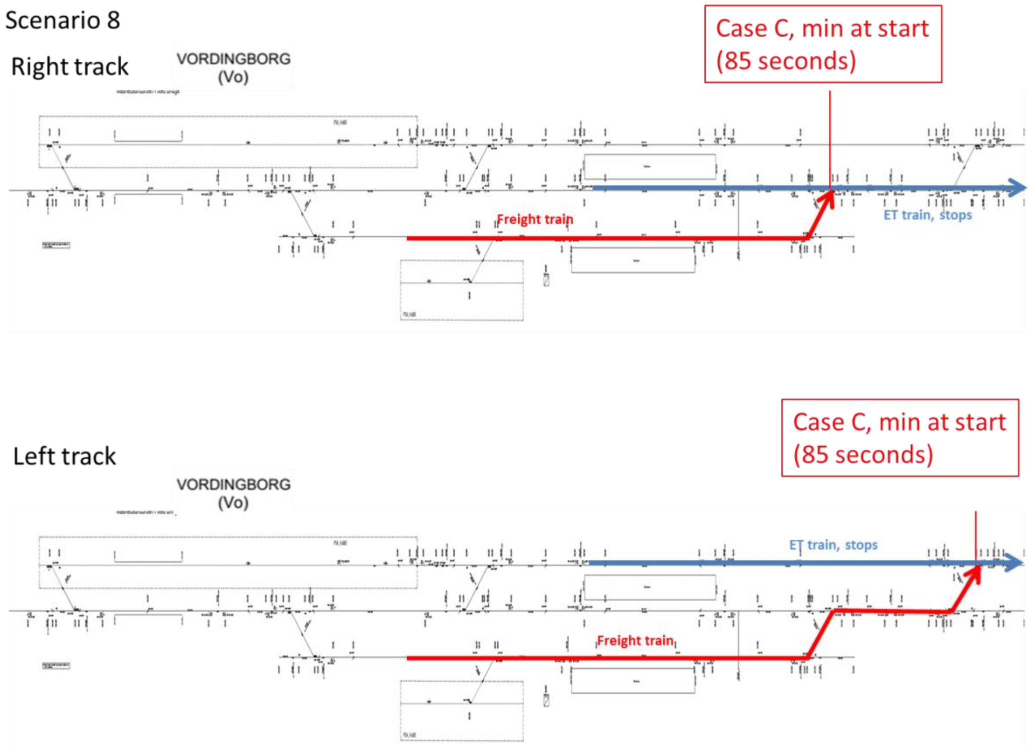


Figure 204 – Scenario 8: Vordingborg use of track

Headway Case C is detected at the splitting point Spsk-Vo-N001 (left track) and Spsk-Vo-N003 (right track).

Scenarios	Track	Section	1st Train	2nd Train	Case	Technical Headway [sec]	Separate Tracks in Station	Headway Results [sec]
8	Left	Vordingborg – Lundby	ET 350m, bp 180 stop at Vordingborg	EG 1000m, bp 80, stop at Vordingborg	C	85 at start	Vordingborg	101/85
	Right	Vordingborg – Lundby	ET 350m, bp 180 stop at Vordingborg	EG 1000m, bp 80, stop at Vordingborg	C	85 at start	Vordingborg	71/85

Table 31 – Headway Scenario 8 Results Overview

Left Track

The minimum achievable headway is 101 seconds (required headway 85 seconds) detected at the splitting point Spsk-Vo-N001 at 116+392 (Figure 205). This is the minimum achievable headway in this scenario considering the route setting and release times. For left track headway is constrained by the long distance between the starting point of trains and splitting point, i.e. when ET train clears splitting point EG train is still far away.

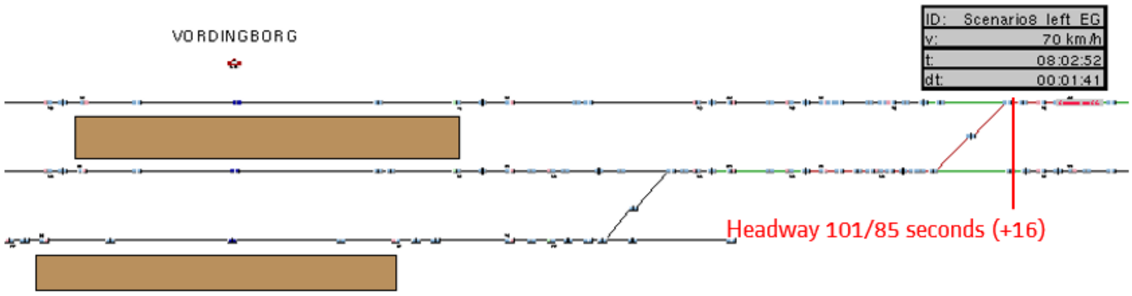


Figure 205 – Headway Case C Vordingborg – Lundby, Freight/ET left track, headway 101 seconds

Here below is shown the train graph with the blocking time diagram of both trains (Figure 206).

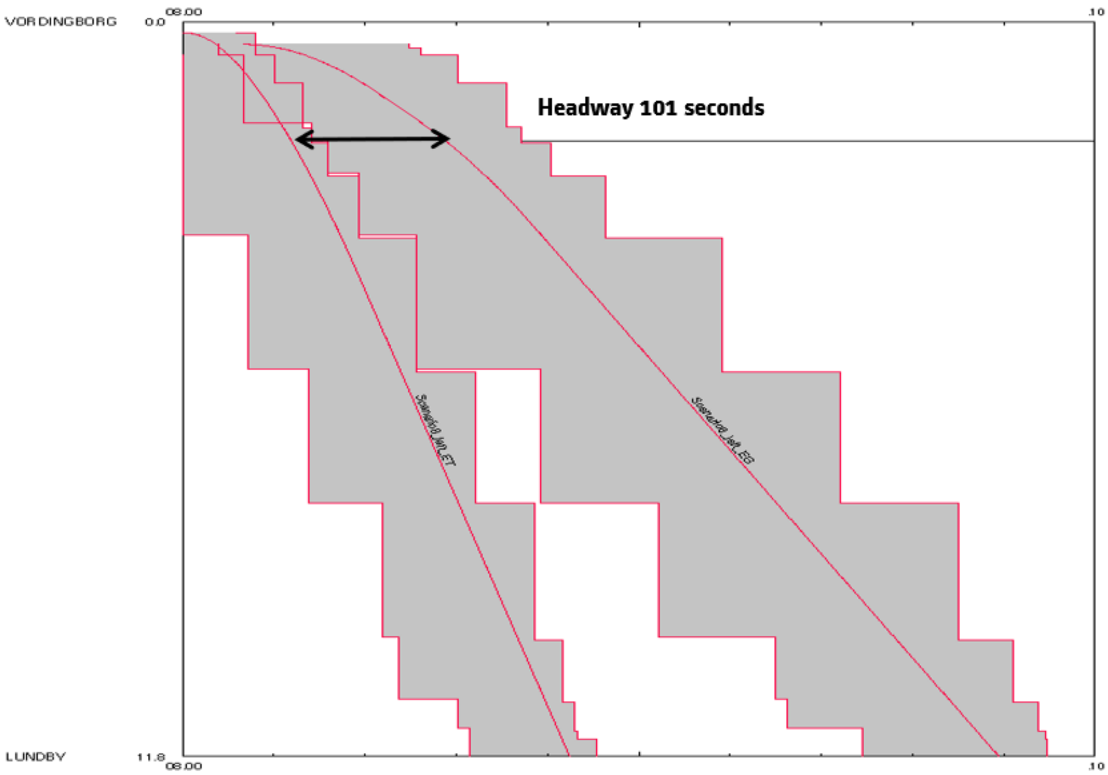


Figure 206 – Blocking time Case C Vordingborg – Lundby, Freight/ET left track, headway 101 seconds

As shown in the speed profile below the 2nd train at 101 second headway has no perturbations (Figure 207).

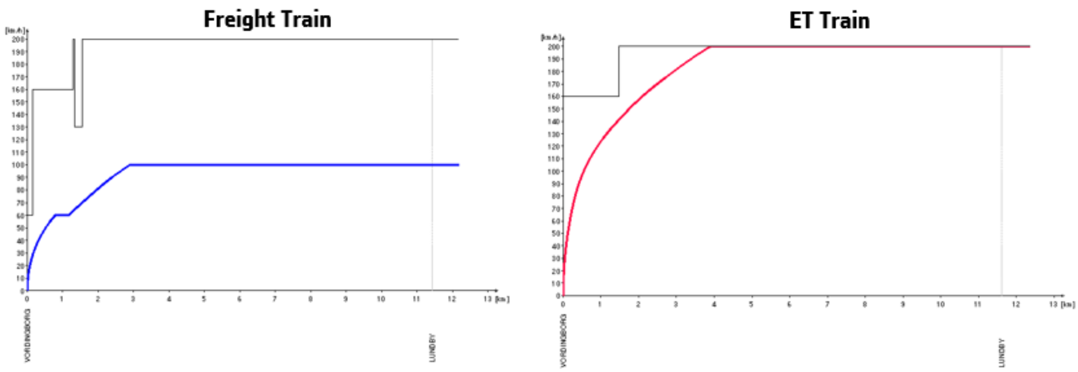


Figure 207 – Train Speed diagram Case C Vordingborg – Lundby, Freight/ET left track

Right Track

The minimum achievable headway is 71 seconds (required headway 85 seconds) detected at the splitting point Spsk-Vo-N003 at 117+773 (Figure 208). This is the minimum achievable headway in this scenario considering the route setting and release times.

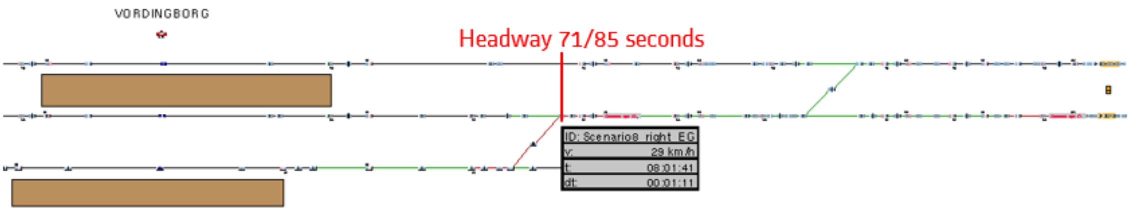


Figure 208 – Headway Case C Vordingborg – Lundby, Freight/ET right track, headway 71 seconds

Here below is shown the train graph with the blocking time diagram of both trains (Figure 209).

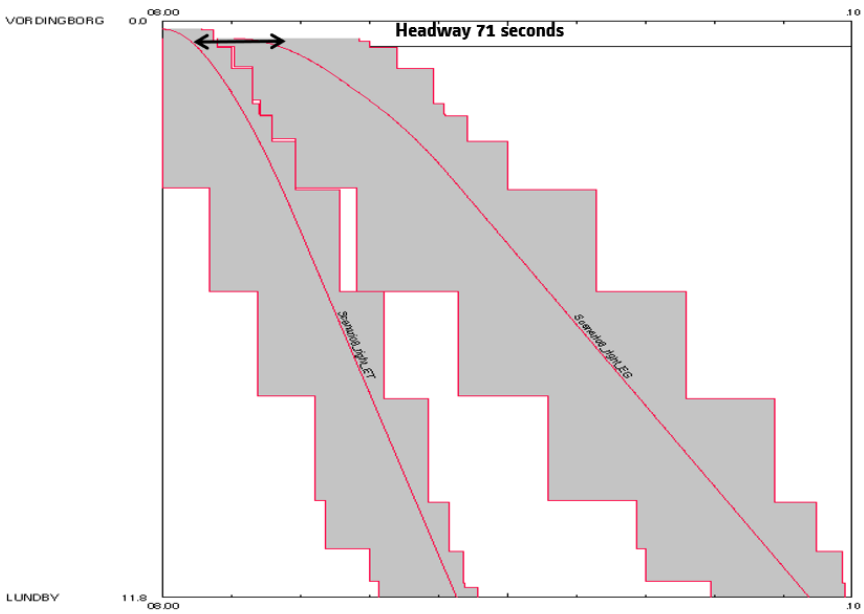


Figure 209 – Blocking time Case C Vordingborg – Lundby, Freight/ET right track, headway 71 seconds

As shown in the speed profile below the 2nd train at 71 second headway has no perturbations (Figure 210).

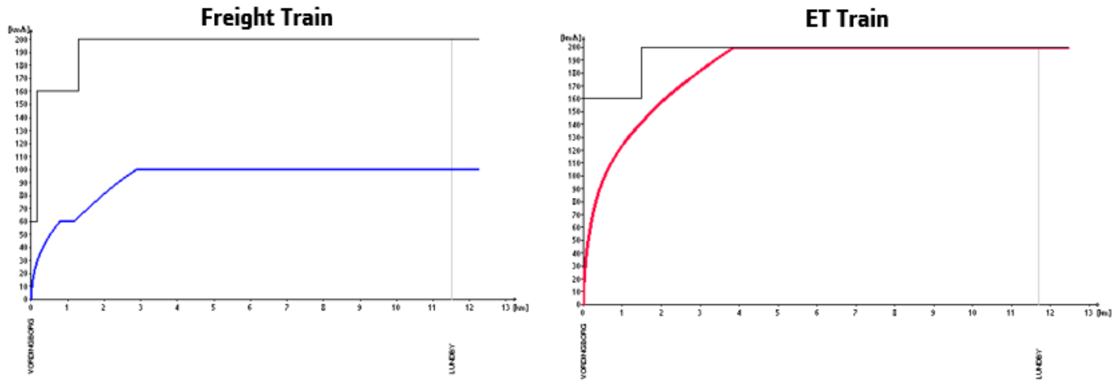


Figure 210 – Train Speed diagram Case C Vordingborg – Lundby, Freight/ET right track

5.4.5.9 Scenario 9

In this scenario the first train is the ET train starting from standstill at the end of the platform in Vordingborg, the second train is the freight train that is starting from standstill from the same station on the overtaking track (Figure 211 ,Table 32).

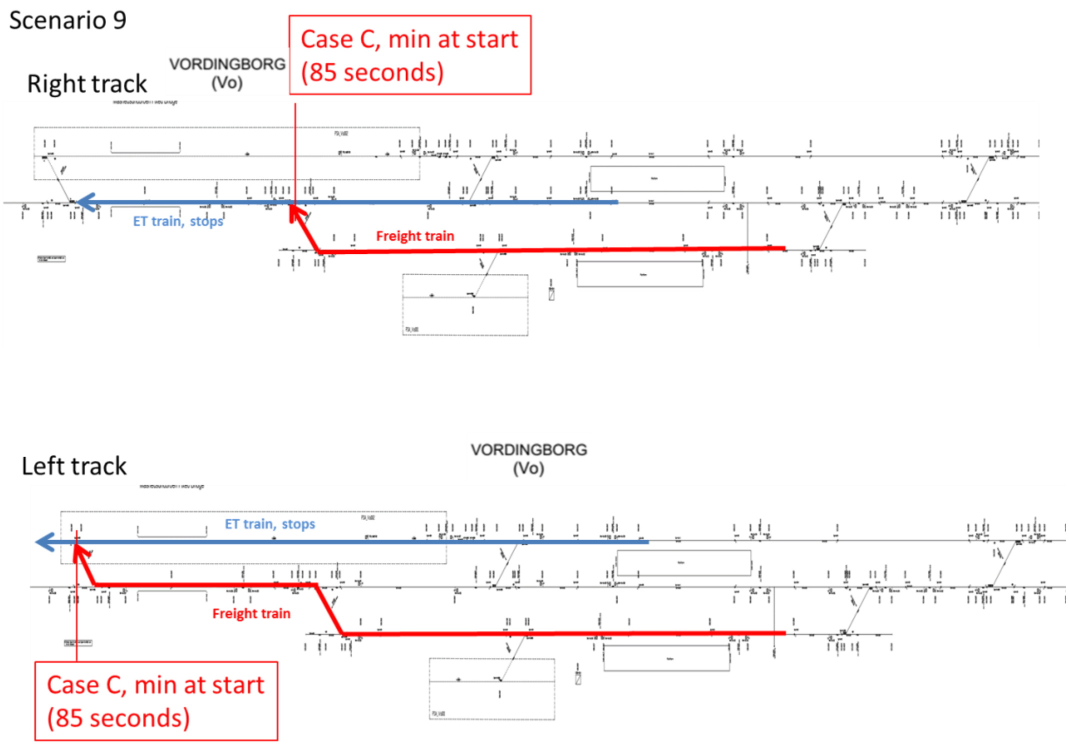


Figure 211 – Scenario 9: Vordingborg use of track

Headway Case C is detected at the splitting point Spsk-Vo-N010 (left track) and Spsk-Vo-N012 (right track).

Scenarios	Track	Section	1st Train	2nd Train	Case	Technical Headway [sec]	Separate Tracks in Station	Headway Results [sec]
9	Left	Vordingborg – Orehoved	ET 350m, bp 180, stop at Vordingborg	EG 1000m, bp 80, stop at Vordingborg	C	85 at start	Vordingborg	75/85
	Right	Vordingborg – Orehoved	ET 350m, bp 180, stop at Vordingborg	EG 1000m, bp 80, stop at Vordingborg	C	85 at start	Vordingborg	90/85

Table 32 – Headway Scenario 9 Results Overview

For left track headway is reached while for right track headway is constrained by the splitting point being far away from starting point, i.e. when ET train clears splitting point EG train is still far away.

Left Track

The minimum achievable headway is 75 seconds (required headway 85 seconds) detected at the splitting point Spsk-Vo-N010 at 119+247 (Figure 212). This is the minimum achievable headway in this scenario considering the route setting and release times.

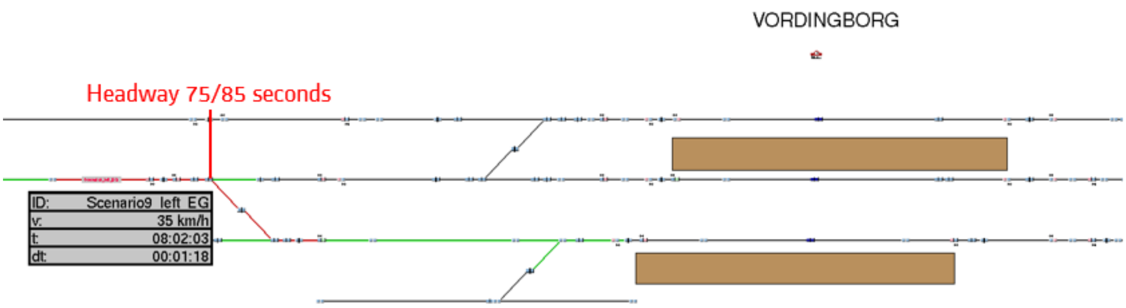


Figure 212 – Headway Case C Vordingborg – Orehoved, Freight/ET left track, headway 75 seconds

Here below is shown the train graph with the blocking time diagram of both trains (Figure 213).

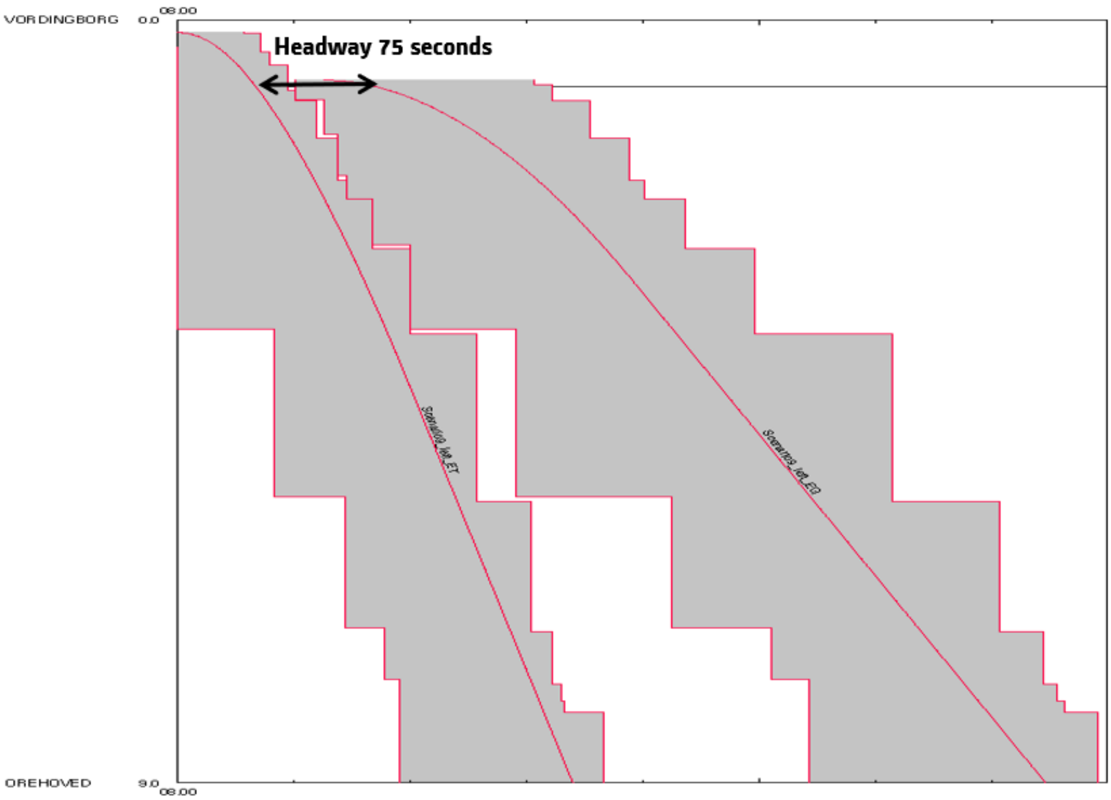


Figure 213 – Blocking time Case C Vordingborg – Orehoved, Freight/ET left track, headway 75 seconds

As shown in the speed profile below the 2nd train at 75 second headway has no perturbations (Figure 214).

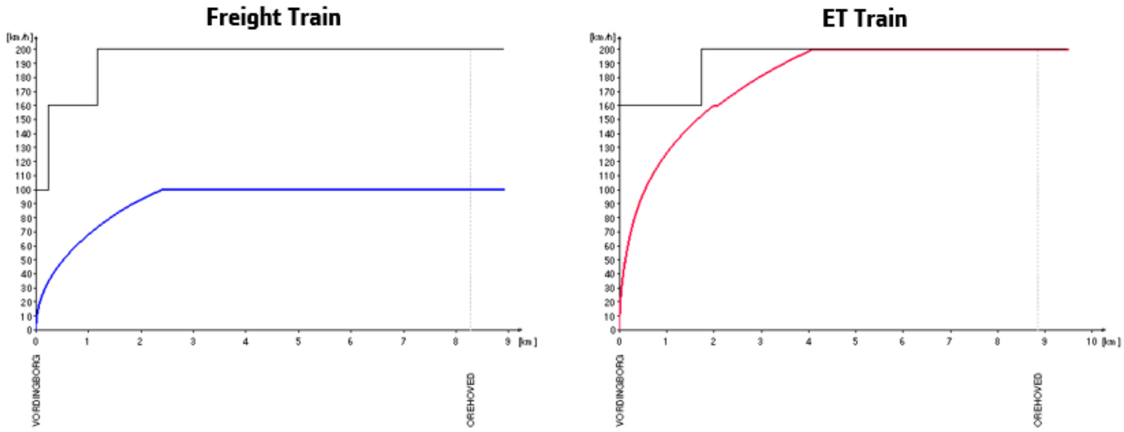


Figure 214 – Train Speed diagram Case C Vordingborg – Orehoved, Freight/ET left track

Right Track

The minimum achievable headway is 90 seconds (required headway 85 seconds) detected at the splitting point Spsk-Vo-N012 at 120+406 (Figure 215). This is the minimum achievable headway in this scenario considering the route setting and release times. For right track, headway is constrained by the splitting point being far away from starting point; i.e. when ET train clears splitting point EG train is still far away;

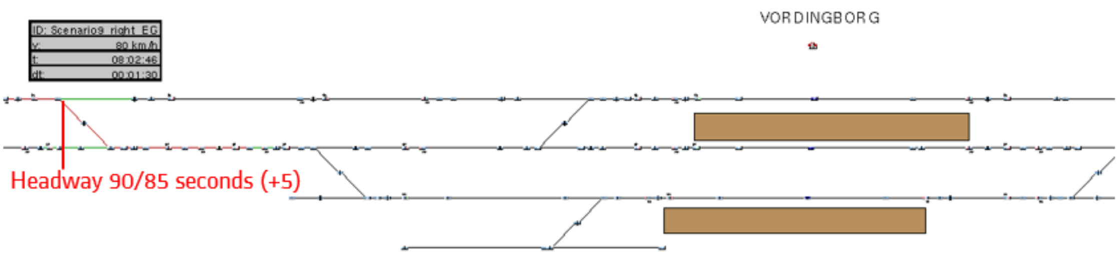


Figure 215 – Headway Case C Vordingborg – Orehoved, Freight/ET right track, headway 90 seconds

Here below is shown the train graph with the blocking time diagram of both trains (Figure 216).

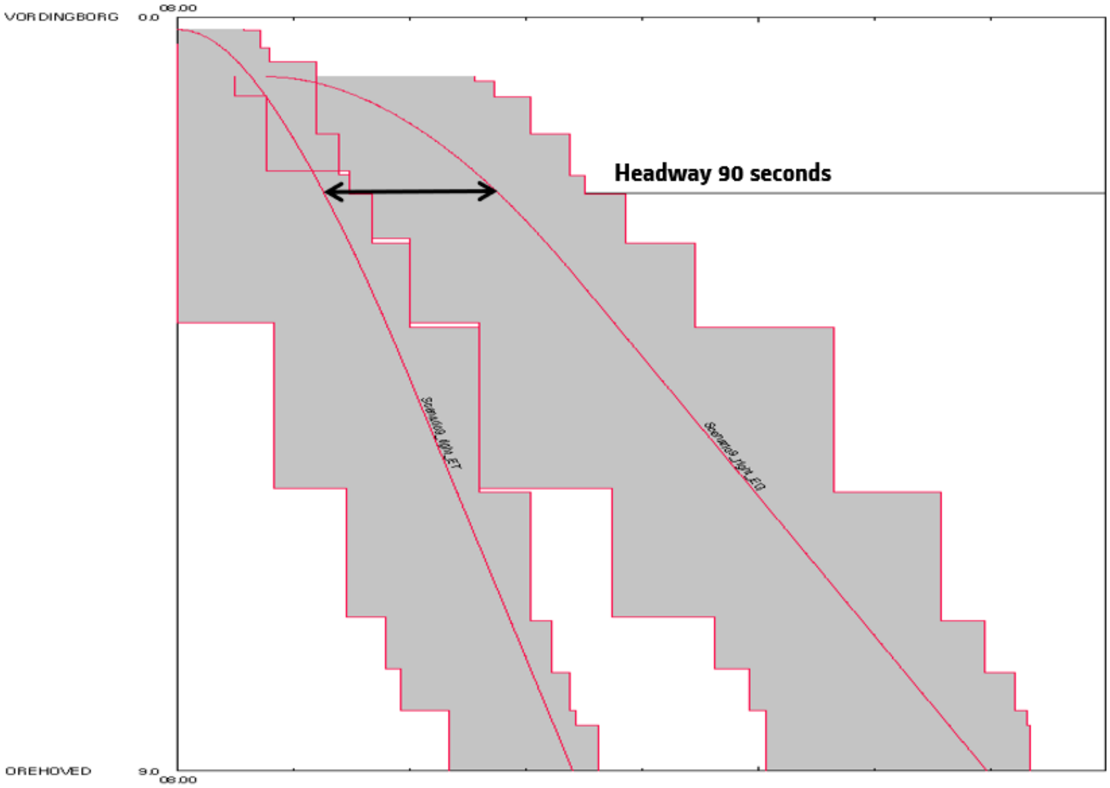


Figure 216 – Blocking time Case C Vordingborg – Orehoved, Freight/ET right track, headway 90 seconds

As shown in the speed profile below the 2nd train at 90 second headway has no perturbations (Figure 217).

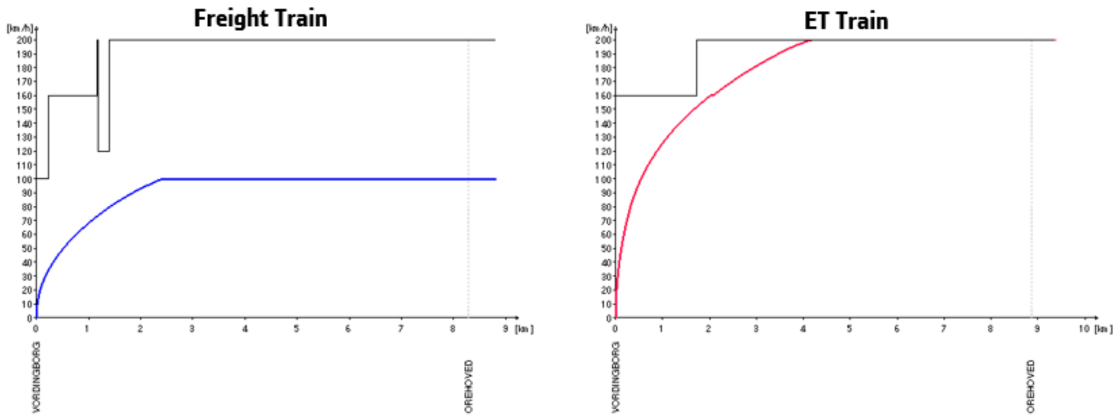


Figure 217 – Train Speed diagram Case C Vordingborg – Orehoved, Freight/ET right track

5.4.5.10 Scenario 10

In this scenario the first train is freight train that is running from Orehoved to Vordingborg direction, stops on the overtaking track in Vordingborg, followed by the ET passenger stop train that stops at the end of the platform in the same station (Figure 218 ,Table 33).

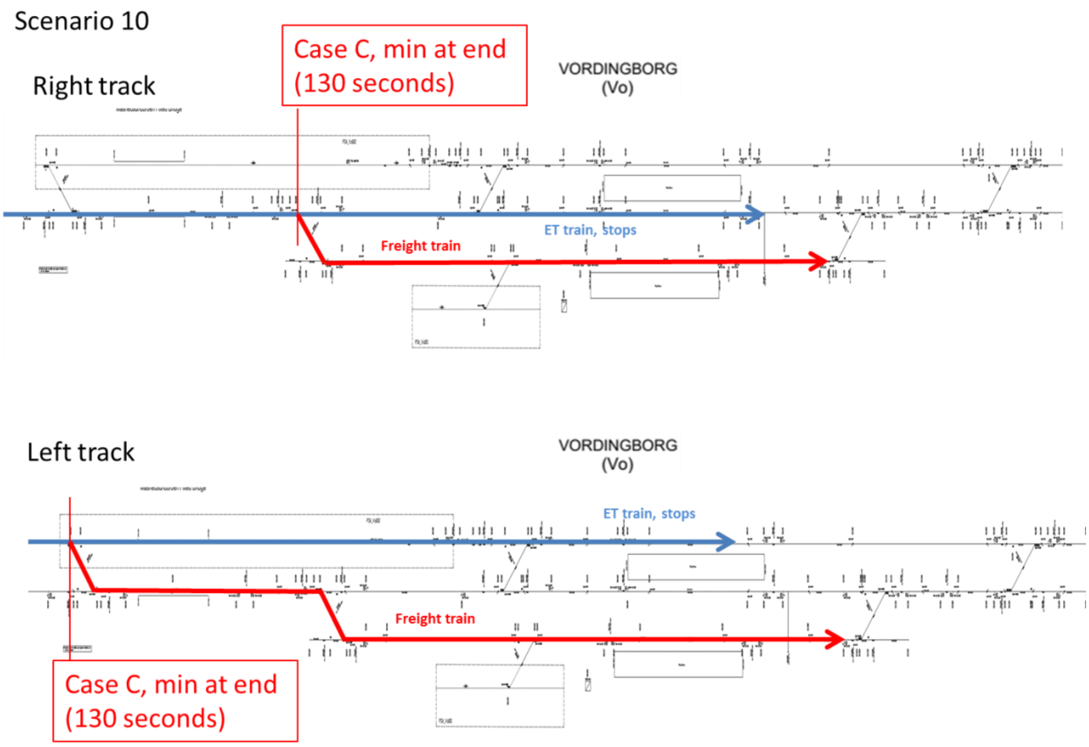


Figure 218 – Scenario 10: Vordingborg use of track

Headway Case C detected at the splitting points Spsk-Vo-N010 (right track) and Spsk-Vo-N012 (left track) in Vordingborg.

Scenarios	Track	Section	1st Train	2nd Train	Case	Technical Headway [sec]	Separate Tracks in Station	Headway Results [sec]
10	Left	Orehoved - Vordingborg	EG 1000m, bp 80, stop at Vordingborg	ET 350m, bp 180, stop at Vordingborg	C	130 at end	Vordingborg	111/130
	Right	Orehoved - Vordingborg	EG 1000m, bp 80, stop at Vordingborg	ET 350m, bp 180, stop at Vordingborg	C	130 at end	Vordingborg	160/130

Table 33 – Headway Scenario 10 Results Overview

The bottleneck is the splitting point section for right track; the longest freight train to respect the headway requirements is 790 m while headway requirement is reached on left track.

Left Track

In this scenario the available overtaking track length is higher than 1040 m, the freight train length used for the simulation is 1000 m.

The minimum achievable headway is 111 seconds (required headway 130 seconds) detected at the splitting point Spsk-Vo-N012 at 120+406 (Figure 219); to obtain the minimum headway the approach section to MB protecting the splitting point has been already optimized.

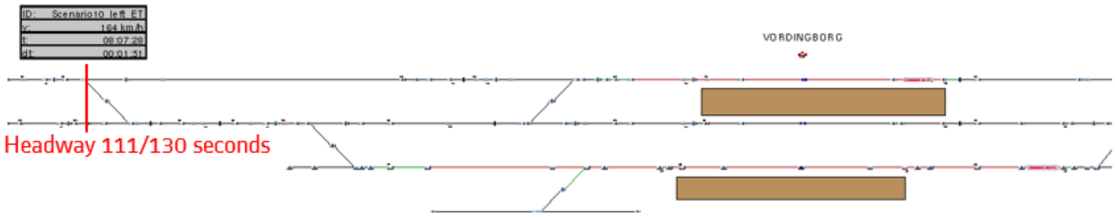


Figure 219 – Headway Case C Orehoved – Vordingborg, Freight/ET left track, headway 111 seconds

Here below is shown the train graph with the blocking time diagram of both trains (Figure 220).

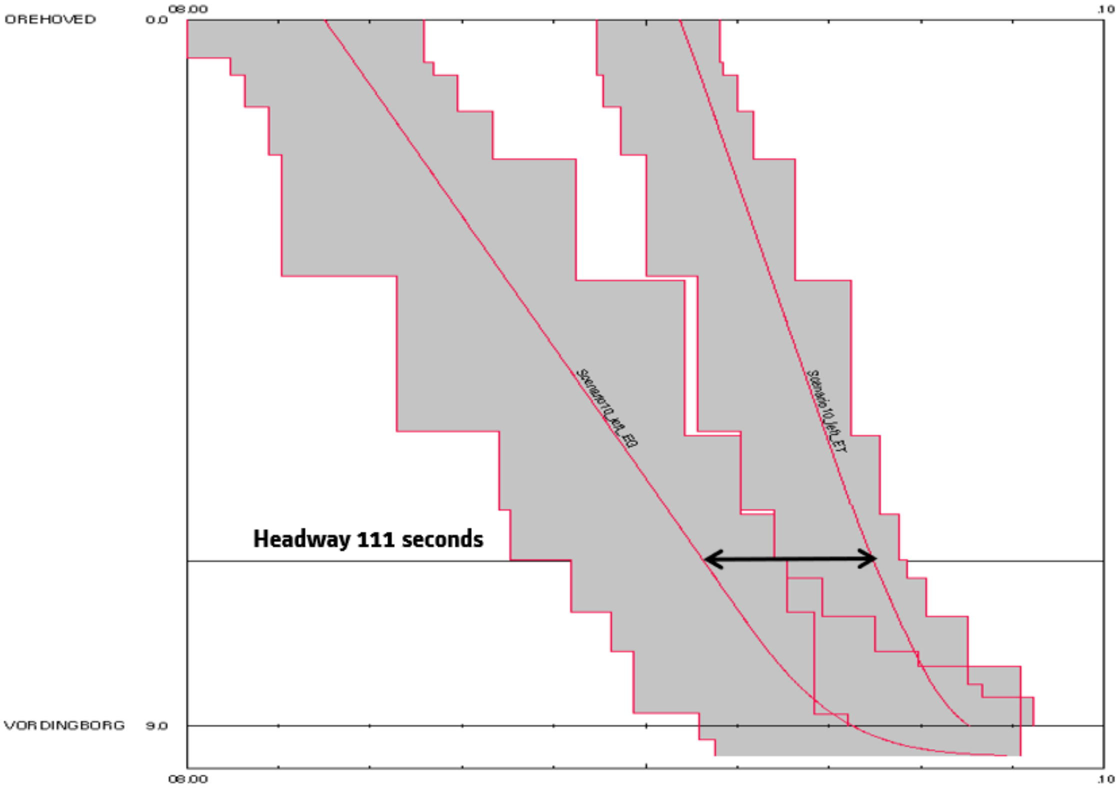


Figure 220 – Blocking time Case C Orehoved – Vordingborg, Freight/ET left track, headway 111 seconds

As shown in the speed profile below the 2nd train at 111 second headway has no perturbations (Figure 221).

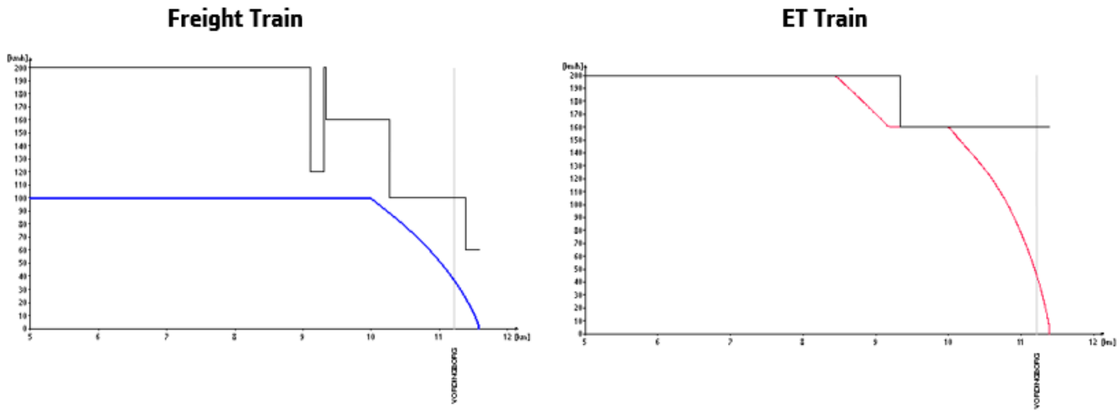


Figure 221 – Train Speed diagram Case C Orehoved – Vordingborg, Freight/ET left track

Here below is shown the train graph with blocking time diagram of both trains at 110 seconds headway, to show that the bottleneck is the marker board (km 120+421), that is as close as possible to the splitting point Spsk-Vo-N012 (Figure 222).

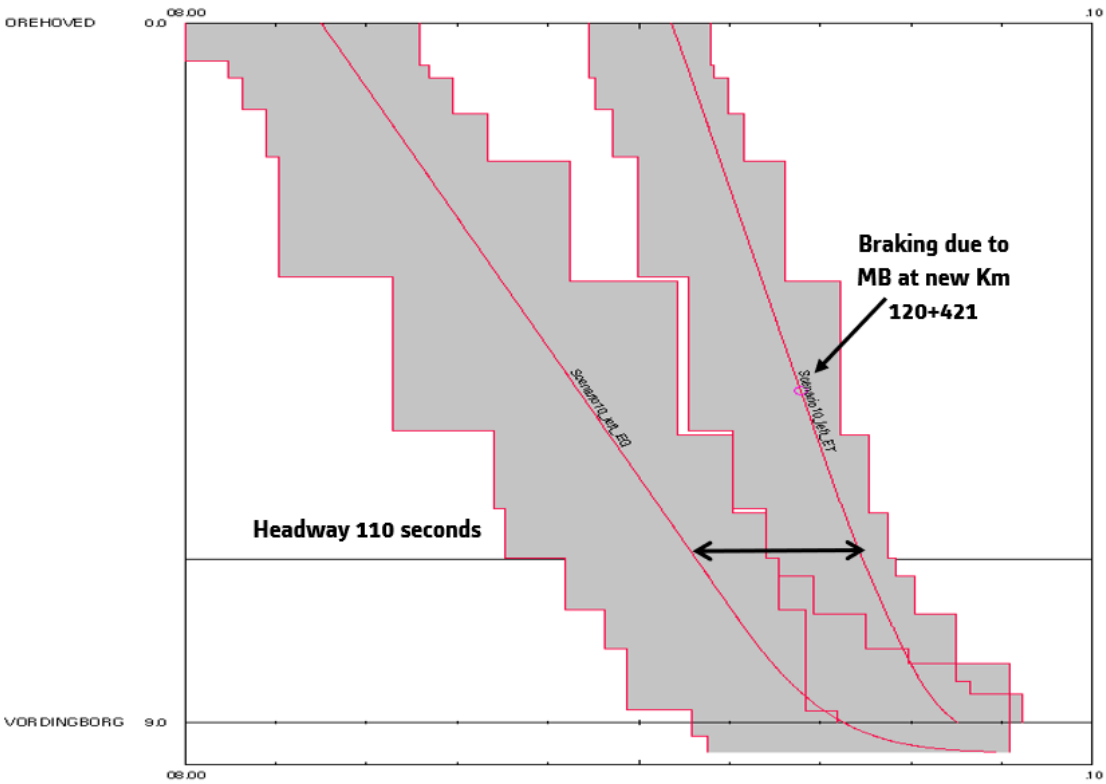


Figure 222– Blocking time Case C Orehoved – Vordingborg, Freight/ET left track, headway 110 seconds

Right Track

In this scenario the available overtaking track length is higher than 1040 m, the freight train length used for the simulation is 1000 m.

The minimum achievable headway is 160 seconds (required headway 130 seconds) detected at the splitting point Spsk-Vo-N010 at 119+247 (Figure 223); to obtain the minimum headway the approach section to MB protecting the splitting point has been already optimized. The longest freight train to respect the headway requirements is 790 m.

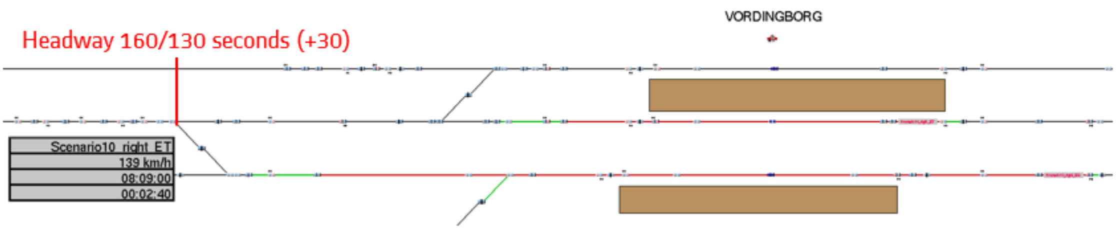


Figure 223 – Headway Case C Orehoved – Vordingborg, Freight/ET right track, headway 160 seconds

Here below is shown the train graph with the blocking time diagram of both trains (Figure 224).

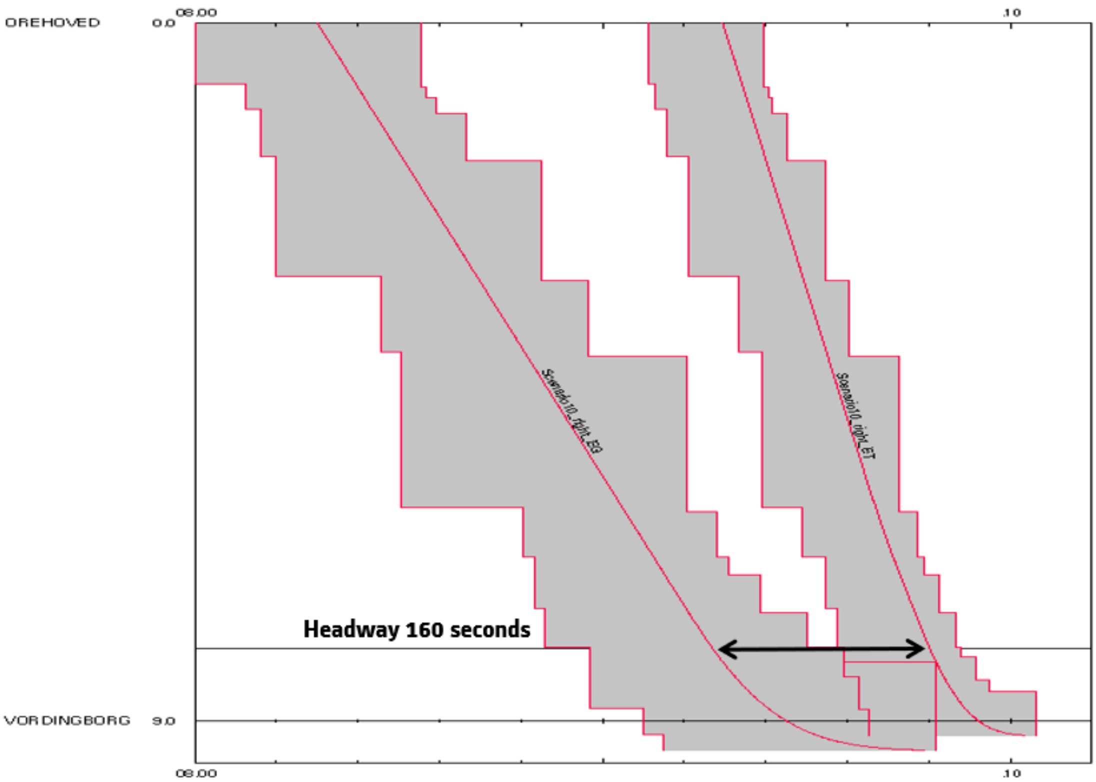


Figure 224 – Blocking time Case C Orehoved – Vordingborg, Freight/ET right track, headway 160 seconds

As shown in the speed profile below the 2nd train at 160 second headway has no perturbations (Figure 225).

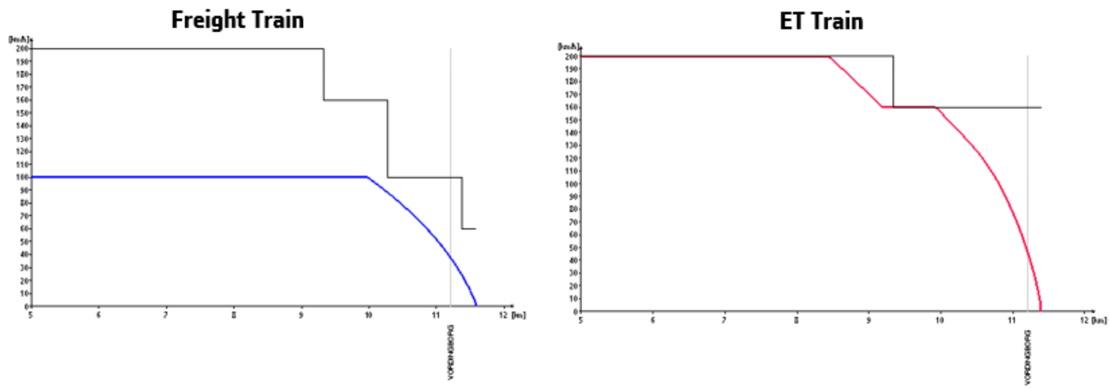


Figure 225 – Train Speed diagram Case C Orehoved – Vordingborg, Freight/ET right track

Here below is shown the train graph with blocking time diagram of both trains at 159 seconds headway, to show that the bottleneck is the Mrk-Vo-234, that is as close as possible to the splitting point Spsk-Vo-N010 (Figure 226).

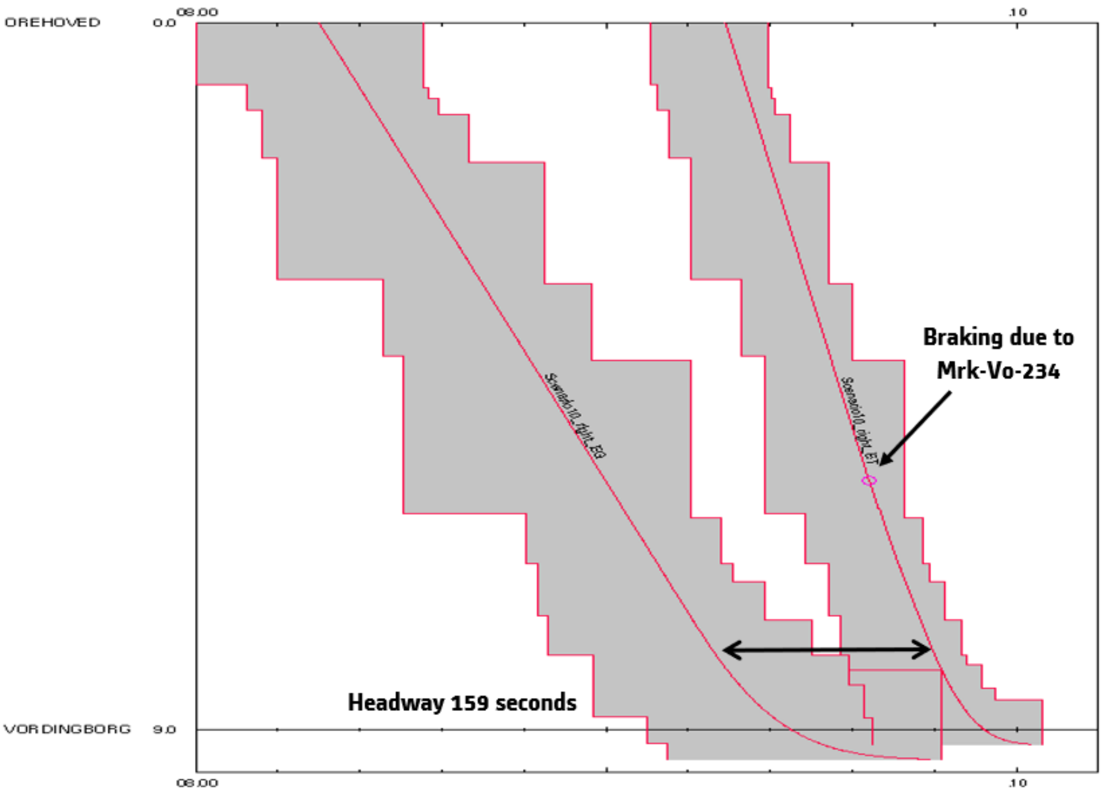


Figure 226 – Blocking time Case C Orehoved – Vordingborg, Freight/ET right track, headway 159 seconds

5.4.5.11 Scenario 11

In this scenario the first train is freight train that is running from Vordingborg to Orehoved direction, stops on the overtaking track in Orehoved, followed by the ET passenger non-stop train (Figure 227, Table 34).

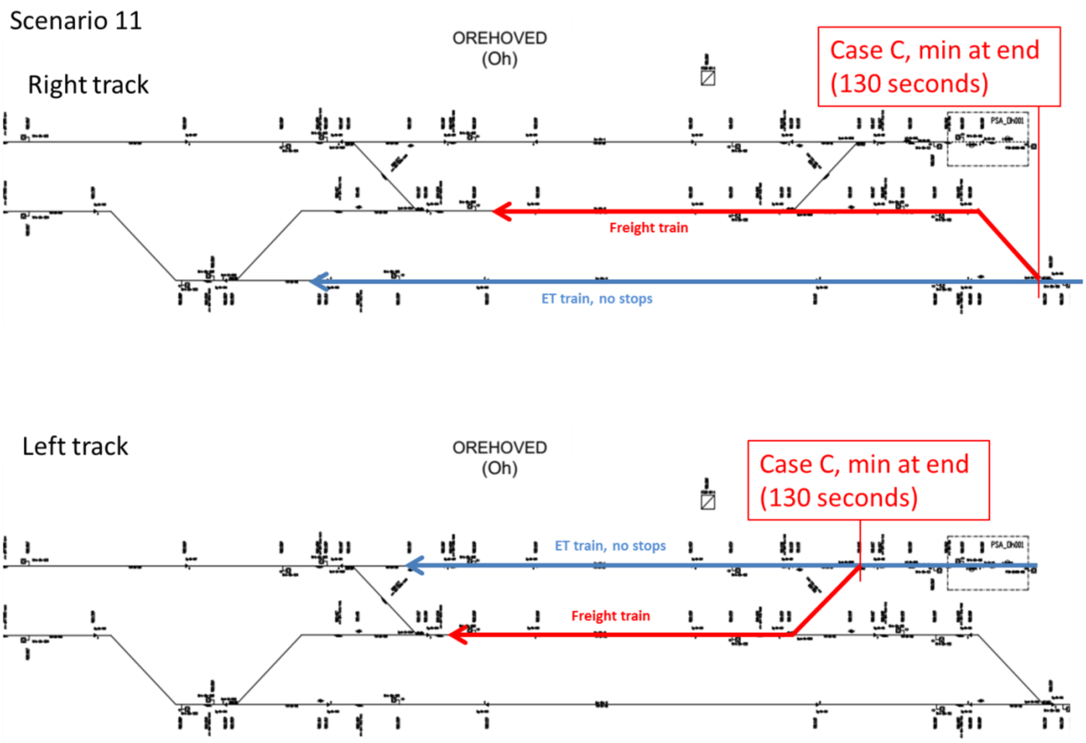


Figure 227 – Scenario 11: Orehoved use of track

Headway Case C detected at the splitting points Spsk-Oh-N001 (left track) and Spsk-Oh-N002 (right track) in Orehoved.

Scenarios	Track	Section	1st Train	2nd Train	Case	Technical Headway [sec]	Separate Tracks in Station	Headway Results SL [sec]
11	Left	Vordingborg-Orehoved	EG 1000m, bp 80, stop at Orehoved	ET 350m, bp 180, no stop	C	130 at end	Orehoved	128/130
	Right	Vordingborg-Orehoved	EG 1000m, bp 80, stop at Orehoved	ET 350m, bp 180, no stop	C	130 at end	Orehoved	171/130

Table 34 – Headway Scenario 11 Results Overview

The bottleneck is the splitting point section mainly for right track, due to the short overtaking track. The longest freight train to respect the headway requirements is 810 m.

Left Track

In this scenario the available overtaking track length is higher than 1040 m, the freight train length used for the simulation is 1000 m.

The minimum achievable headway is 128 seconds (required headway 130 seconds) detected at the splitting point Spsk-Oh-N001 at 126+341 (Figure 228); to obtain the minimum headway the approach section to MB protecting the splitting point has been already optimized.

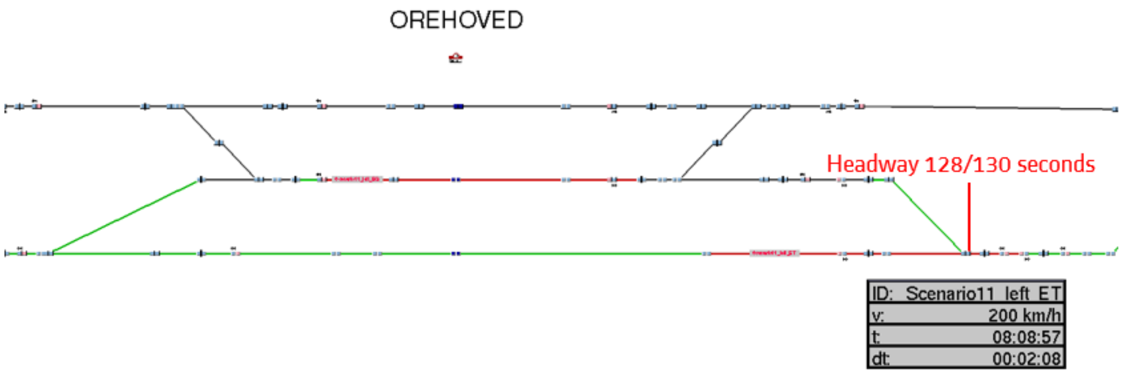


Figure 228 – Headway Case C Vordingborg – Orehoved Freight/ET left track, headway 128 seconds

Here below is shown the train graph with the blocking time diagram of both trains (Figure 229).

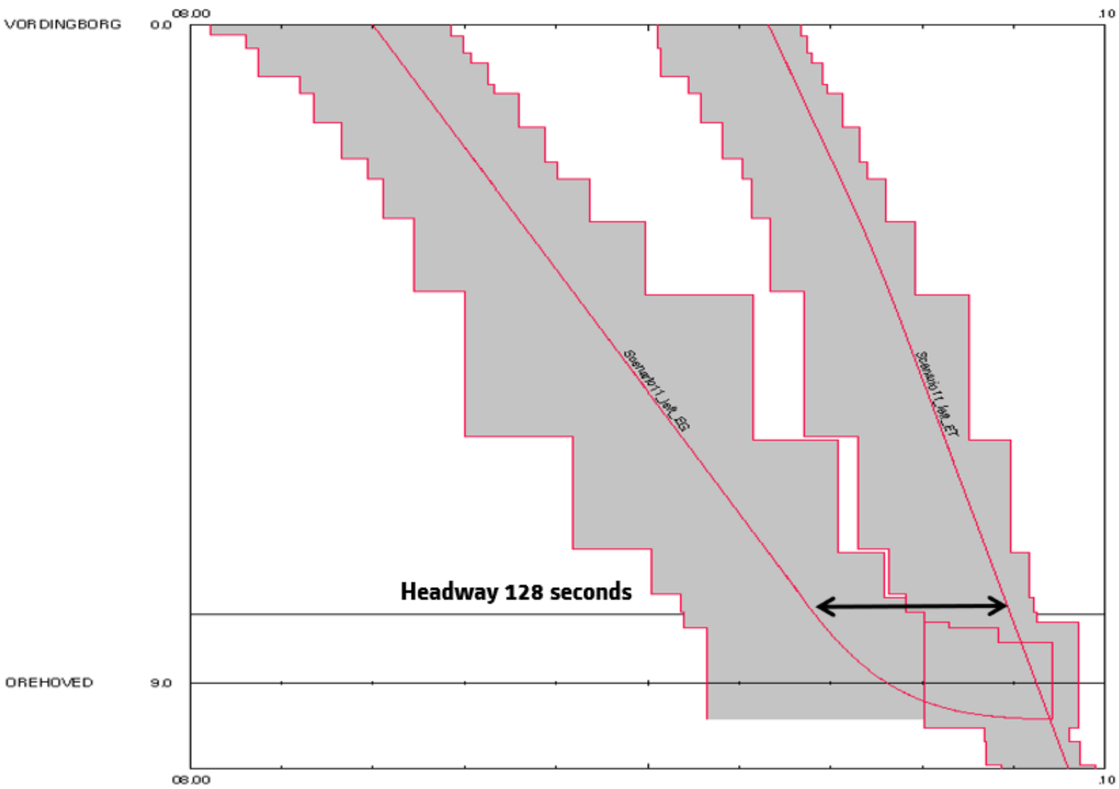


Figure 229 – Blocking time Case C Vordingborg – Orehoved Freight/ET left track, headway 128 seconds

As shown in the speed profile below the 2nd train at 128 second headway has no perturbations (Figure 230).

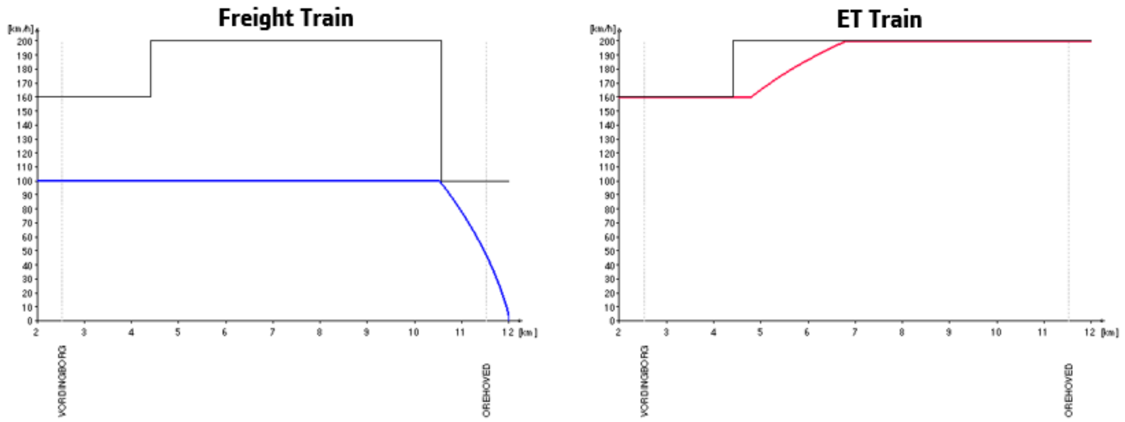


Figure 230 – Train Speed diagram Case C Vordingborg – Orehoved Freight/ET left track

Here below is shown the train graph with blocking time diagram of both trains at 127 seconds headway, to show that the bottleneck is the Mrk-Vo-239 (km 126+322), that is as close as possible to the splitting point Spsk-Vo-N001 (Figure 231).

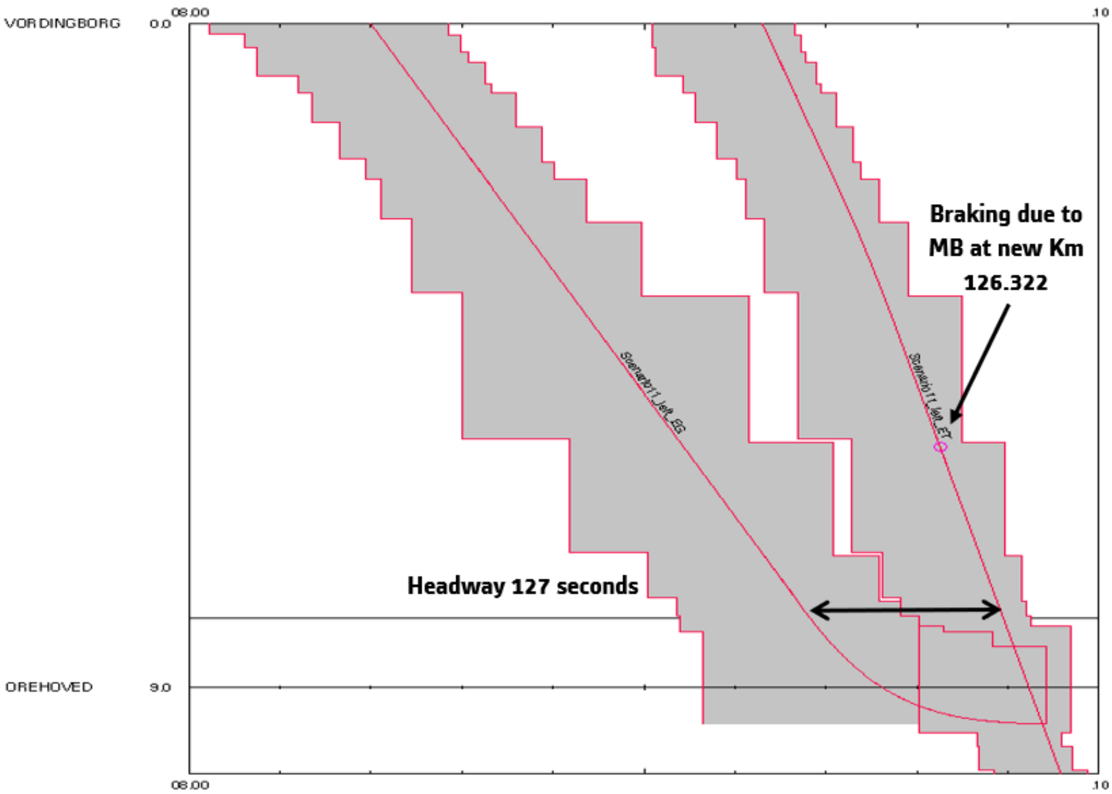


Figure 231 – Blocking time Case C Vordingborg – Orehoved Freight/ET left track, headway 127 seconds

Right Track

In this scenario the available overtaking track length in 1037 m; the freight train length used for the simulation is 990 m.

The minimum achievable headway is 171 seconds (required headway 130 seconds) detected at the splitting point Spsk-Oh-N002 at 126+598 (Figure 232); to obtain the minimum headway the approach section to MB protecting the splitting point has been already optimized. Bottleneck is the splitting point section, due to the short overtaking track.

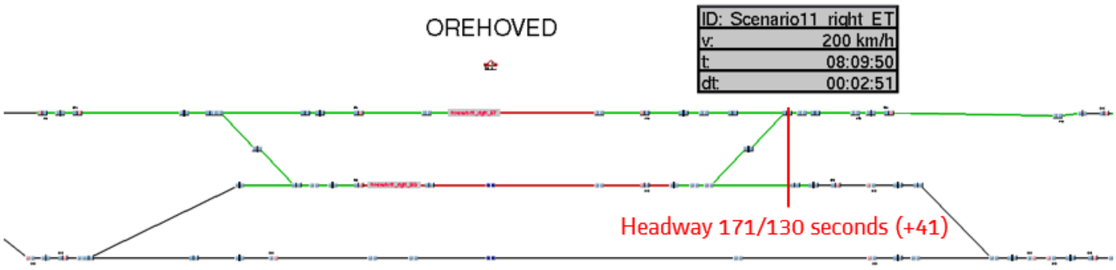


Figure 232 – Headway Case C Vordingborg – Orehoved Freight/ET right track, headway 171 seconds

Here below is shown the train graph with the blocking time diagram of both trains (Figure 233).

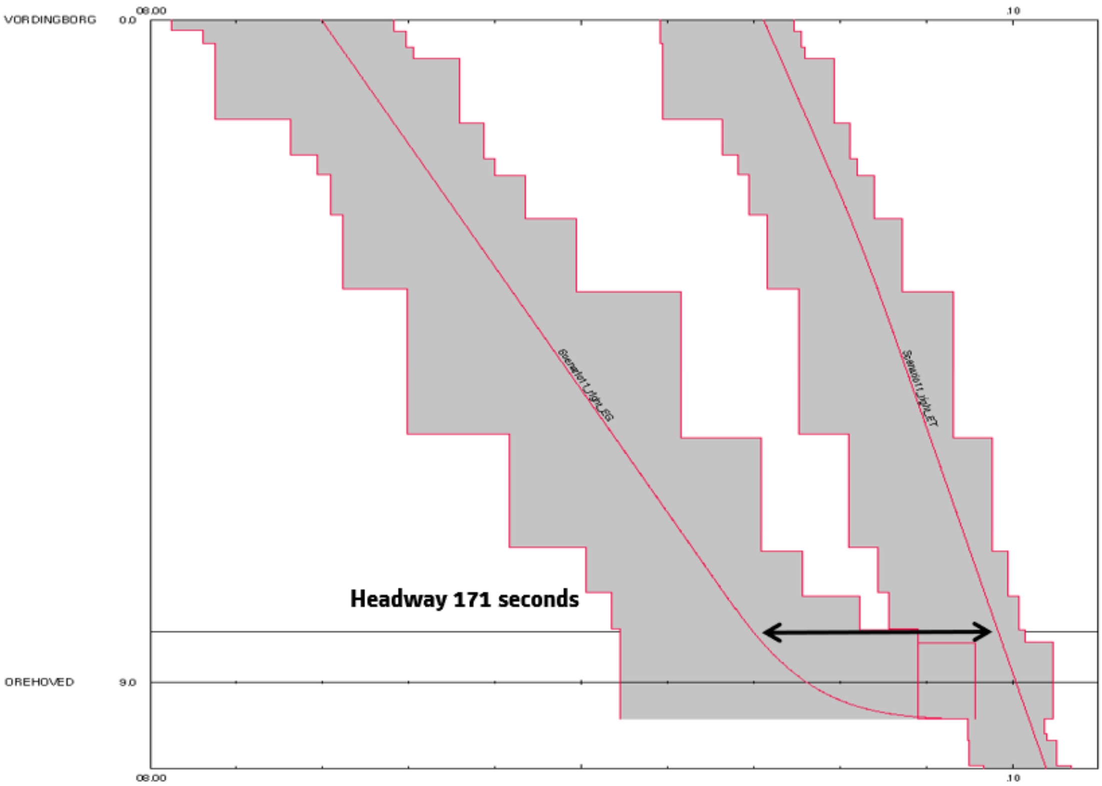


Figure 233 – Blocking time Case C Vordingborg – Orehoved Freight/ET right track, headway 171 seconds

As shown in the speed profile below the 2nd train at 171 second headway has no perturbations (Figure 234).

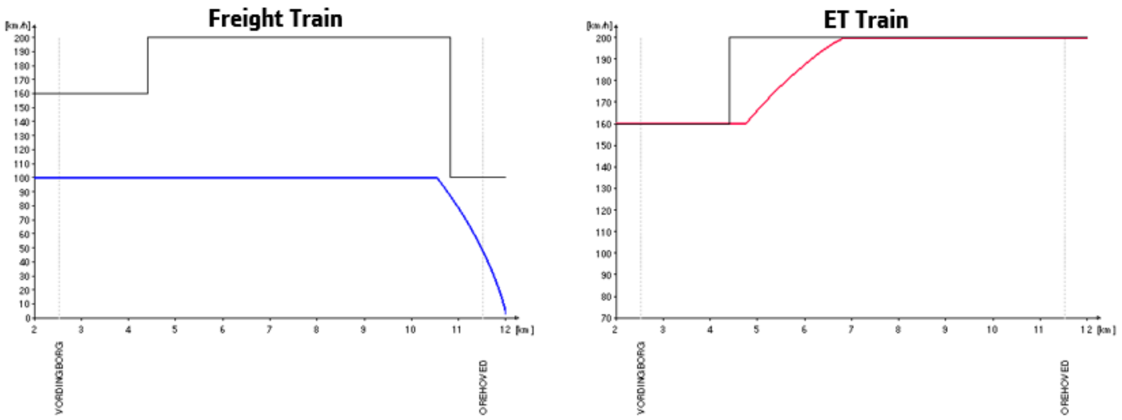


Figure 234 – Train Speed diagram Case C Vordingborg – Orehoved Freight/ET right track

Here below is shown the train graph with blocking time diagram of both trains at 170 seconds headway, to show that the bottleneck is the Mrk-Oh-110, that is as close as possible to the splitting point Spsk-Vo-N002 (Figure 235).

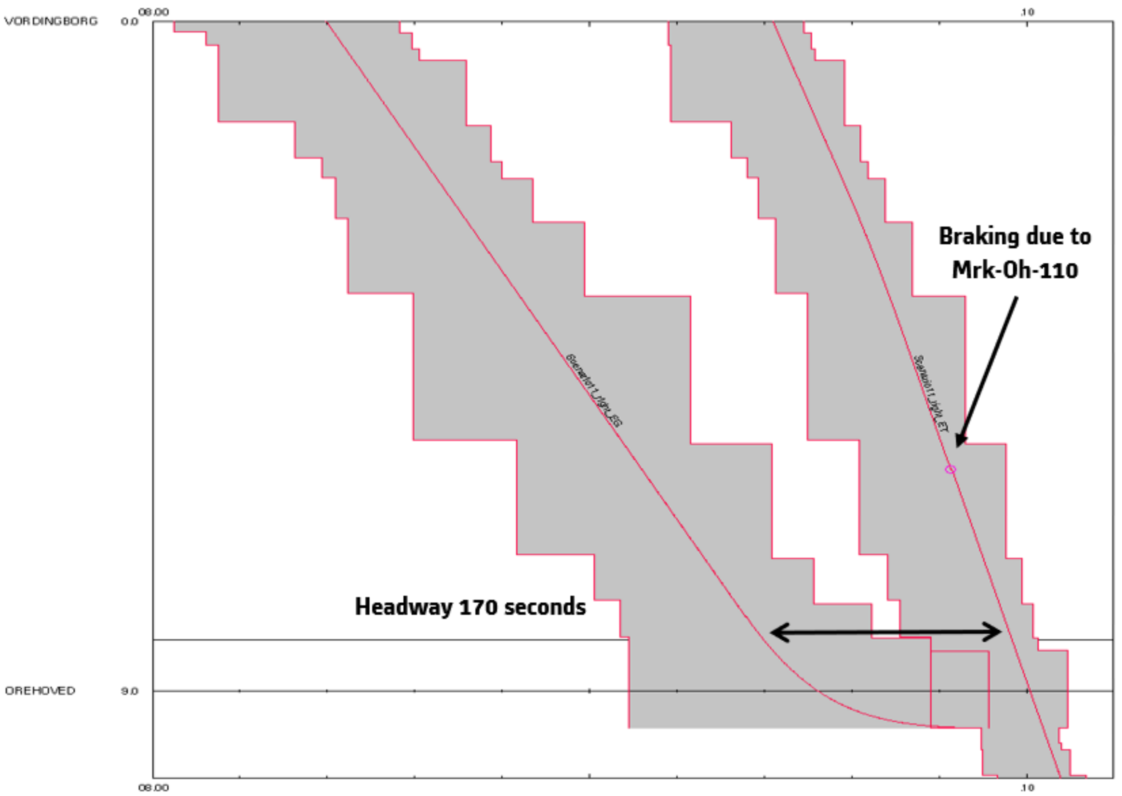


Figure 235 – Blocking time Case C Vordingborg – Orehoved Freight/ET right track, headway 170 seconds

5.4.5.12 Scenario 12

In this scenario the first train is the non-stopping ET train that runs at maximum speed through Orehoved in Vordingborg direction, the second train is the freight train that is starting from standstill in Orehoved (Figure 236, Table 35).

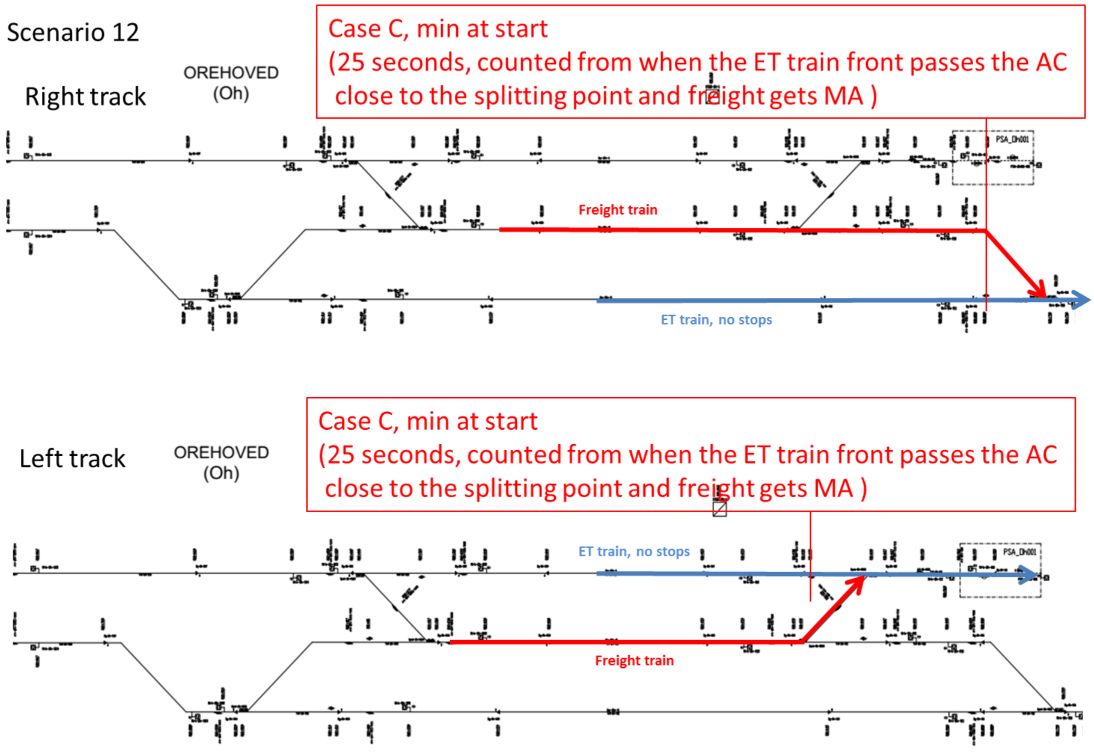


Figure 236 – Scenario 12: Orehoved use of track

Headway Case C is detected from when the passenger train front passes the axle counter close to the splitting point to when the freight train gets a movements authority. This time is governed by the ET travel time along the splitting point section length plus train length.

Scenarios	Track	Section	1st Train	2nd Train	Case	Technical Headway [sec]	Separate Tracks in Station	Headway Results SL [sec]
12	Left	Orehoved - Vordingborg	ET 350m, bp 180, no stop	EG 1000m, bp 80, stop at Orehoved	C	25 at start	Orehoved	29/25
	Right	Orehoved - Vordingborg	ET 350m, bp 180, no stop	EG 1000m, bp 80, stop at Orehoved	C	25 at start	Orehoved	32/25

Table 35 – Headway Scenario 12 Results Overview

Left Track

In this scenario the minimum achievable headway is 29 seconds (required headway 25 seconds) (Figure 237):

- from when the passenger train front passes the axle counter (At-Oh-110/111) close to the splitting point;
- to when the freight train gets a movements authority after;

to obtain the minimum headway the sectioning towards open line is optimized for EG train timely MA update.
This is the minimum achievable headway in this scenario considering the route setting and release times.

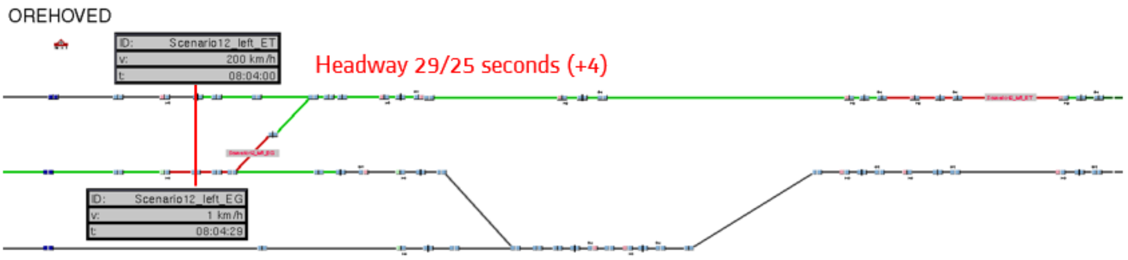


Figure 237 – Headway Case C Orehoved – Vordingborg Freight/ET left track, headway 29 seconds

Here below is shown the train graph with the blocking time diagram of both trains (Figure 238).

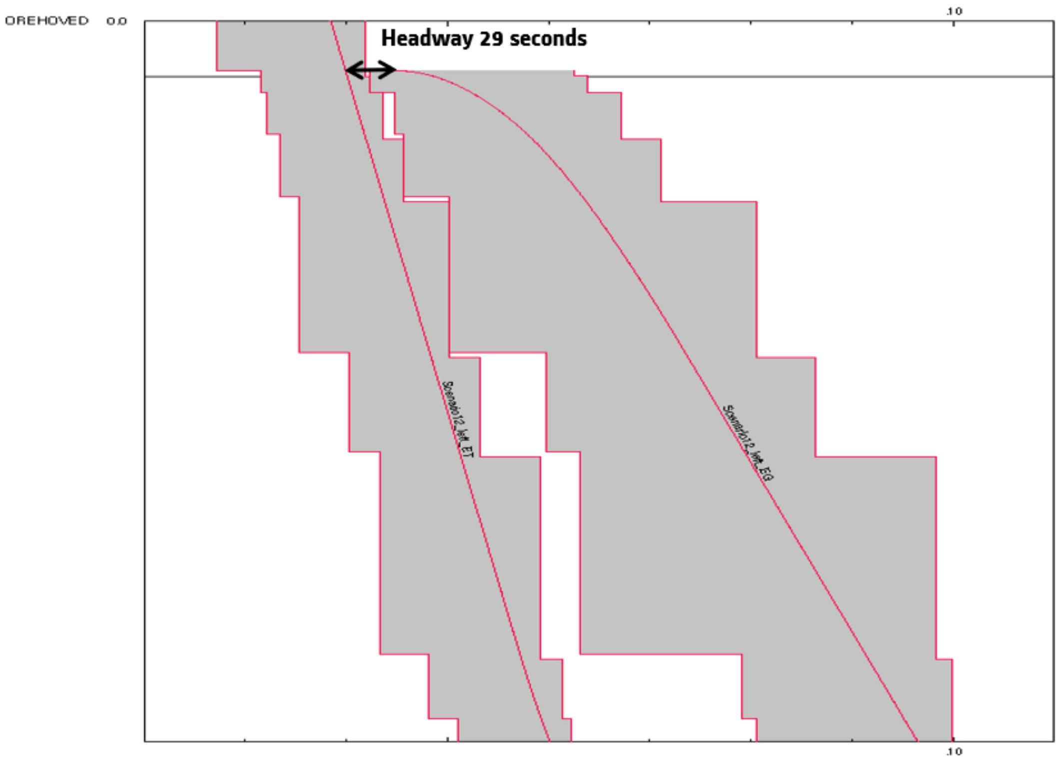


Figure 238 – Blocking time Case C Orehoved – Vordingborg Freight/ET left track, headway 29 seconds.

As shown in the speed profile below the 2nd train at 29 second headway has no perturbations (Figure 239).

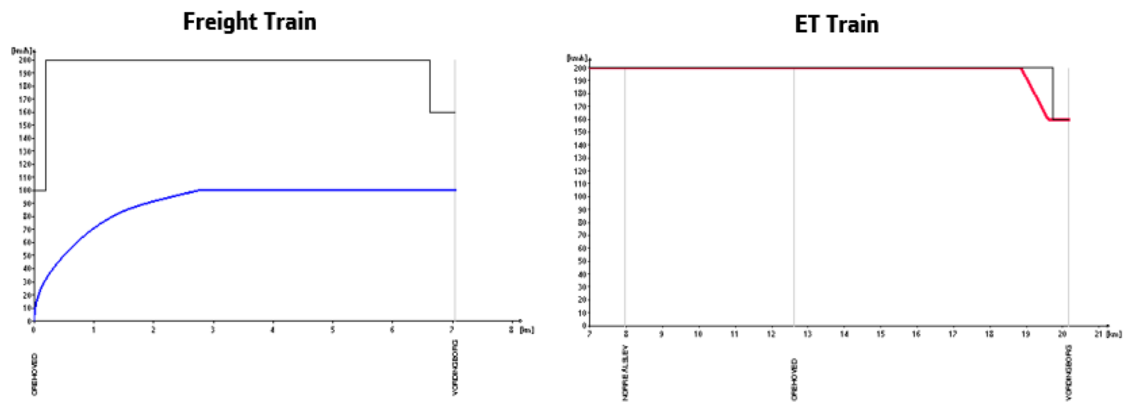


Figure 239 – Train Speed diagram Case C Orehoved – Vordingborg Freight/ET left track

Right Track

In this scenario the minimum achievable headway is 32 seconds (required headway 25 seconds) (Figure 240):

- from when the passenger train front passes the axle counter (At-Oh-310/311) close to the splitting point;
- to when the freight train gets a movements authority after;

to obtain the minimum headway the sectioning towards open line is optimized for EG train timely MA update.
This is the minimum achievable headway in this scenario considering the route setting and release times.

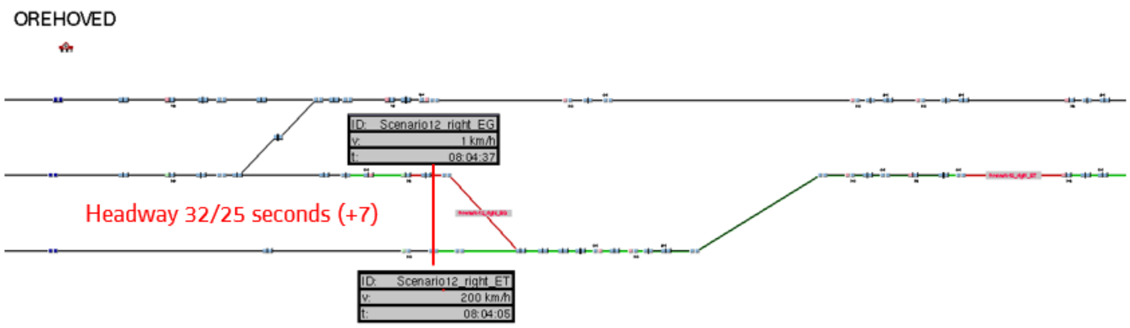


Figure 240 – Headway Case C Orehoved – Vordingborg Freight/ET right track, headway 32 seconds

Here below is shown the train graph with the blocking time diagram of both trains (Figure 241).

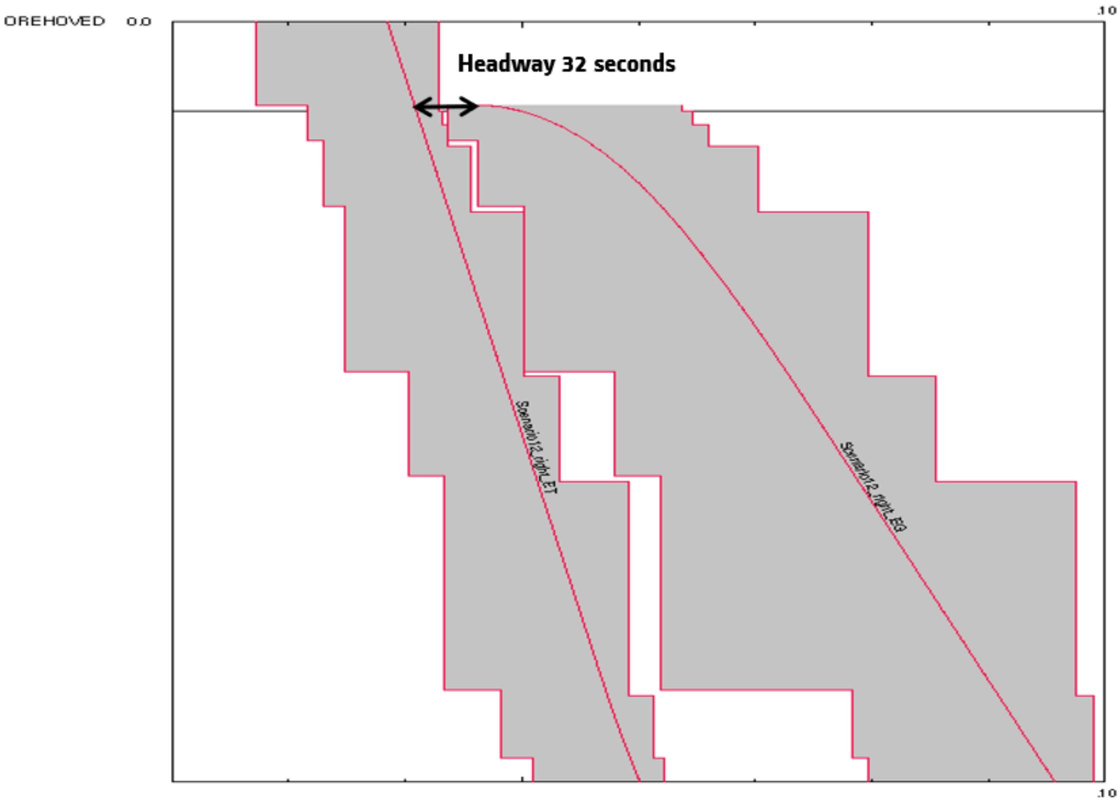


Figure 241 – Blocking time Case C Orehoved – Vordingborg Freight/ET right track, headway 32 seconds

As shown in the speed profile below the 2nd train at 32 second headway has no perturbations (Figure 242).

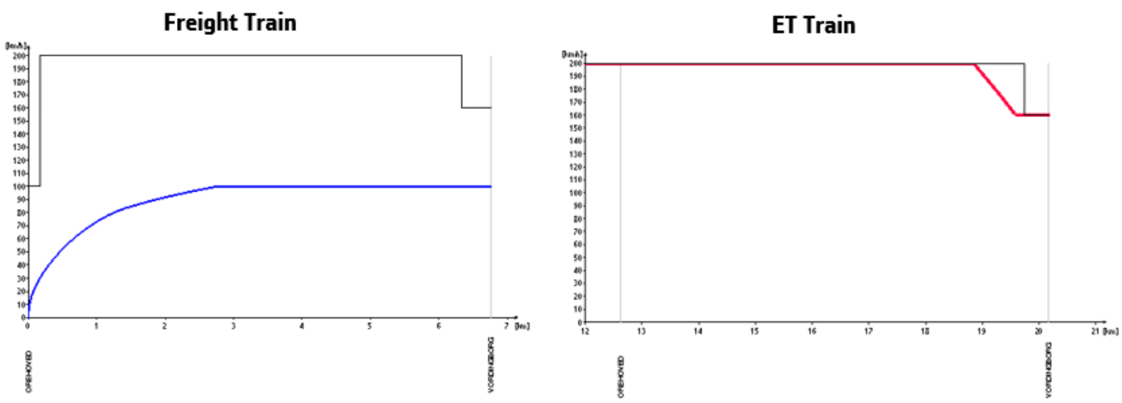


Figure 242 – Train Speed diagram Case C Orehoved – Vordingborg Freight/ET right track

5.4.5.13 Scenario 13

In this scenario the first train is the non-stopping ET train that runs at maximum speed through Orehoved station in Nørre Alslev direction, the second train is the freight train that is starting from standstill in Orehoved (Figure 243, Table 36).

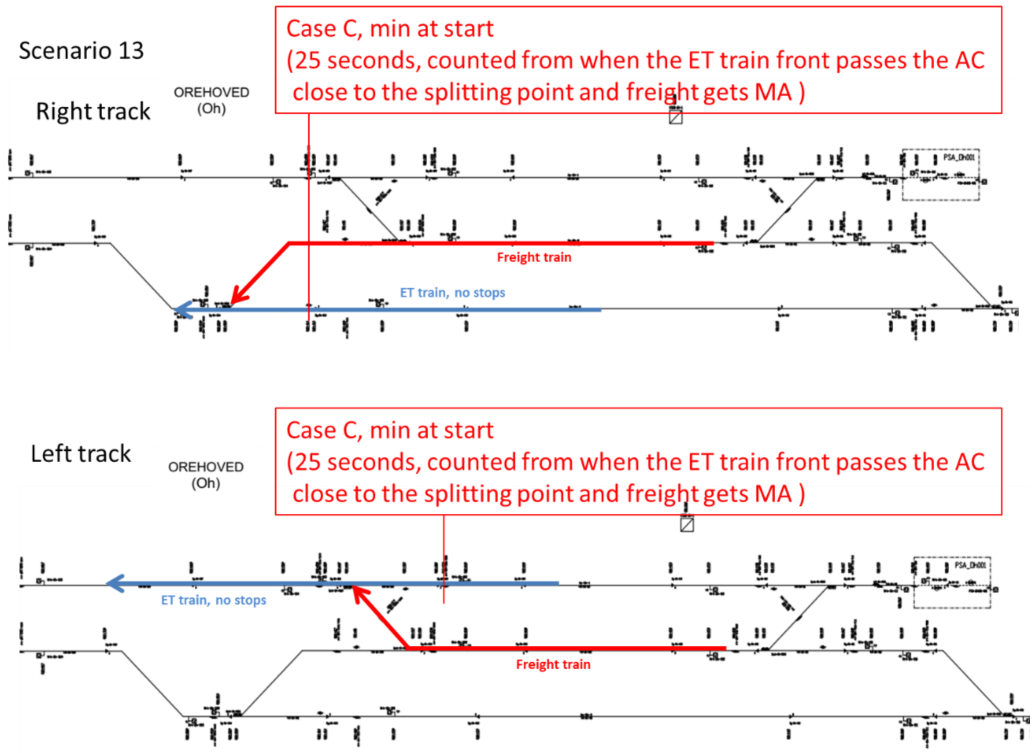


Figure 243 – Scenario 13: Orehoved use of track

Headway Case C is detected from when the passenger train front passes the axle counter close to the splitting point to when the freight train gets a movements authority. This time is governed by the ET travel time along the splitting point section length plus train length.

Scenarios	Track	Section	1st Train	2nd Train	Case	Technical Headway [sec]	Separate Tracks in Station	Headway Results [sec]
13	Left	Orehoved – Nørre Alslev	ET 350m, bp 180, no stop	EG 1000m, bp 80, stop at Orehoved	C	25 at start	Orehoved	29/25
	Right	Orehoved – Nørre Alslev	ET 350m, bp 180, no stop	EG 1000m, bp 80, stop at Orehoved	C	25 at start	Orehoved	30/25

Table 36 – Headway Scenario 13 Results Overview

Left Track

In this scenario the minimum achievable headway is 29 seconds (required headway 25 seconds) (Figure 244):

- from when the passenger train front passes the axle counter (At-Oh-311/321) close to the splitting point;
- to when the freight train gets a movements authority after;

to obtain the minimum headway the sectioning towards open line is optimized for EG train timely MA update.
This is the minimum achievable headway in this scenario considering the route setting and release times.

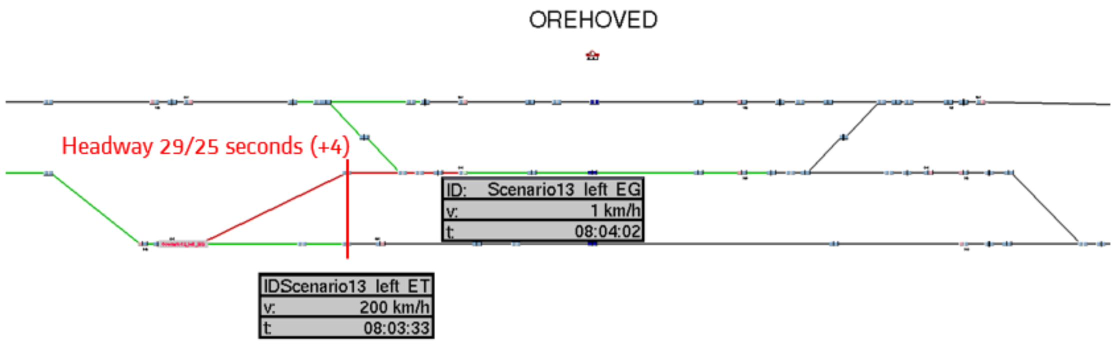


Figure 244 – Headway Case C Orehoved – Nørre Alslev Freight/ET left track, headway 29 seconds

Here below is shown the train graph with the blocking time diagram of both trains (Figure 245).

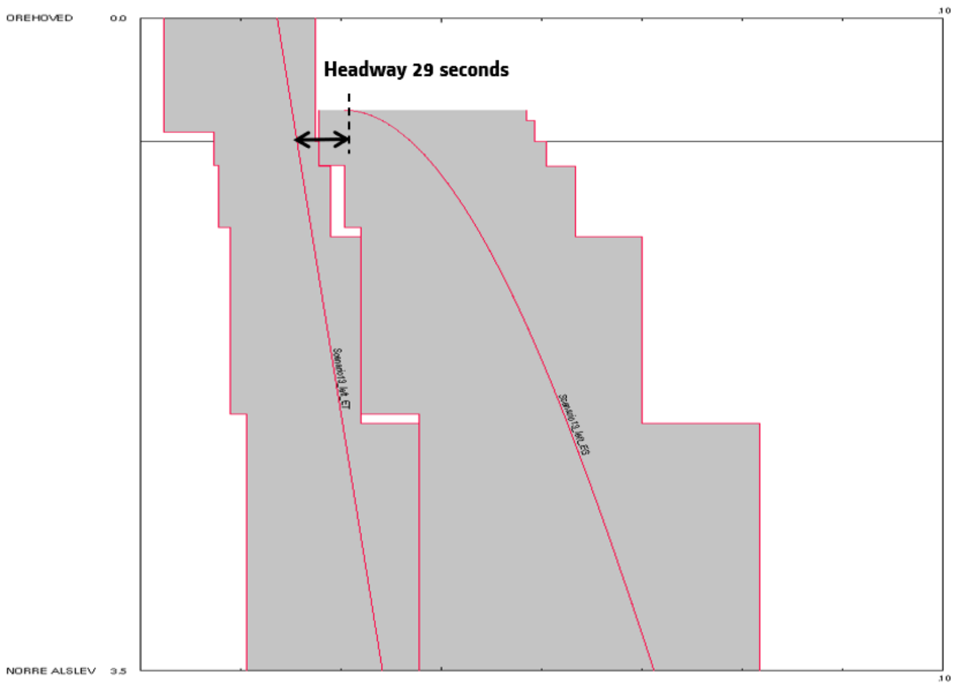


Figure 245 – Blocking time Case C Orehoved – Nørre Alslev Freight/ET left track, headway 29 seconds

As shown in the speed profile below the 2nd train at 29 second headway has no perturbations (Figure 246).

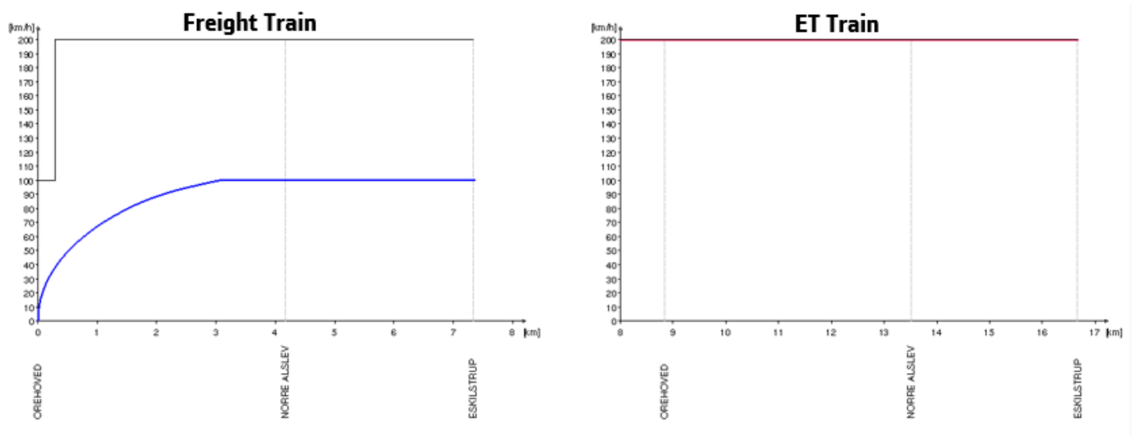


Figure 246 – Train Speed diagram Case C Orehoved – Vordingborg Freight/ET left track

Right Track

In this scenario the minimum achievable headway is 30 seconds (required headway 25 seconds) (Figure 247):

- from when the passenger train front passes the axle counter (At-Oh-112/121) close to the splitting point;
- to when the freight train gets a movements authority after;

to obtain the minimum headway the sectioning towards open line is optimized for EG train timely MA update.

This is the minimum achievable headway in this scenario considering the route setting and release times.

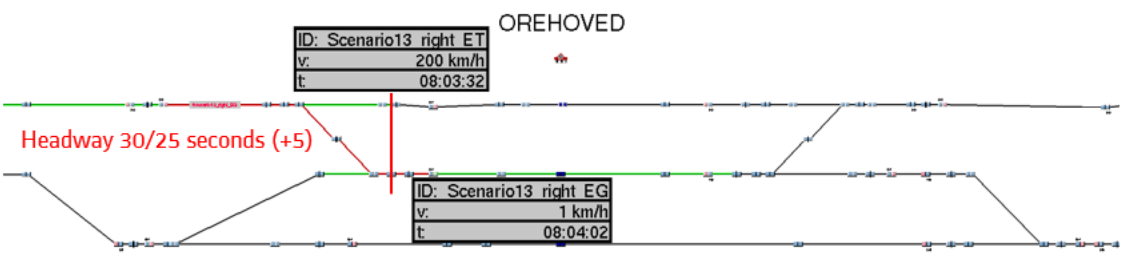


Figure 247 – Headway Case C Orehoved – Nørre Alslev Freight/ET right track, headway 30 seconds

Here below is shown the train graph with the blocking time diagram of both trains (Figure 248).

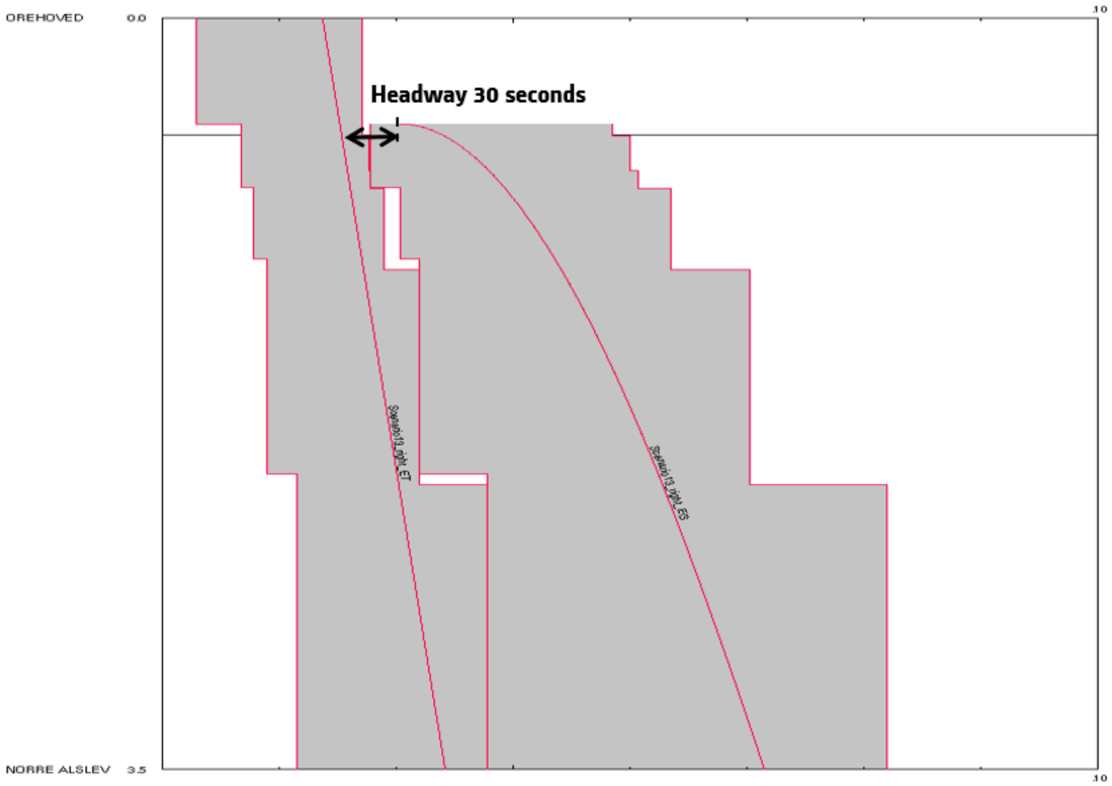


Figure 248 – Blocking time Case C Orehoved – Nørre Alslev Freight/ET right track, headway 30 seconds

As shown in the speed profile below the 2nd train at 30 second headway has no perturbations (Figure 249).

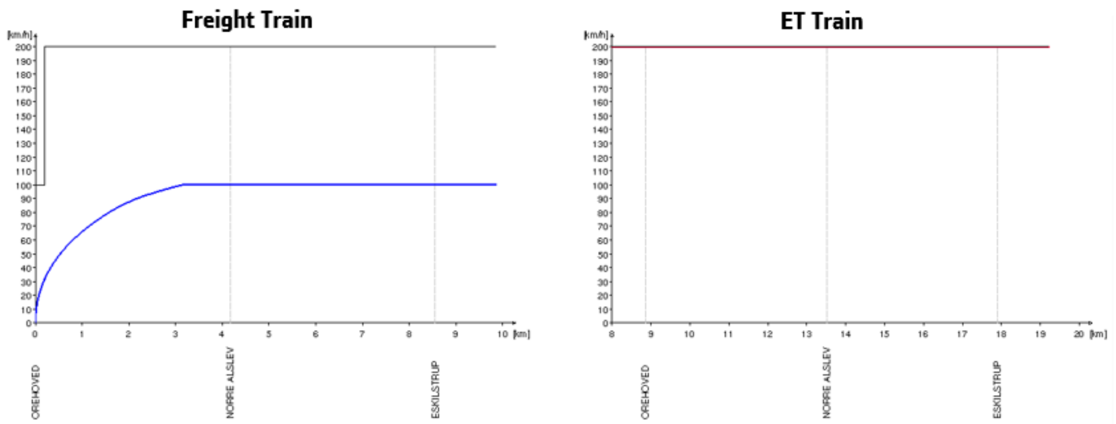


Figure 249 – Train Speed diagram Case C Orehoved – Nørre Alslev Freight/ET right track

5.4.5.14 Scenario 14

In this scenario the first train is freight train that is running from Nørre Alslev to Orehoved, stops on the overtaking track in Orehoved, followed by the ET passenger non-stop train (Figure 250, Table 37).

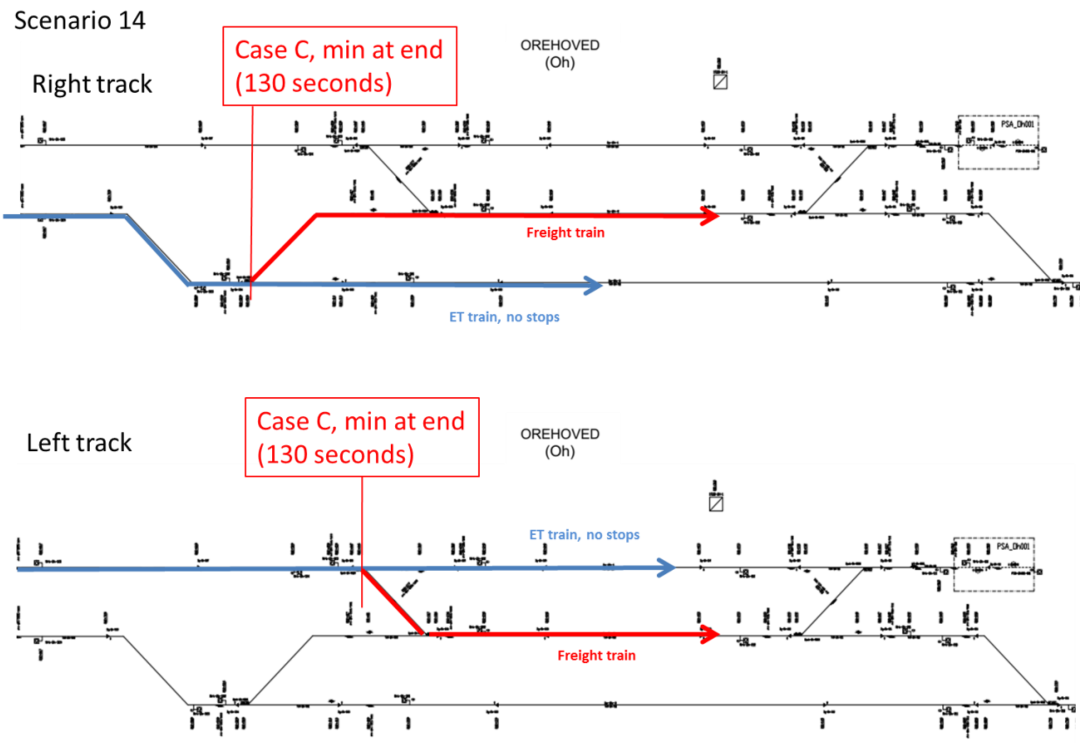


Figure 250 – Scenario 14: Orehoved use of track

Headway Case C detected at the splitting points Spsk-Oh-N005 and Spsk-Oh-N006 in Orehoved.

Scenarios	Track	Section	1st Train	2nd Train	Case	Technical Headway [sec]	Separate Tracks in Station	Headway Results [sec]
14	Left	Nørre Alslev – Orehoved	EG 1000m, stop at Orehoved	ET 350m, bp 180, no stop	C	130 at end	Orehoved	180/130
	Right	Nørre Alslev – Orehoved	EG 1000m, stop at Orehoved	ET 350m, bp 180, no stop	C	130 at end	Orehoved	126/130

Table 37 – Headway Scenario 14 Results Overview

The bottleneck is the splitting point section for left track, due to reduced distance (i.e. it is just 1040 m versus a train length of 1000 m) between splitting point and EOA for EG train. The longest freight train to respect the headway requirements is 770 m. On right track the shift of At-Oh-222/321 to anticipate the release of diverging route has been applied with significantly improve of achievable headway.

Left Track

In this scenario the available overtaking track length is just 1040 m, the freight train length used for the simulation is 1000 m.

The minimum achievable headway is 180 seconds (required headway 130 seconds) detected at the splitting point Spsk-Vo-N005 at 124+994 (Figure 251); to obtain the minimum headway the approach section to MB protecting the splitting point has been already optimized. The longest freight train to respect the headway requirements is 770 m.

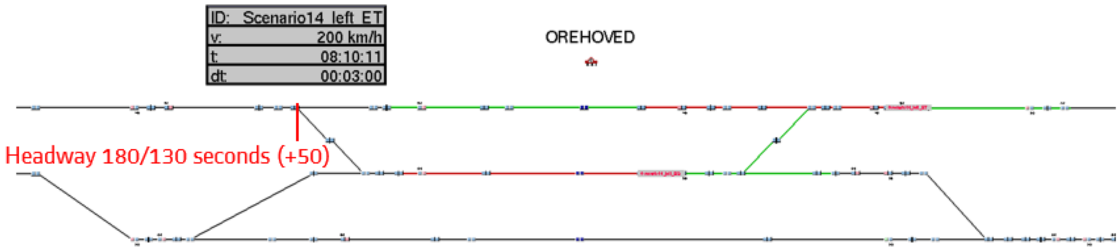


Figure 251 – Headway Case C Nørre Alslev – Orehoved Freight/ET left track, headway 180 seconds

Here below is shown the train graph with the blocking time diagram of both trains (Figure 252).

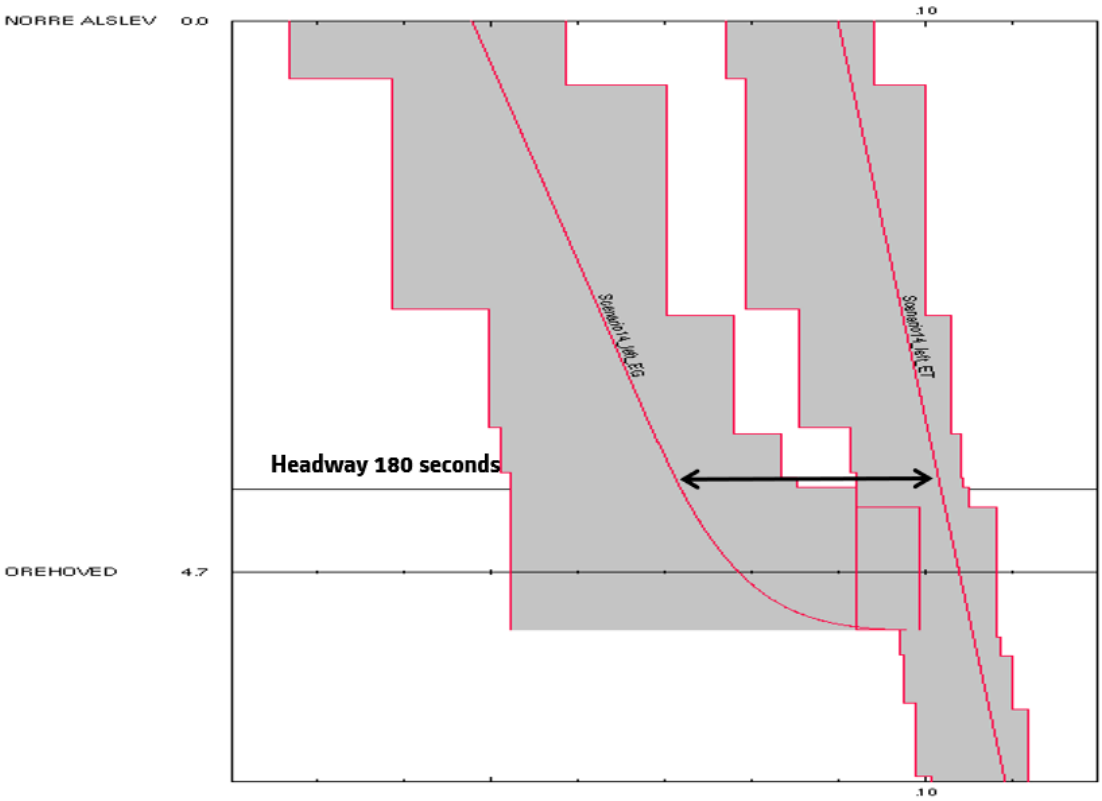


Figure 252 – Blocking time Case C Nørre Alslev – Orehoved Freight/ET left track, headway 180 seconds

As shown in the speed profile below the 2nd train at 180 second headway has no perturbations (Figure 253).

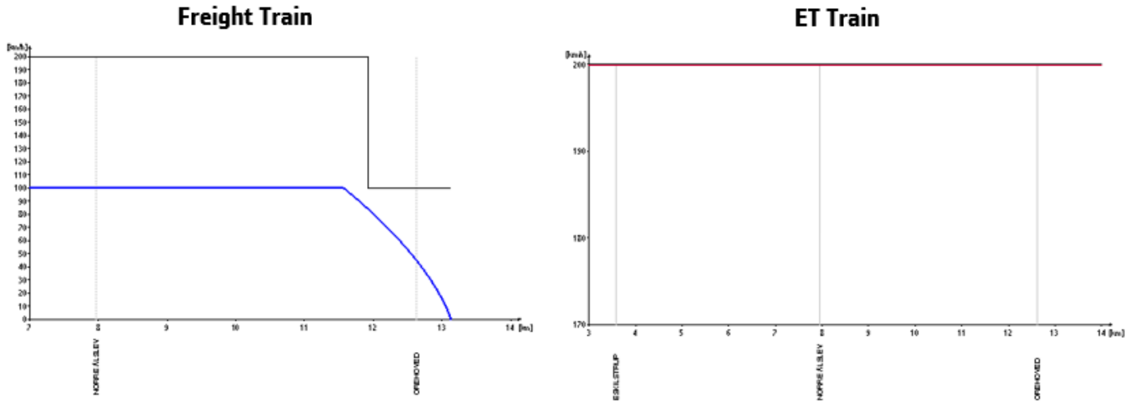


Figure 253 – Train Speed diagram Case C Nørre Alslev – Orehoved Freight/ET left track

Here below is shown the train graph with blocking time diagram of both trains at 179 seconds headway, to show that the bottleneck is the Mrk-Oh-124, that is as close as possible to the splitting point Spsk-Oh-N005 (Figure 254).

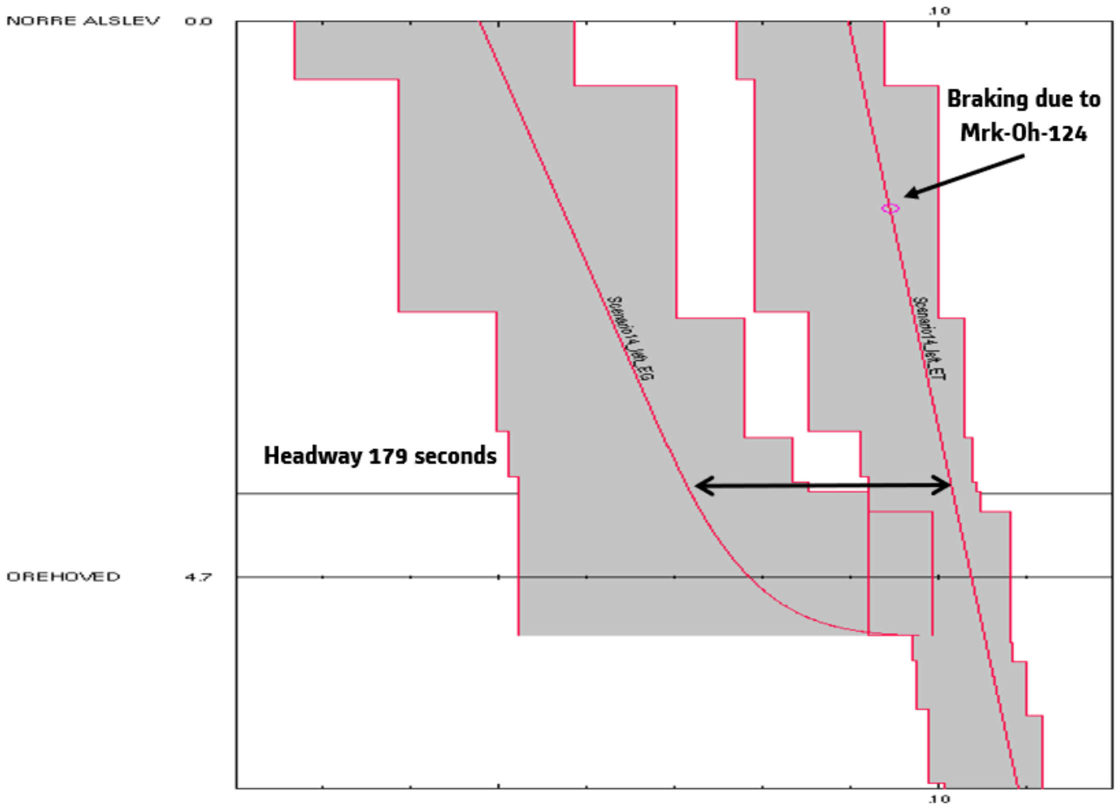


Figure 254 – Blocking time Case C Nørre Alslev – Orehoved Freight/ET left track, headway 179 seconds

Right Track

In this scenario the available overtaking track length is higher than 1040 m, the freight train length used for the simulation is 1000 m.

The minimum achievable headway is 126 seconds (required headway 130 seconds) detected at the splitting point Spsk-Vo-N006 at 128+074 (Figure 255); to obtain the minimum headway the approach section to MB protecting the splitting point has been already optimized.

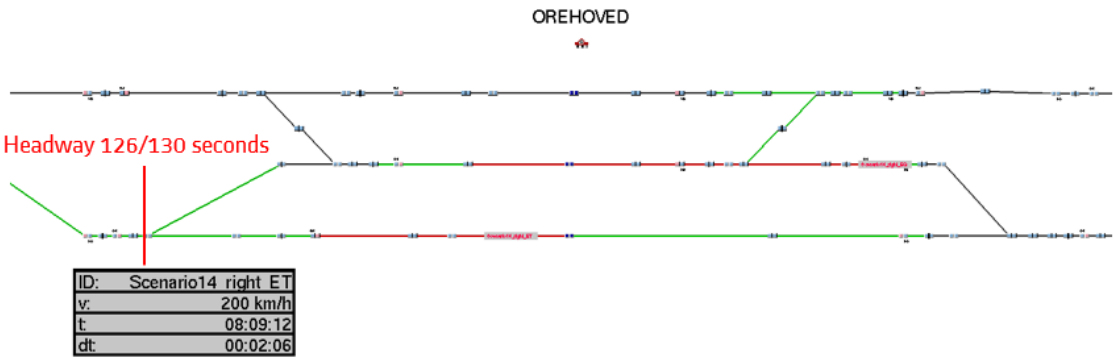


Figure 255 – Headway Case C Nørre Alslev – Orehoved Freight/ET right track, headway 126 seconds

Here below is shown the train graph with the blocking time diagram of both trains (Figure 256).

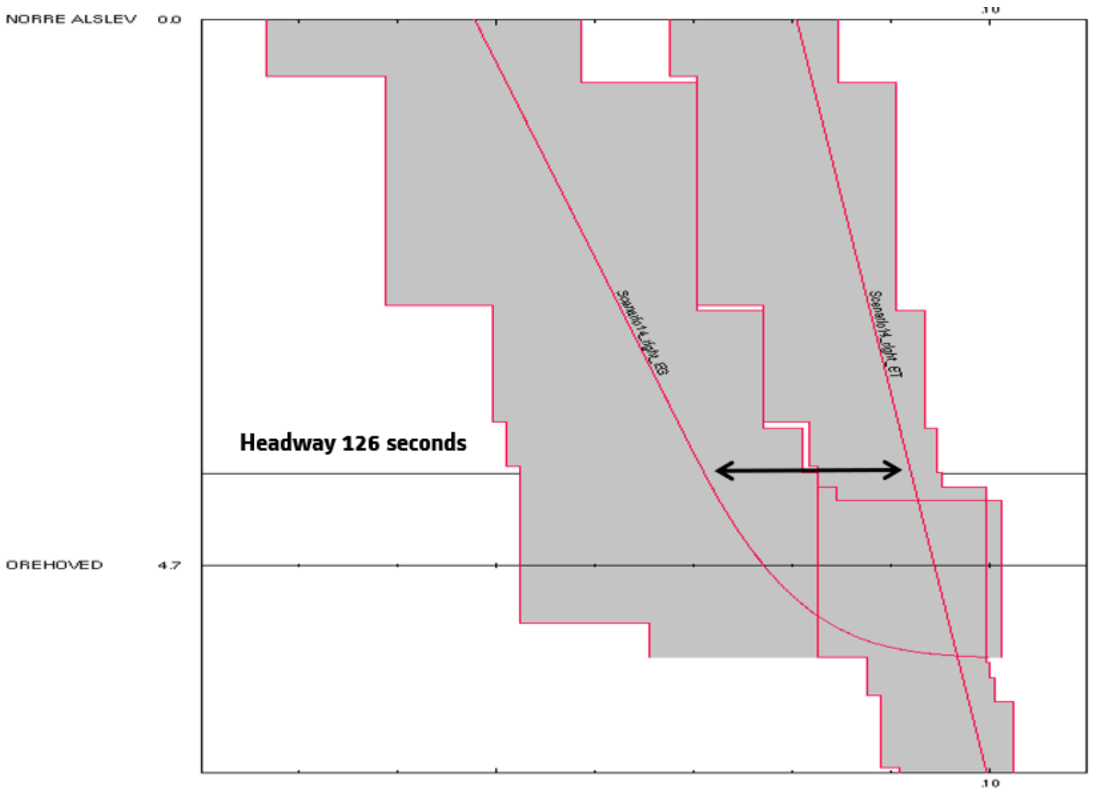


Figure 256 – Blocking time Case C Nørre Alslev – Orehoved Freight/ET right track, headway 126 seconds

As shown in the speed profile below the 2nd train at 126 second headway has no perturbations (Figure 257).

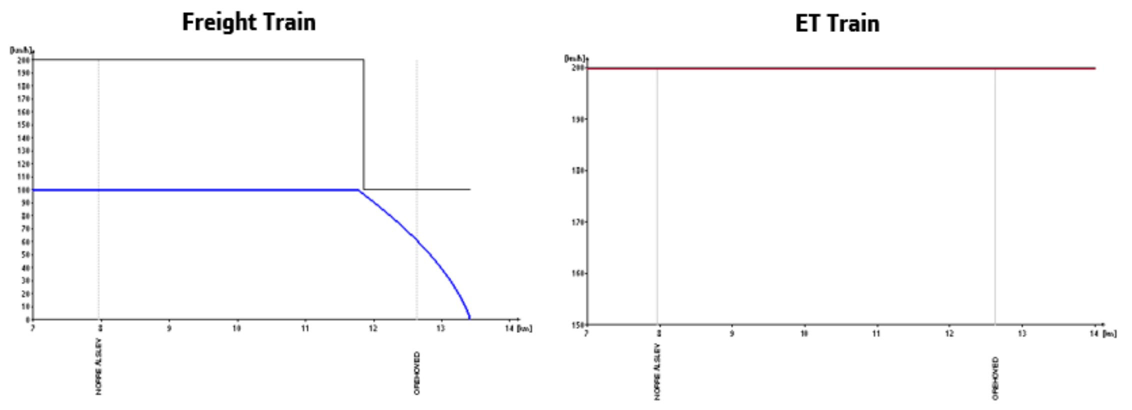


Figure 257 – Train Speed diagram Case C Nørre Alslev – Orehoved Freight/ET right track

Here below is shown the train graph with blocking time diagram of both trains at 125 seconds headway, to show that the bottleneck is the Mrk-Oh-323, that is as close as possible to the splitting point Spsk-Oh-N006 (Figure 258).

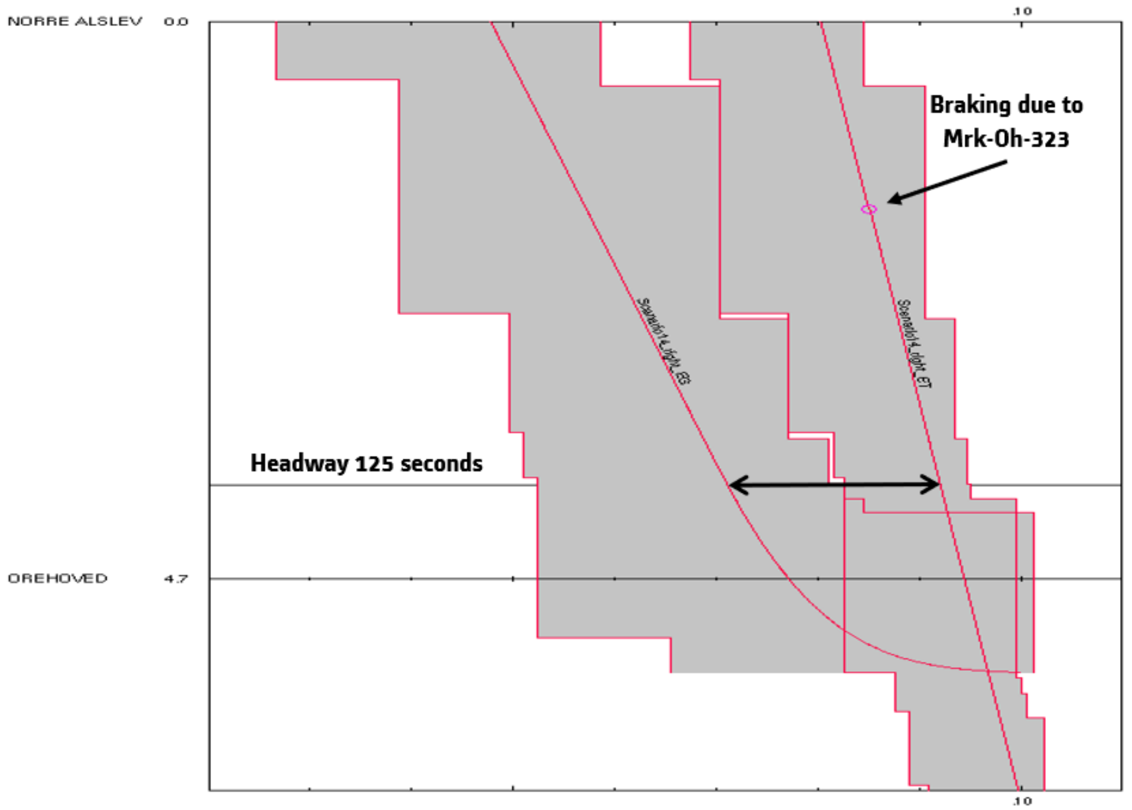


Figure 258 – Blocking time Case C Nørre Alslev – Orehoved Freight/ET right track, headway 125 seconds

5.4.5.15 Scenario 15

In this scenario the first train is freight train that is running from Nørre Alslev to Nykøbing F direction, stops on the overtaking track in Nykøbing F., followed by the ET passenger train that stops in the same station (Figure 259, Table 38).

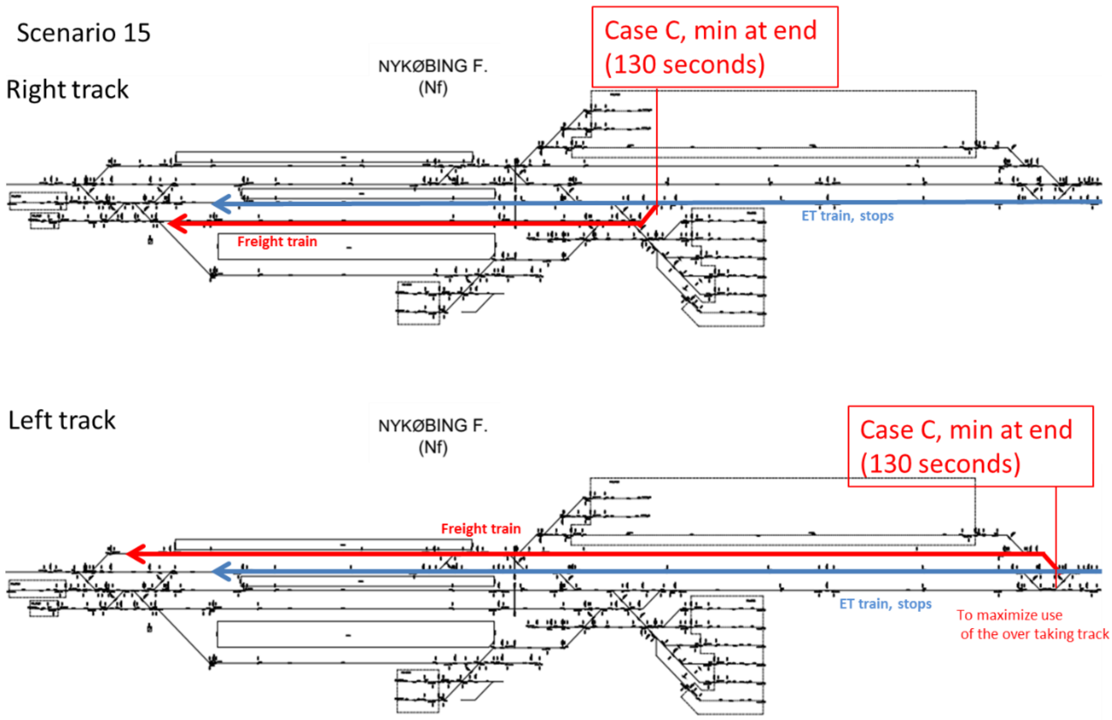


Figure 259 – Scenario 15: Nykøbing F. use of track

Headway Case C detected at the splitting points Spsk-Nf-N003 (right track) and Spsk-Nf-N013 (left track) in Nykøbing F.

Scenarios	Track	Section	1st Train	2nd Train	Case	Technical Headway [sec]	Separate Tracks in Station	Headway Results [sec]
15	Left	Nørre Alslev–Nykøbing F	EG 1000m, bp 80, stop at Nykøbing F	ET 350m, stop at Nykøbing F	C	130 at end	Nykøbing F	157/130
	Right	Nørre Alslev–Nykøbing F	EG 1000m, bp 80, stop at Nykøbing F	ET 350m, stop at Nykøbing F	C	130 at end	Nykøbing F	123/130

Table 38 – Headway Scenario 15 Results Overview

The bottleneck is the splitting point section for left track, due to the very short overtaking track and low diverging speed (60 Km/h). The longest freight train to respect the headway requirements is 480 m. Headway requirement is reached on right track.

Left Track

In this scenario the available overtaking track length in 627 m; the freight train length used for the simulation is 580 m.

The minimum achievable headway is 157 seconds (required headway 130 seconds) detected at the splitting point Spsk-Nf-N013 at 145+889 (Figure 260); to obtain the minimum headway the approach section to MB protecting the splitting point has been already optimized. The longest freight train to respect the headway requirements is 480 m.

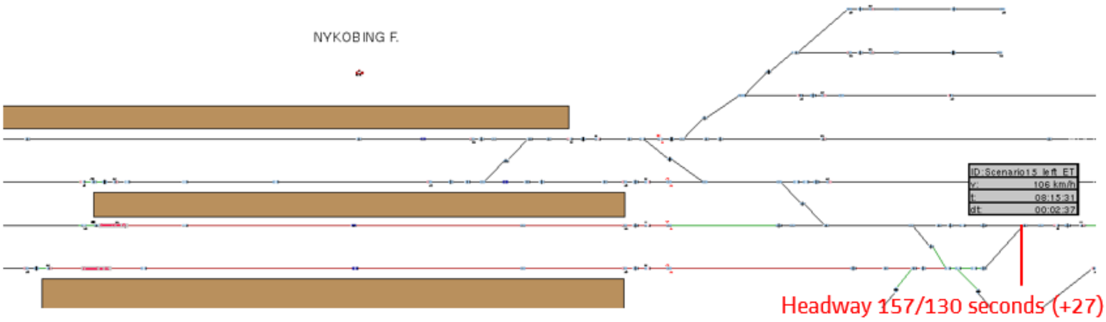


Figure 260 – Headway Case C Nørre Alslev – Nykøbing F. Freight/ET left track, headway 157 seconds

Here below is shown the train graph with the blocking time diagram of both trains (Figure 261).

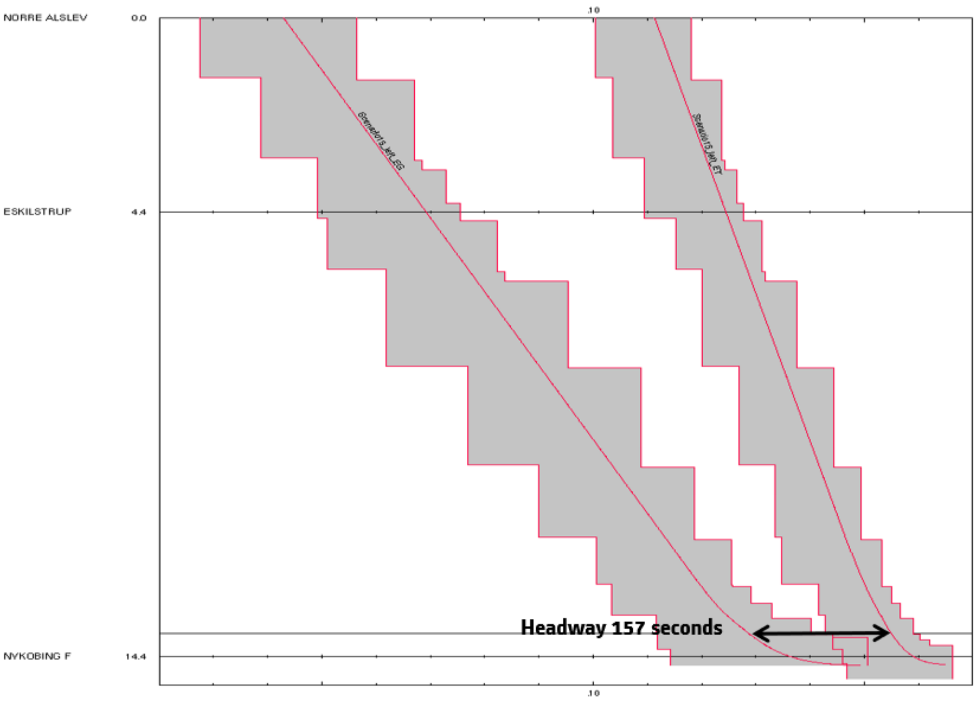


Figure 261 – Blocking time Case C Nørre Alslev – Nykøbing F. Freight/ET left track, headway 157 seconds

As shown in the speed profile below the 2nd train at 157 second headway has no perturbations (Figure 262).

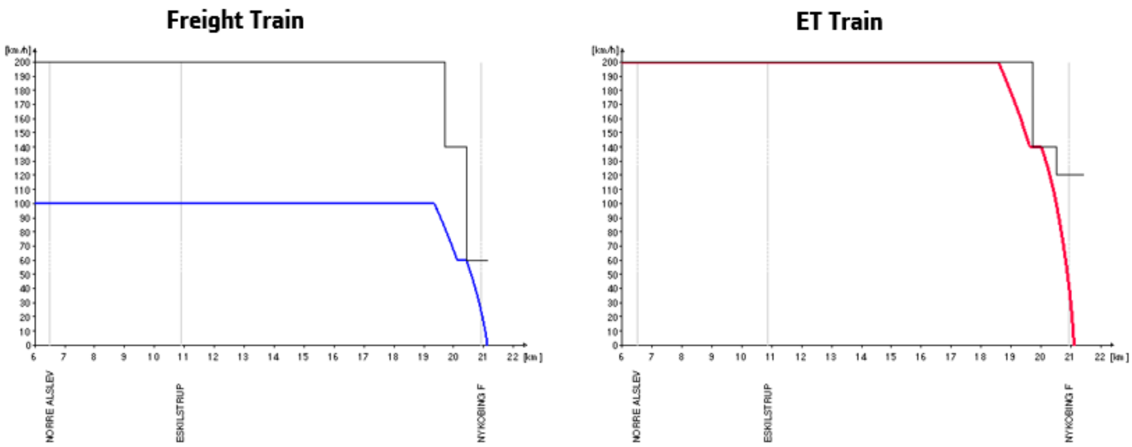


Figure 262 – Train Speed diagram Case C Nørre Alslev – Nykøbing F. Freight/ET left track

Here below is shown the train graph with blocking time diagram of both trains at 156 seconds headway, to show that the bottleneck is the Mrk-Oh-317, that is as close as possible to the splitting point Spsk-Oh-N013 (Figure 263).

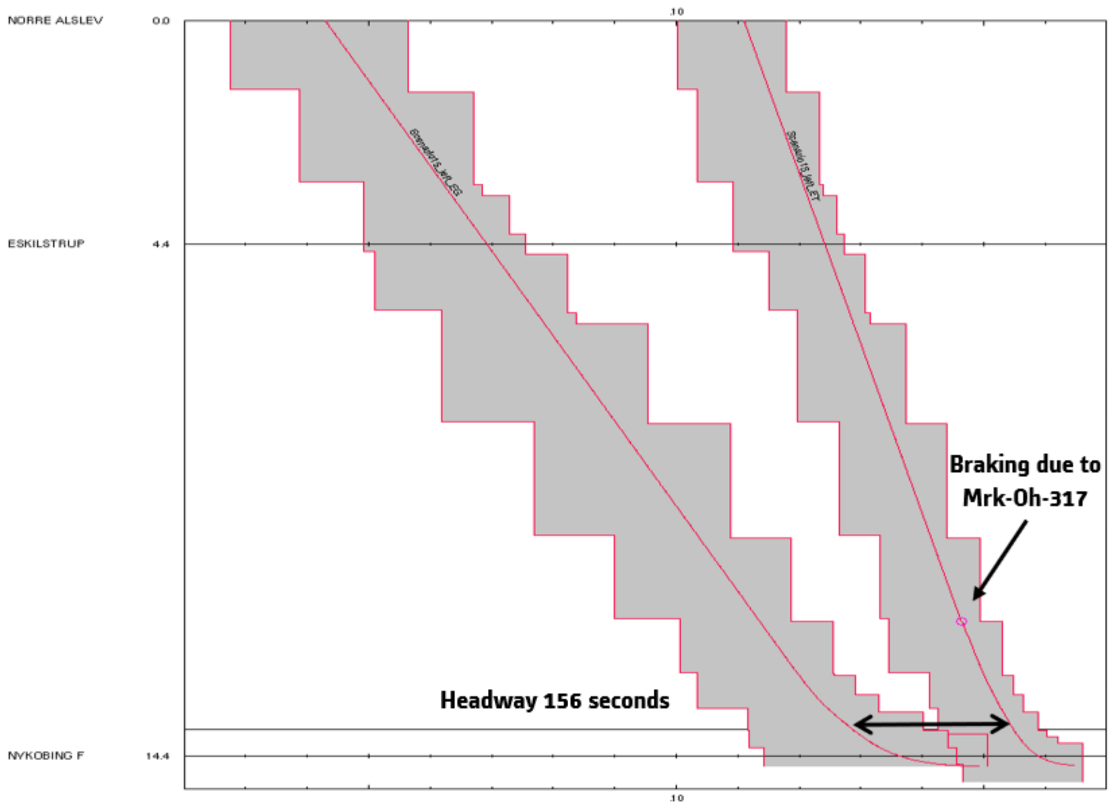


Figure 263 – Blocking time Case C Nørre Alslev – Nykøbing F. Freight/ET left track, headway 156 seconds

Right Track

In this scenario the available overtaking track length is higher than 1040 m, the freight train length used for the simulation is 1000 m.

The minimum achievable headway is 123 seconds (required headway 130 seconds) detected at the splitting point Spsk-Nf-N003 at 144+916 (Figure 264); to obtain the minimum headway the approach section to MB protecting the splitting point has been already optimized.

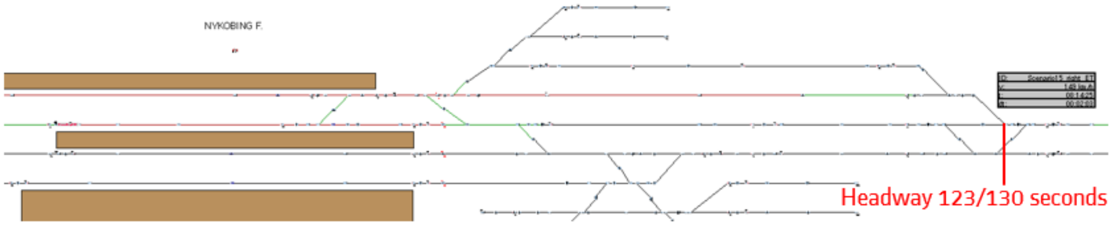


Figure 264 – Headway Case C Nørre Alslev – Nykøbing F. Freight/ET right track, headway 123 seconds

Here below is shown the train graph with the blocking time diagram of both trains (Figure 265).

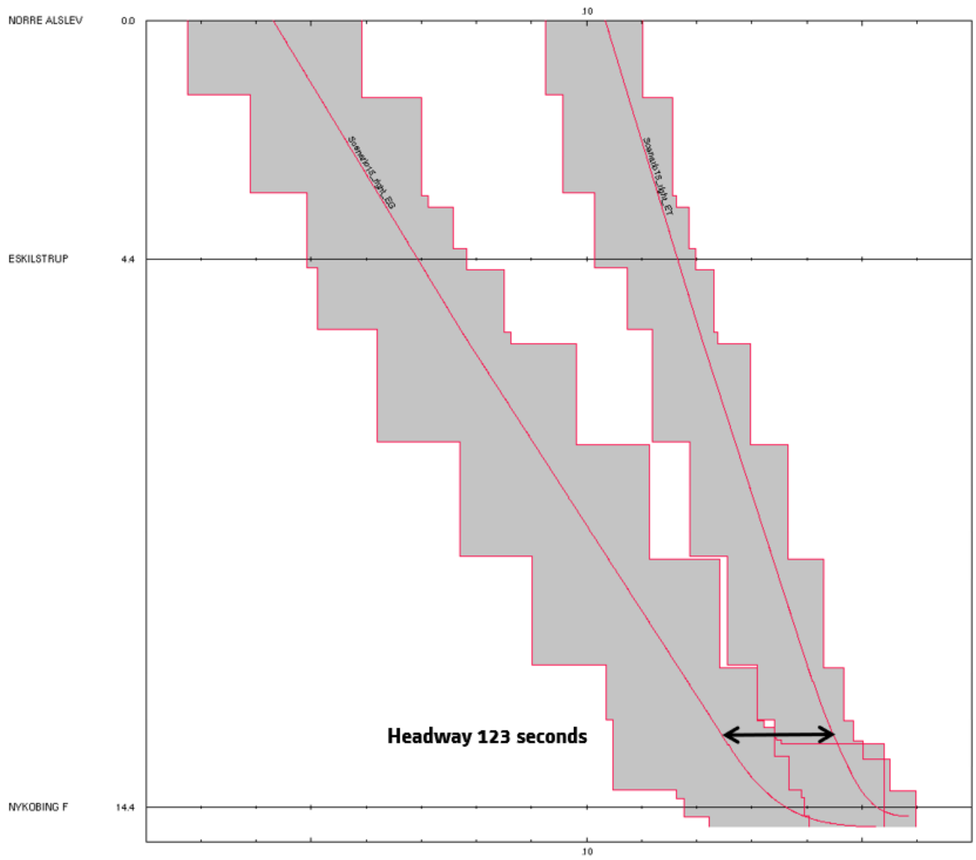


Figure 265 – Blocking time Case C Nørre Alslev – Nykøbing F. Freight/ET right track, headway 123 seconds

As shown in the speed profile below the 2nd train at 123 second headway has no perturbations (Figure 266).

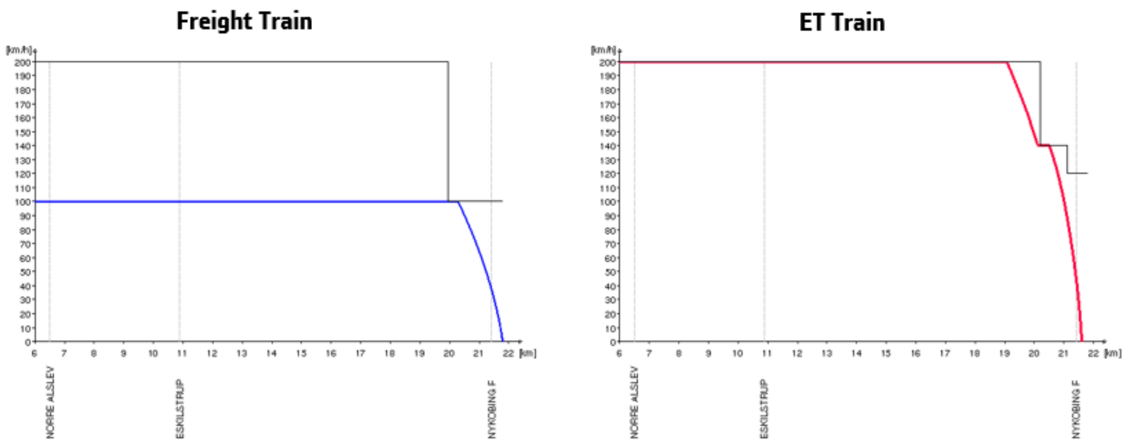


Figure 266 – Train Speed diagram Case C Nørre Alslev – Nykøbing F. Freight/ET right track

Here below is shown the train graph with blocking time diagram of both trains at 122 seconds headway, to show that the bottleneck is the Mrk-Oh-213, that is as close as possible to the splitting point Spsk-Oh-N003 (Figure 267).

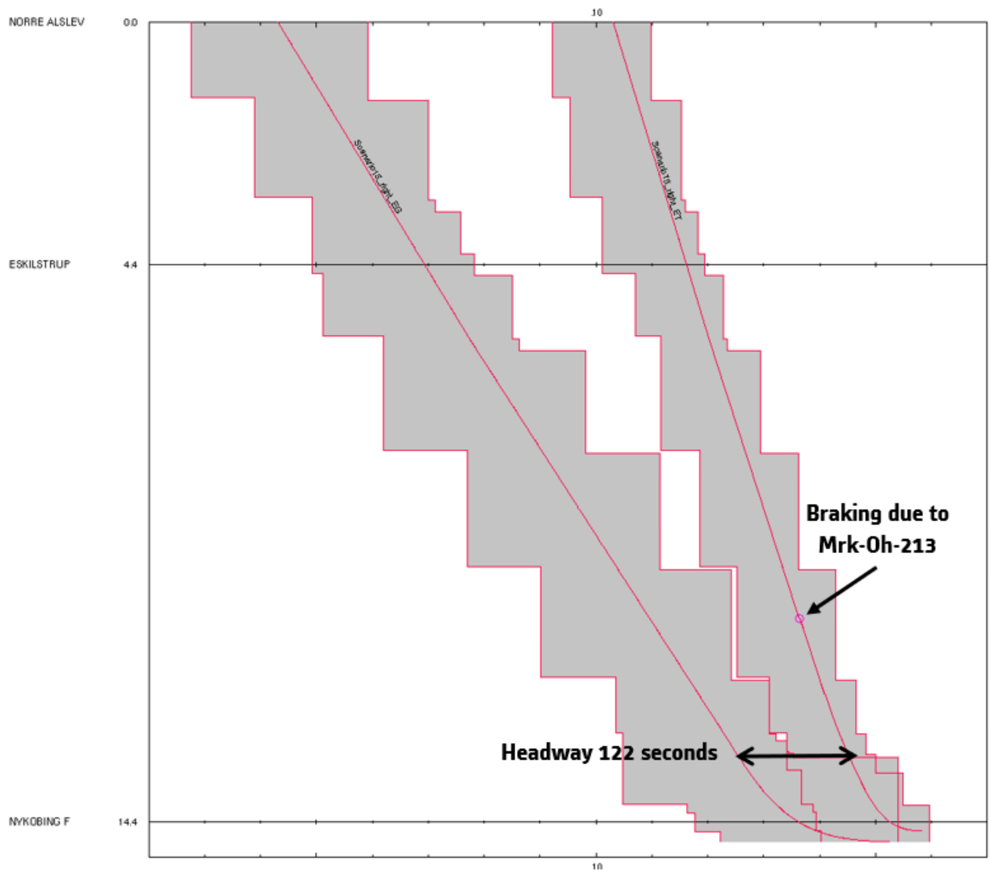


Figure 267 – Blocking time Case C Nørre Alslev – Nykøbing F. Freight/ET right track, headway 122 seconds

5.4.5.16 Scenario 16

In this scenario the first train is the ET train starting from standstill at the end of the platform in Nykøbing, the second train is the freight train that starting from standstill from the same station on the overtaking track (Figure 268, Table 39).

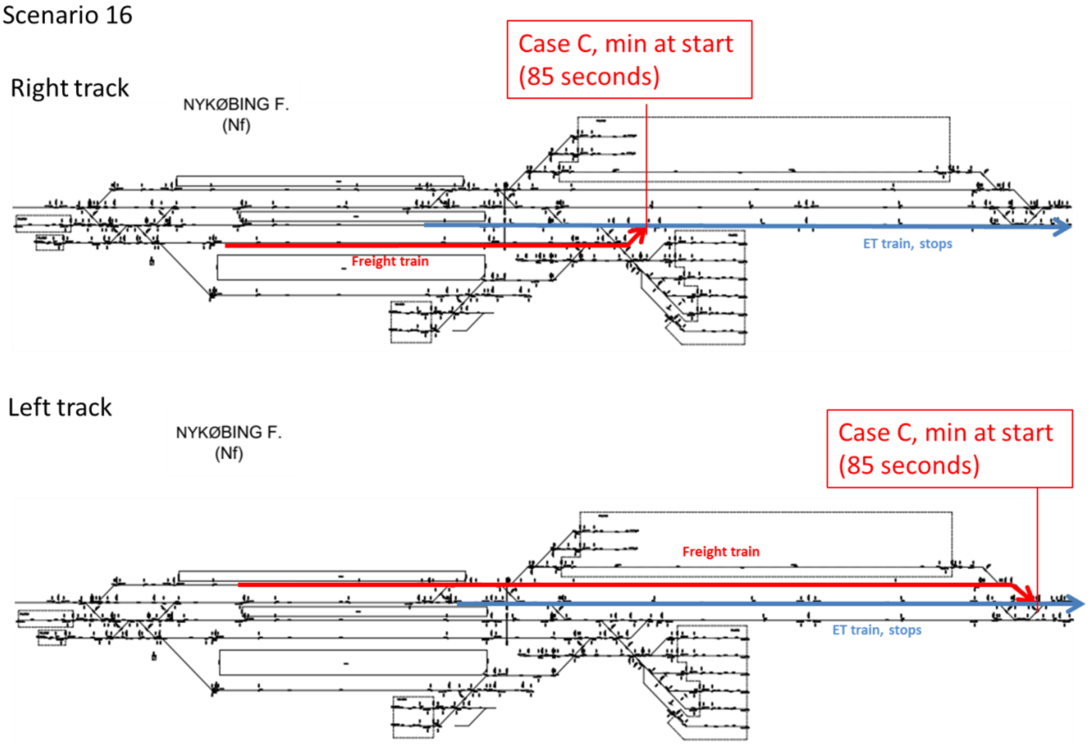


Figure 268 – Scenario 16: Nykøbing F. use of track

Headway Case C is detected at the splitting point Spsk-Vo-N003 (left track) and Spsk-Vo-N013 (right track).

Scenarios	Track	Section	1st Train	2nd Train	Case	Technical Headway [sec]	Separate Tracks in Station	Headway Results [sec]
16	Left	Nykøbing F – Nørre Alslev	ET 350m, bp 180, stop at Nykøbing F	EG 1000m, bp 80, stop at Nykøbing F	C	85 at start	Nykøbing F	86/85
	Right	Nykøbing F – Nørre Alslev	ET 350m, bp 180, stop at Nykøbing F	EG 1000m, bp 80, stop at Nykøbing F	C	85 at start	Nykøbing F	89/85

Table 39 – Headway Scenario 16 Results Overview

For the left track, bottleneck is the relatively long splitting point section (two points at close distance), while for the right track, bottleneck is the relatively long distance between EG starting point (Mrk-Nf-412) and the splitting point.

Left Track

The minimum achievable headway is 86 seconds (required headway 85 seconds) detected at the splitting point Spsk-Nf-N003 at 144+916 (Figure 269). This is the minimum achievable headway in this scenario considering the route setting and release times.

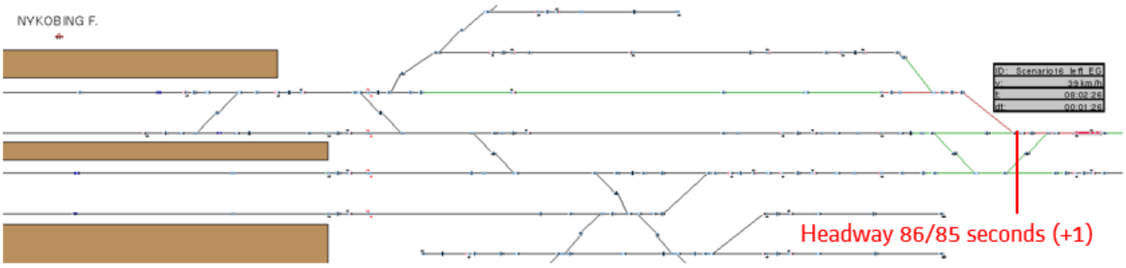


Figure 269 – Headway Case C Nykøbing F. – Nørre Alslev Freight/ET left track, headway 86 seconds

Here below is shown the train graph with the blocking time diagram of both trains (Figure 270).

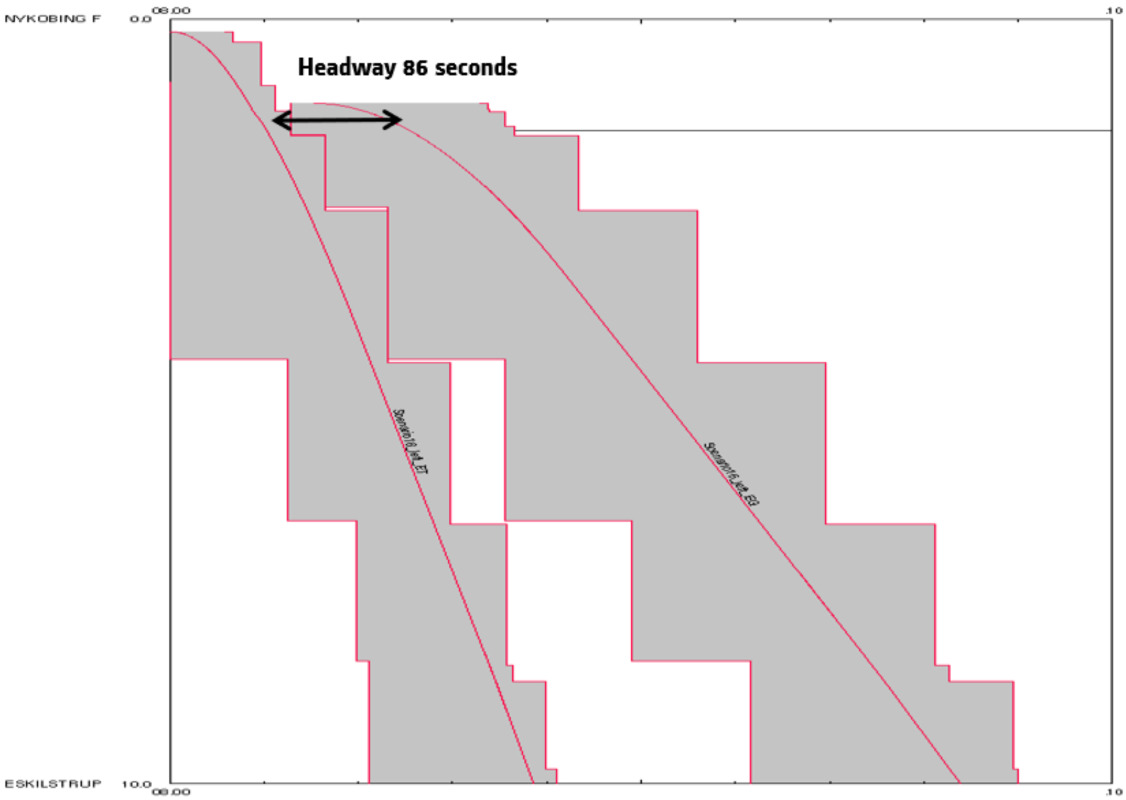


Figure 270 – Blocking time Case C Nykøbing F. – Nørre Alslev Freight/ET left track, headway 86 seconds

As shown in the speed profile below the 2nd train at 86 second headway has no perturbations (Figure 271).

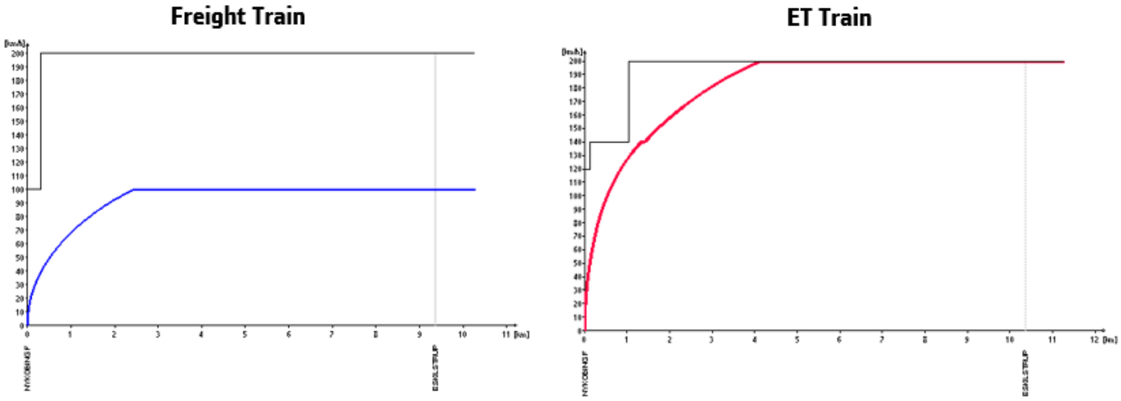


Figure 271 – Train Speed diagram Case C Nykøbing F. – Nørre Alslev Freight/ET left track

Right Track

The minimum achievable headway is 89 seconds (required headway 85 seconds) detected at the splitting point Spsk-Nf-N043 at 145+889 (Figure 272). This is the minimum achievable headway in this scenario considering the route setting and release times.

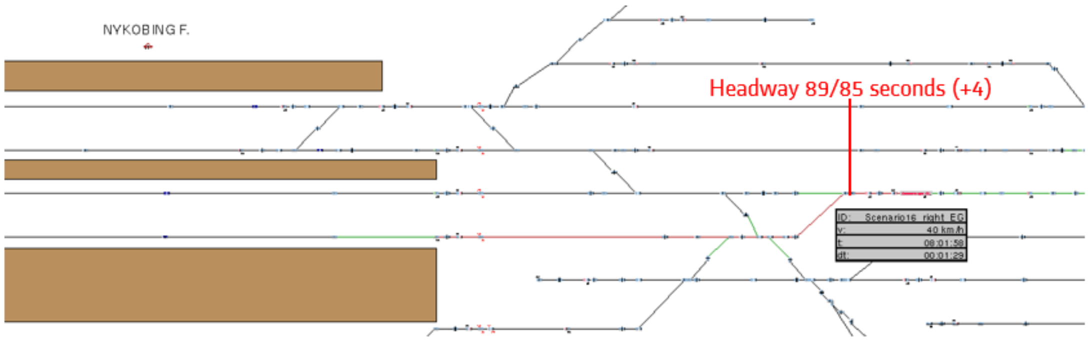


Figure 272 – Blocking time Case C Nykøbing F. – Nørre Alslev Freight/ET right track, headway 89 seconds

As shown in the speed profile below the 2nd train at 89 second headway has no perturbations (Figure 273).

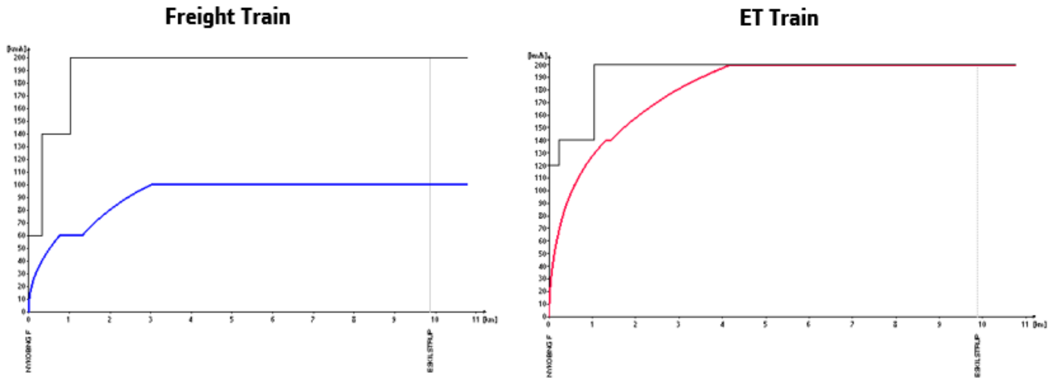


Figure 273 – Train Speed diagram Case C Nykøbing F. – Nørre Alslev Freight/ET right track

5.4.5.17 Scenario 17

In this scenario the first train is the ET train starting from standstill at the end of the platform in Nykøbing F., the second train is the freight train that is starting from standstill from the same station on the overtaking track (Figure 274, Table 40).

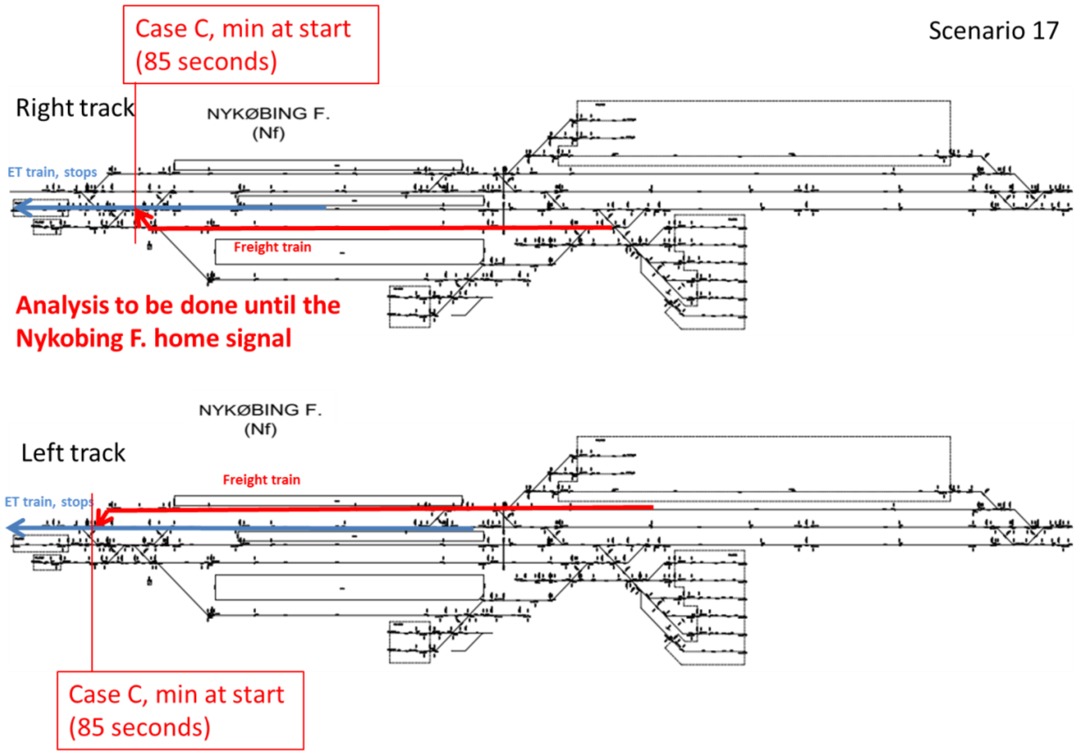


Figure 274 – Scenario 17: Nykøbing F. use of track

Headway Case C is detected at the splitting point Spsk-Nf-N041 (left track) and Spsk-Nf-N044 (right track).

For this scenario the assumption on left track (future double track to Holeby) is to have the first Marker Board after the splitting point at the same location of Mrk-Nf-235.

Scenarios	Track	Section	1st Train	2nd Train	Case	Technical Headway [sec]	Separate Tracks in Station	Headway Results [sec]
17	Left	Nykøbing F – (Holeby)	ET 350m, bp 180, stop at Nykøbing F	EG 1000m, bp 80, stop at Nykøbing F	C	85 at start	Nykøbing F	83/85
	Right	Nykøbing F – (Holeby)	ET 350m, bp 180, stop at Nykøbing F	EG 1000m, bp 80, stop at Nykøbing F	C	85 at start	Nykøbing F	77/85

Table 40 – Headway Scenario 17 Results Overview

Left Track

The minimum achievable headway is 83 seconds (required headway 85 seconds) detected at the splitting point Spsk-Nf-N041 at 146+812 (Figure 275). This is the minimum achievable headway in this scenario considering the route setting and release times.

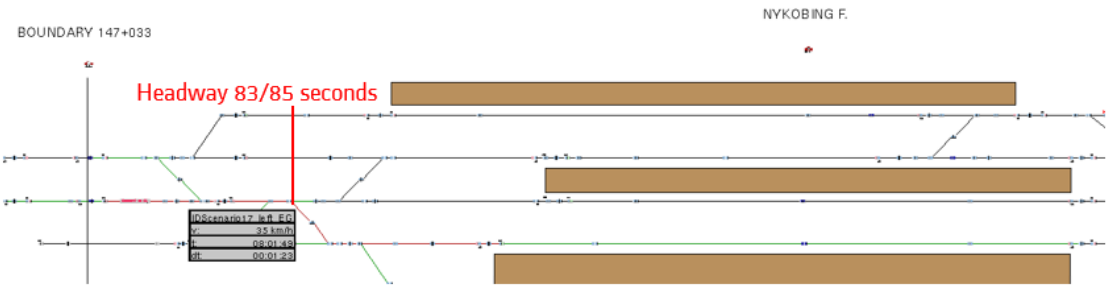


Figure 275 – Headway Case C Nykøbing F. – (Holeby) Freight/ET left track, headway 83 seconds

Here below is shown the train graph with the blocking time diagram of both trains (Figure 276).

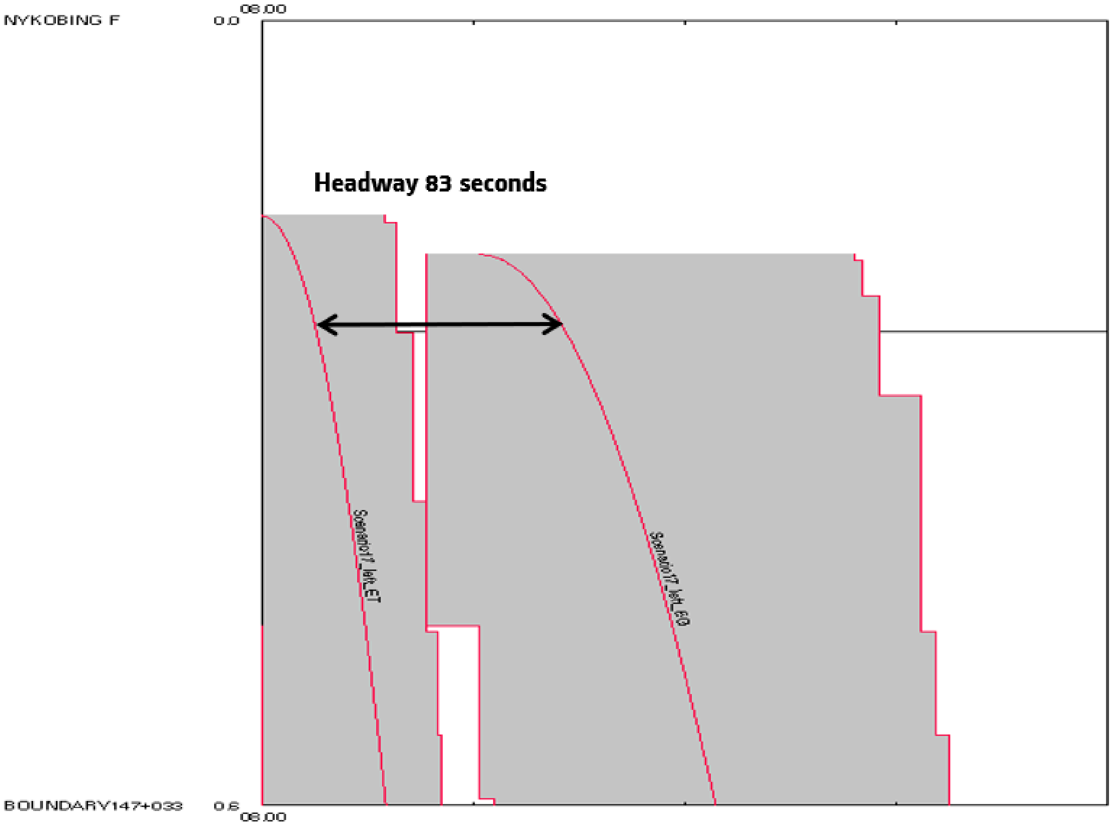


Figure 276 – Blocking time Case C Nykøbing F. – (Holeby) Freight/ET left track, headway 83 seconds

As shown in the speed profile below the 2nd train at 83 second headway has no perturbations (Figure 277).

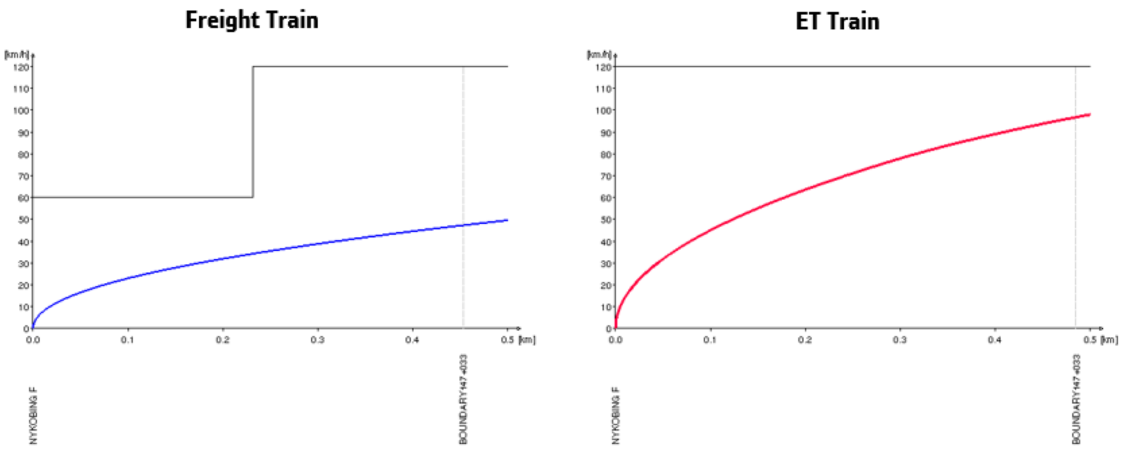


Figure 277 – Train Speed diagram Case C Nykøbing F. – (Holeby) Freight/ET left track

Right Track

The minimum achievable headway is 77 seconds (required headway 85 seconds) detected at the splitting point Spsk-Nf-N044 at 146+937 (Figure 278). This is the minimum achievable headway in this scenario considering the route setting and release times.

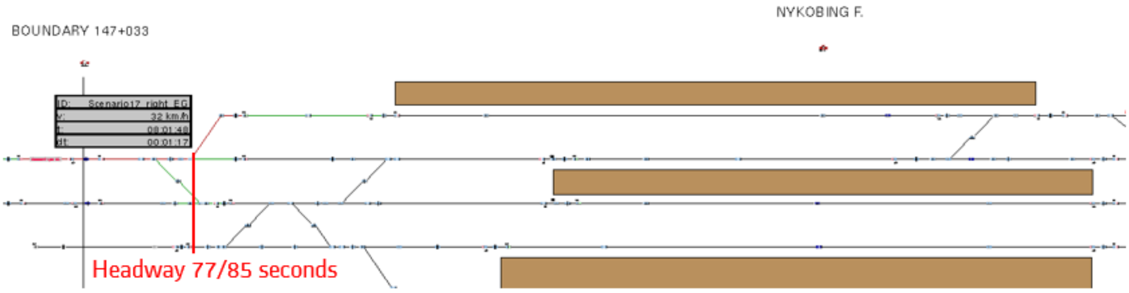


Figure 278 – Headway Case C Nykøbing F. – (Holeby) Freight/ET right track, headway 77 seconds

Here below is shown the train graph with the blocking time diagram of both trains (Figure 279).

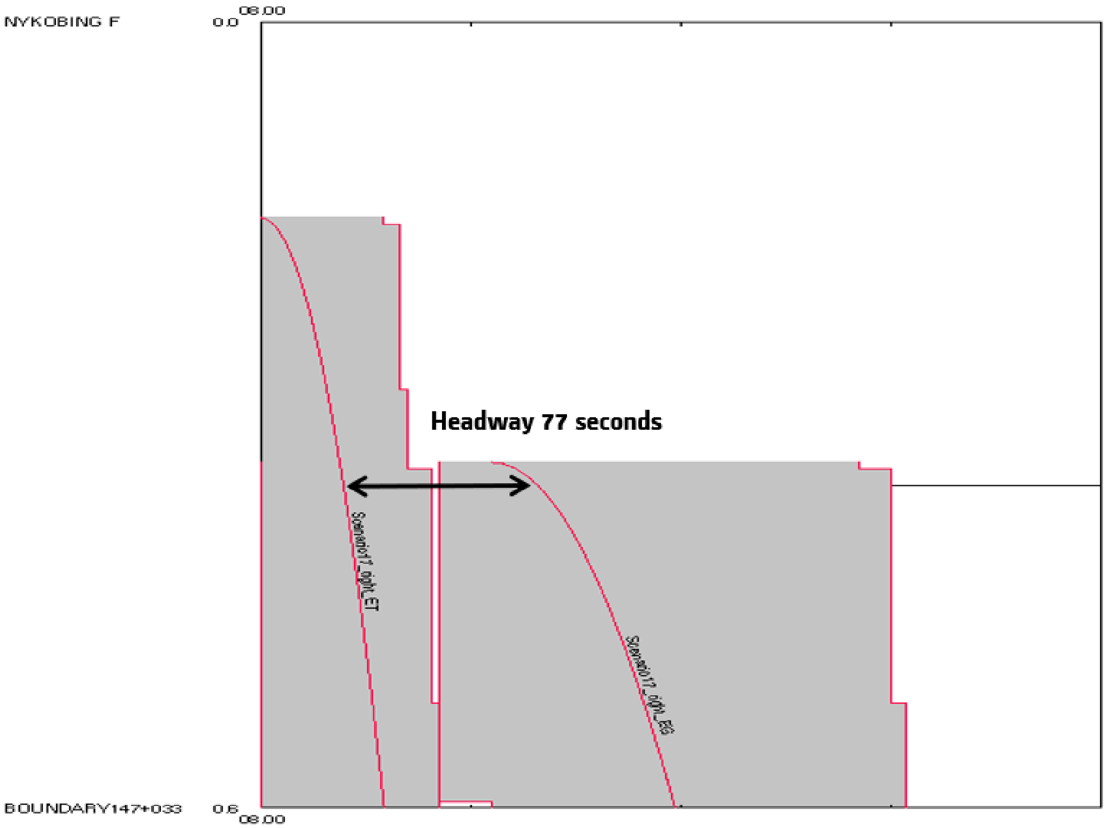


Figure 279 – Blocking time Case C Nykøbing F. – (Holeby) Freight/ET right track, headway 77 seconds

As shown in the speed profile below the 2nd train at 77 second headway has no perturbations (Figure 280).

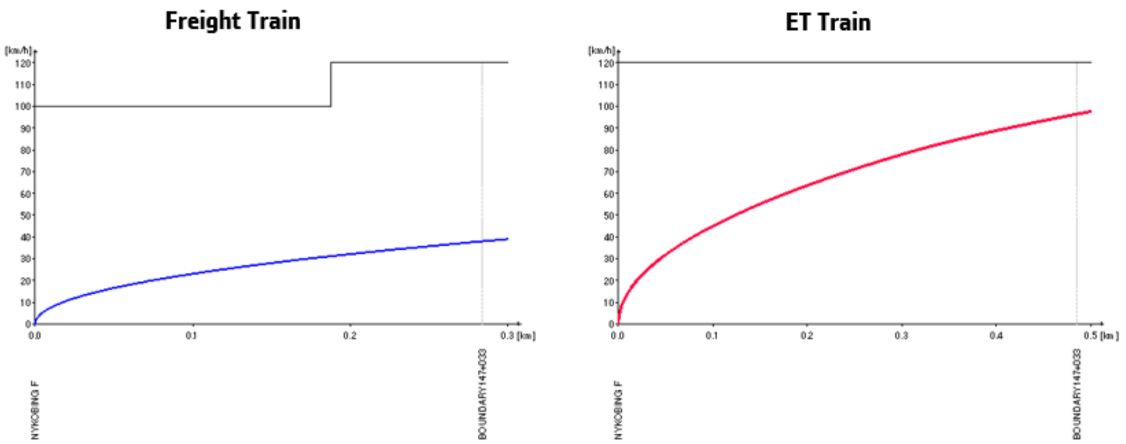


Figure 280 – Train Speed diagram Case C Nykøbing F. – (Holeby) Freight/ET right track

5.4.5.18 Scenario 18

In this scenario the first train is freight train that is running from Holeby to Nykøbing F. direction, stops on the overtaking track in Nykøbing F., followed by the ET passenger train that stops at the end of the platform in the same stations (Figure 281, Table 41).

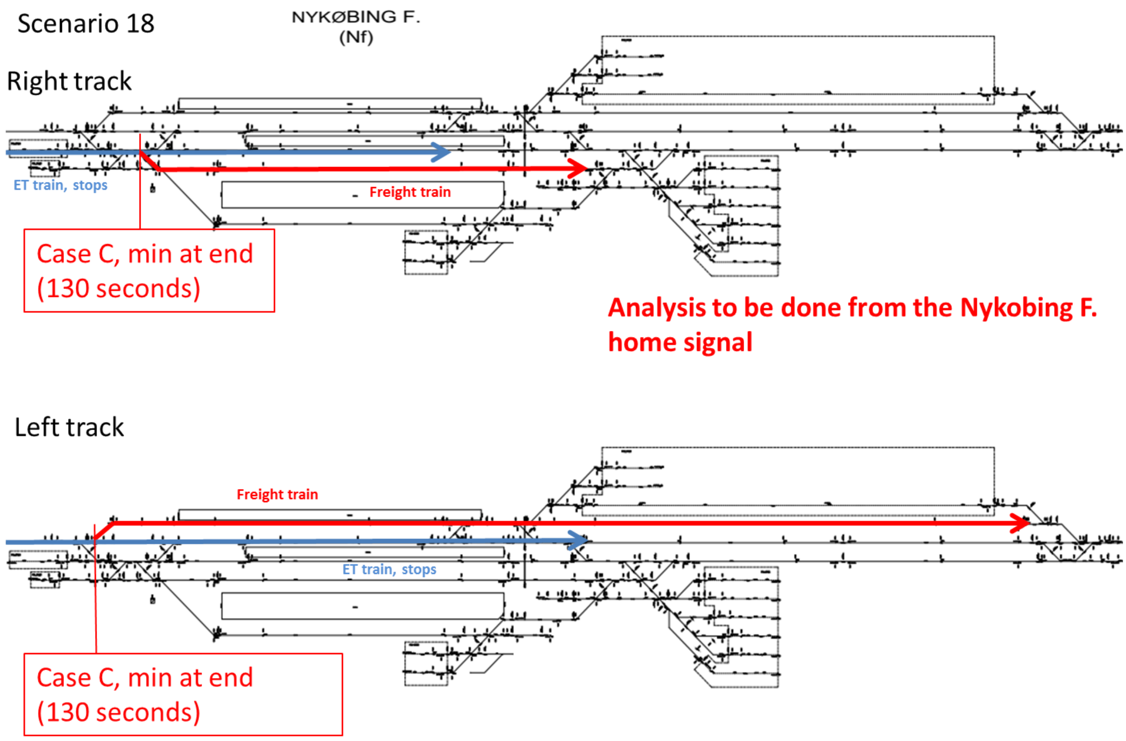


Figure 281 – Scenario 18: Nykøbing F. use of track

Headway Case C detected at the splitting points Spsk-Nf-N041 (right track) and Spsk-Nf-N044 (left track) in Nykøbing.

For this scenario the assumption on right track (future double track from Holeby) is to have the entry Marker Board before the splitting point at the same location of Mrk-Nf-236.

Scenarios	Track	Section	1st Train	2nd Train	Case	Technical Headway [sec]	Separate Tracks in Station	Headway Results [sec]
18	Left	(Holeby) – Nykøbing F	EG 1000m, bp 80, stop at Nykøbing F	ET 350m, bp 180, stop at Nykøbing F	C	130 at end	Nykøbing F	109/130
	Right	(Holeby) – Nykøbing F	EG 1000m, bp 80, stop at Nykøbing F	ET 350m, bp 180, stop at Nykøbing F	C	130 at end	Nykøbing F	127/130

Table 41 – Headway Scenario 18 Results Overview

Left Track

In this scenario the available overtaking track length is higher than 1040 m, the freight train length used for the simulation is 1000 m.

The minimum achievable headway is 109 seconds (required headway 130 seconds) detected at the splitting point Spsk-Nf-N044 at 146+937 (Figure 282); to obtain the minimum headway the approach section to MB protecting the splitting point has been already optimized.

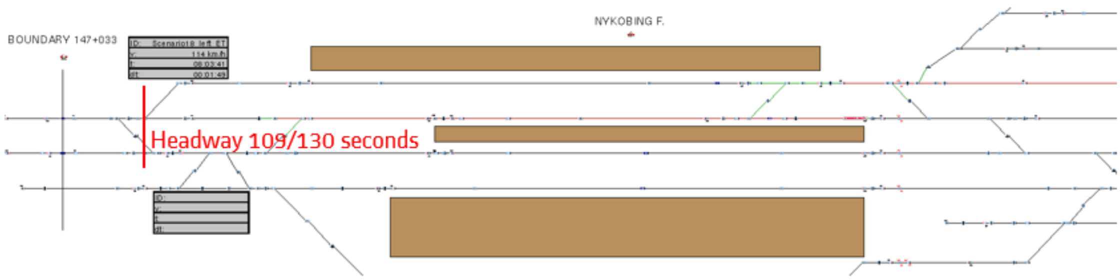


Figure 282 – Headway Case C (Holeby) – Nykøbing F. Freight/ET left track, headway 109 seconds

Here below is shown the train graph with the blocking time diagram of both trains (Figure 283).

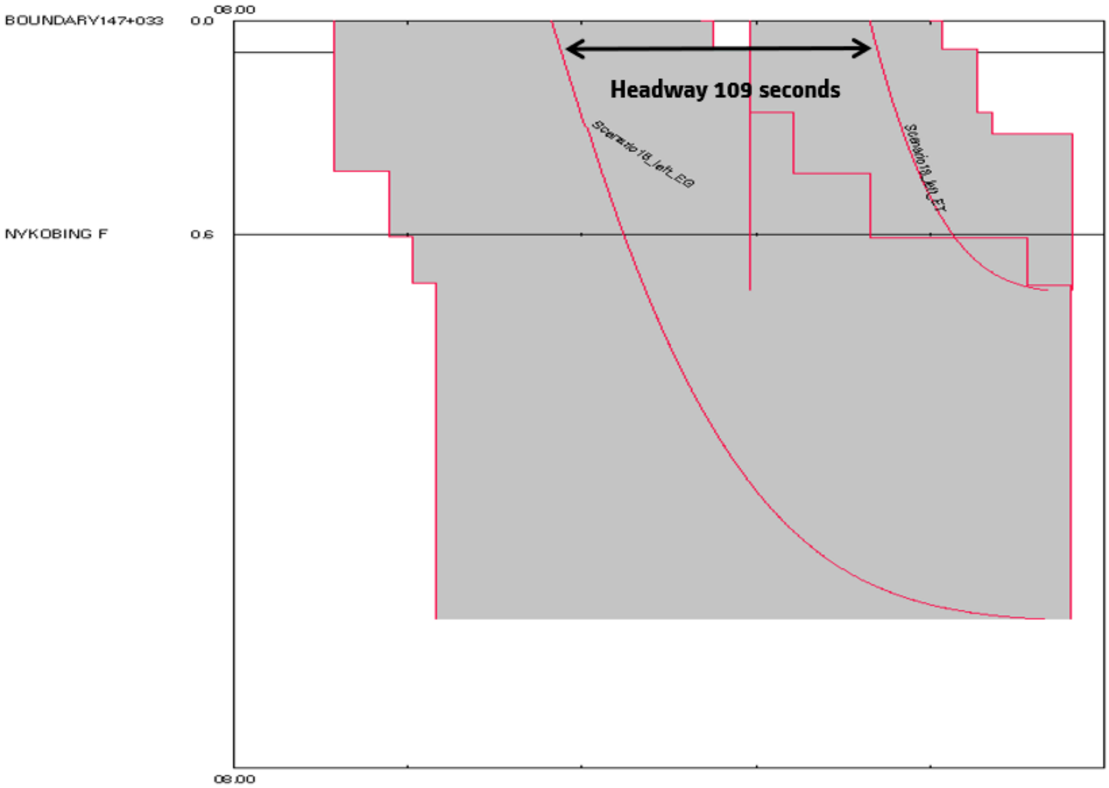


Figure 283 – Blocking time Case C (Holeby) – Nykøbing F. Freight/ET left track, headway 109 seconds

As shown in the speed profile below the 2nd train at 109 second headway has no perturbations (Figure 284).

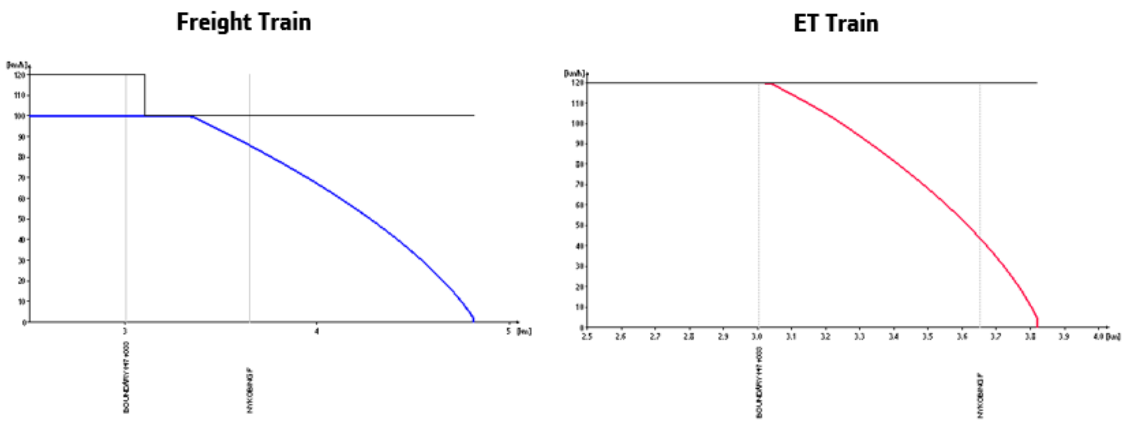


Figure 284 – Train Speed diagram Case C (Holeby) – Nykøbing F. Freight/ET left track

Right Track

In this scenario the available overtaking track length is 478 m; the freight train length used for the simulation is 430 m.

The minimum achievable headway is 127 seconds (required headway 130 seconds) detected at the splitting point Spsk-Nf-N041 at 146+812 (Figure 285); to obtain the minimum headway the approach section to MB protecting the splitting point has been already optimized.

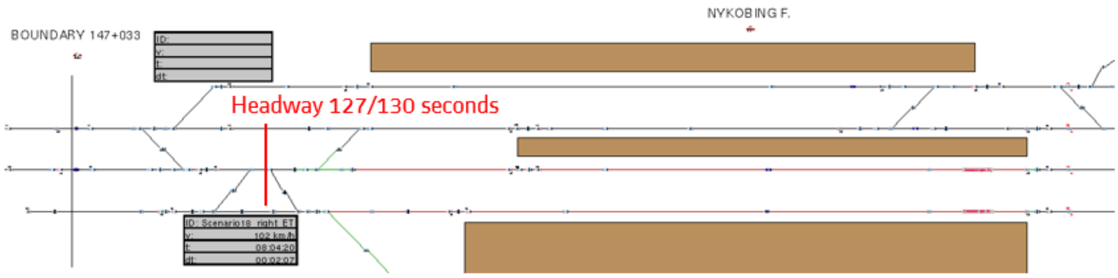


Figure 285 – Headway Case C (Holeby) – Nykøbing F. Freight/ET right track, headway 127 seconds

Here below is shown the train graph with the blocking time diagram of both trains (Figure 286).

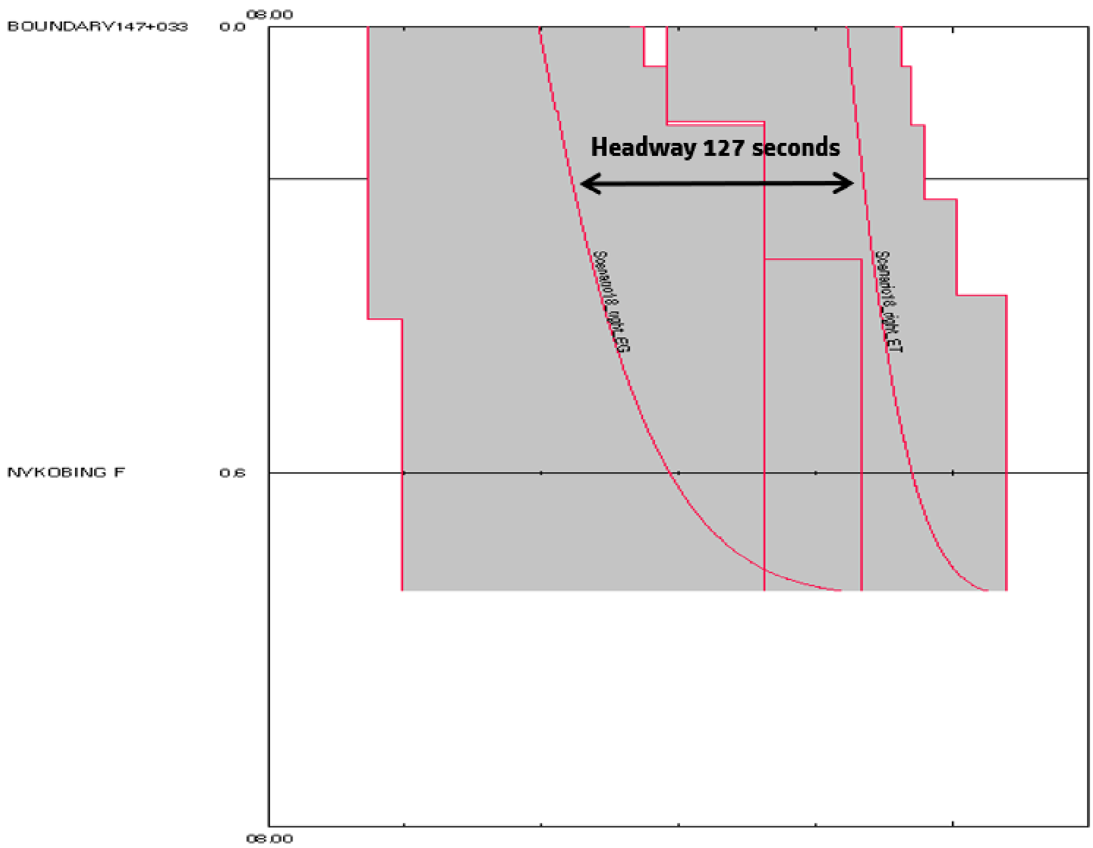


Figure 286 – Blocking time Case C (Holeby) – Nykøbing F. Freight/ET right track, headway 127 seconds

As shown in the speed profile below the 2nd train at 127 second headway has no perturbations (Figure 287).

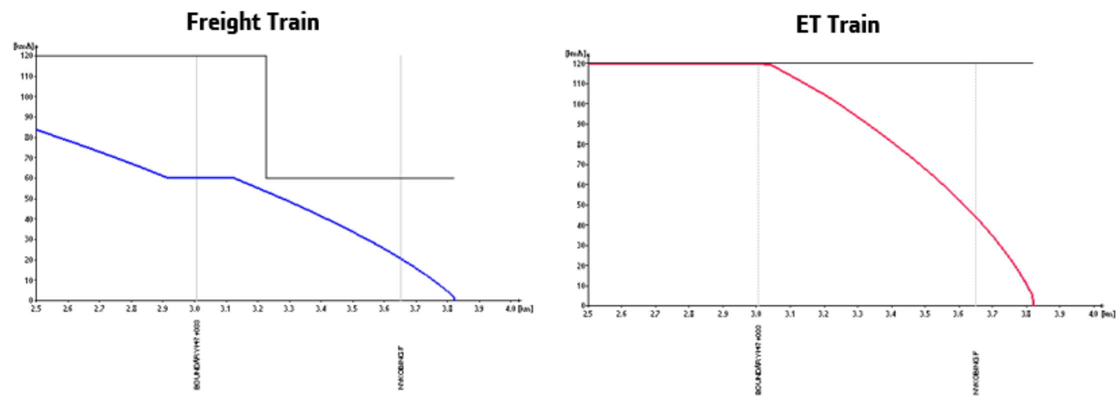


Figure 287 – Train Speed diagram Case C (Holeby) – Nykøbing F. Freight/ET right track

5.4.6. RollOut 8 Simulation Results

In this paragraph will be reported the results for all the headway scenarios simulation of RollOut 8 from Lejre to Holbæk (Figure 288).

For each scenario will be showed the headway requirement, the usage of the track in case of stopping train, the train graph, the running profiles of both trains and eventually the explanation for the scenarios that doesn't meet the requirements.

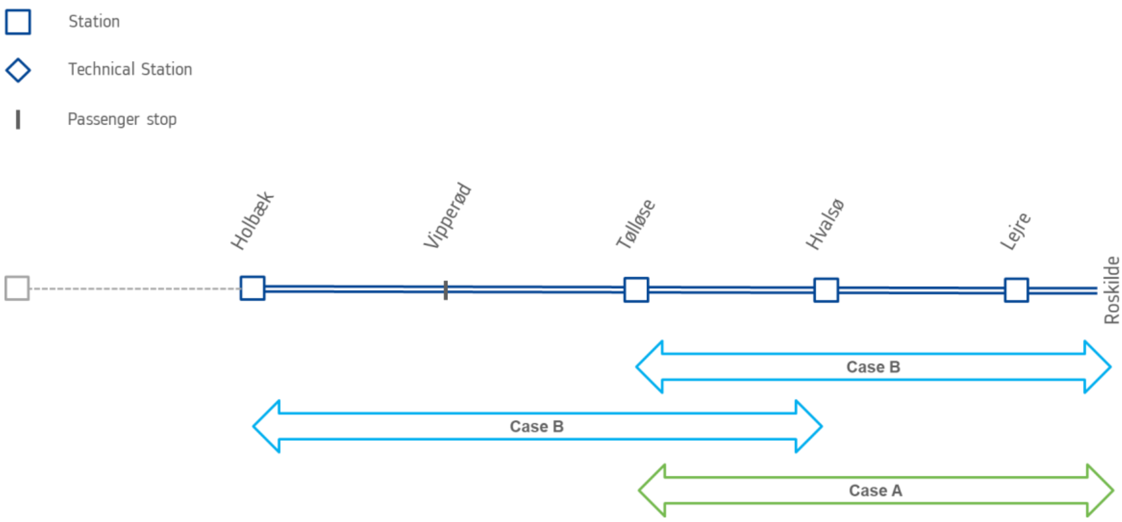


Figure 288 – R08: portion of line under capacity analysis

5.4.6.1 Scenario 1

In this scenario the focus is on the line, the two non-stop IR4 trains are running at 160 Km/h from new rollout boundary at Roskilde to Tølløse; the minimum achievable headway is 108 seconds (required headway 225 seconds) (Table 42).

The speed profile of each train is compliant with the track speed profile (Cant Deficiency 150 mm), the entry speed on the boundary at 38+335 km is 160 Km/h for right track, 120 Km/h for left track.

Headway is detected at the Marker Board Mrk-Lj-212 (kilometer 40+231), Balise Bg-Hv-212 (kilometer 47+243), Marker Board Mrk-Tø-114 (kilometer 54+175) on the left track and at the Marker Board Mrk-Lj-112 (kilometer 40+231), Balise Bg-Hv-112 (kilometer 47+243), Marker Board Mrk-Tø-212 (kilometer 54+175) on the right track.

Scenarios	Track	Section	1st Train	2nd Train	Case	Technical Headway [sec]	Separate Tracks in Station	Headway Results [sec]
1	Left	(Roskilde) – Tølløse	IR4 Stop at Roskilde	IR4 Stop at Roskilde	A	225	Roskilde	108/225
	Right	(Roskilde) – Tølløse	IR4 Stop at Roskilde	IR4 Stop at Roskilde	A	225	Roskilde	108/225

Table 42 – Headway Scenario 1 Results Overview

Here below is shown the train graph with the blocking time diagram of both IR4 trains at maximum speed at 108 seconds headway on both tracks (Figure 289).

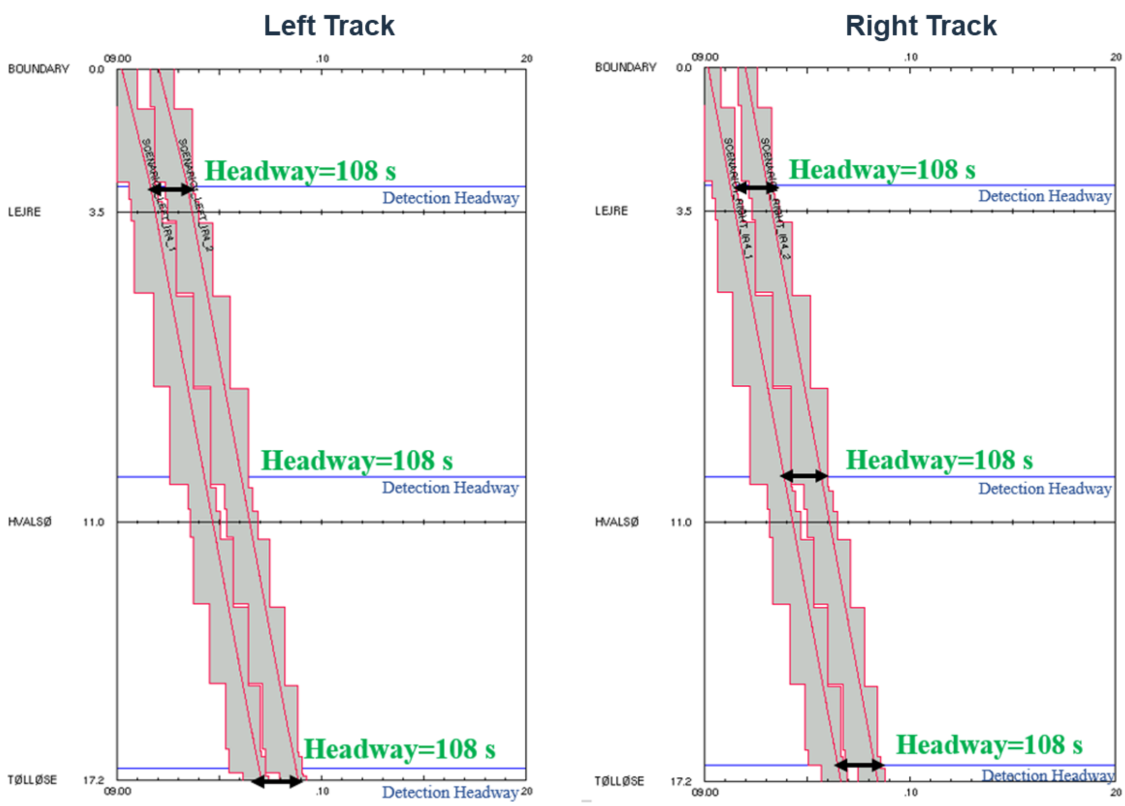


Figure 289 – Blocking time Case A (Roskilde) – Tøllose, IR4 train at 160 km/h

As shown in the speed profile below the 2nd train running at 108 second headway has no perturbations (Figure 290).

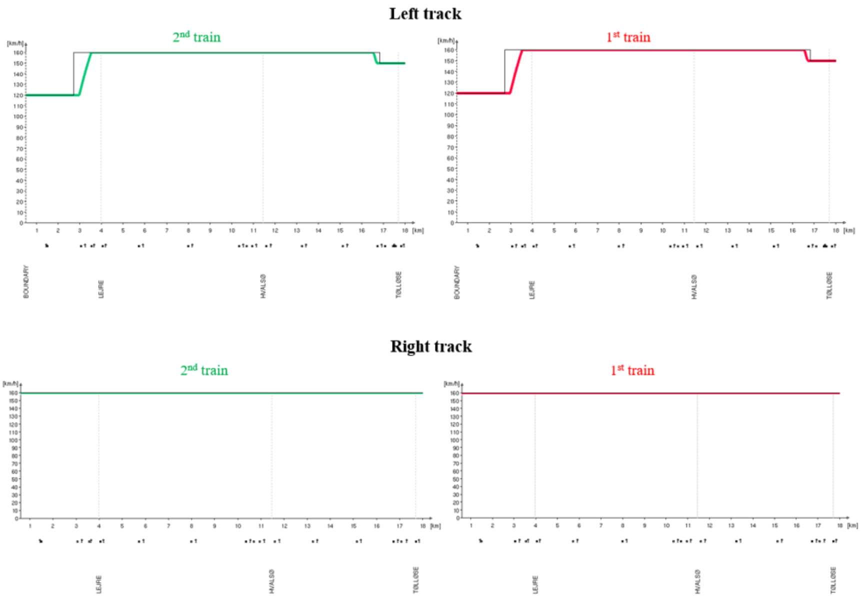


Figure 290 – Train Speed diagram Case A (Roskilde) – Tølløse, IR4 train at 160 km/h

5.4.6.1 Scenario 2

In this scenario the focus is on the line, two no stops IR4 trains are running at 160 Km/h from Tølløse to new rollout boundary at Roskilde; the minimum achievable headway is 118 seconds on the left track and 119 seconds on the right track (required headway 225 seconds on both track) (Table 43).

The speed profile of each train is compliant with the track speed profile (Cant Deficiency 150 mm), the entry speed on Tølløse is 160 Km/h on the left track and 150 km/h on the right track.

Headway is detected at the Marker Board Mrk-Tø-212 (kilometer 54+175), Balise Bg-Hv-112 (kilometer 47+243), Balise Bg-Lj-110 (kilometer 38+390) on the left track and at the Balise Bg-Tø-114 (kilometer 54+392), Balise Bg-Hv-212 (kilometer 47+243), Balise Bg-Lj-210 (kilometer 38+390) on the right track.

Scenarios	Track	Section	1st Train	2nd Train	Case	Technical Headway [sec]	Separate Tracks in Station	Headway Results [sec]
1	Left	Tølløse – (Roskilde)	IR4 Stop at Roskilde	IR4 Stop at Roskilde	A	225	Roskilde	118/225
	Right	Tølløse – (Roskilde)	IR4 Stop at Roskilde	IR4 Stop at Roskilde	A	225	Roskilde	119/225

Table 43 – Headway Scenario 2 Results Overview

Here below is shown the train graph with the blocking time diagram of both IR4 trains at maximum speed at 118 seconds headway on left track and 119 seconds on right track (Figure 291).

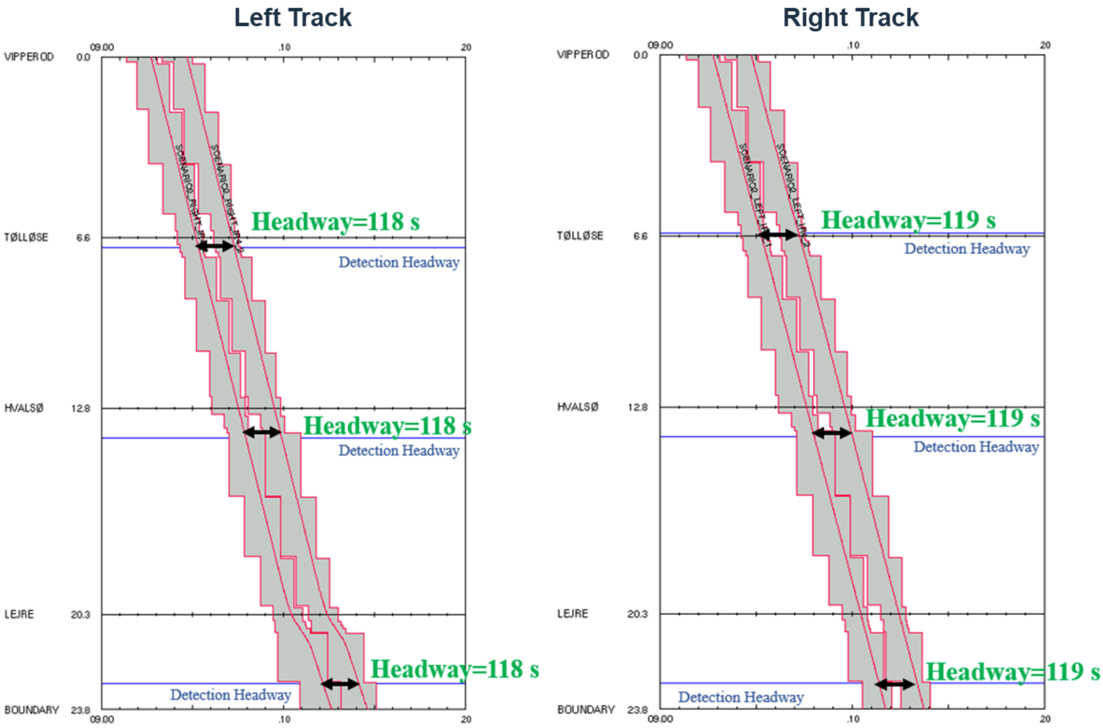


Figure 291 – Blocking time Case A Tøllose – (Roskilde), IR4 train at 160 km/h

As shown in the speed profile below the 2nd train running at 118 second headway for left track and at 119 seconds for right track, has no perturbations (Figure 292).

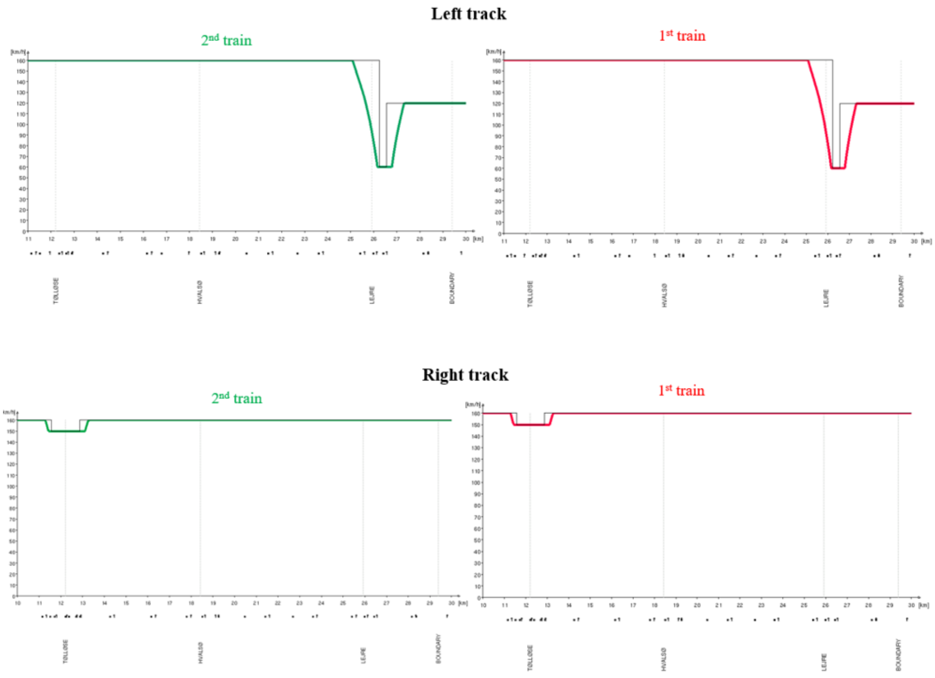


Figure 292 – Train Speed diagram Case A Tøllose – (Roskilde), IR4 train at 160 km/h

5.4.6.1 Scenario 3

In this scenario the first IR4 train is running from Roskilde to Tølløse direction and it is followed by another IR4 train; first train stops at Roskilde, while the second train stops at Roskilde, Lejre and Hvalsø (Figure 293).

The minimum achievable headway is 78 seconds on the left track and 67 seconds on the right track (required headway 105 seconds on both track) (Table 44).

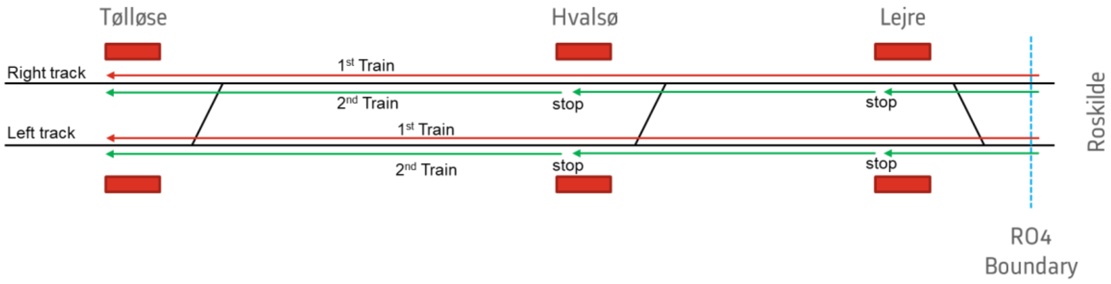


Figure 293 – Scenario 3: Roskilde to Tølløse use of the track

The speed profile of each train is compliant with the track speed profile (Cant Deficiency 150 mm), the entry speed on the boundary at 38+335 km is 160 Km/h for right track, 120 Km/h for left track.

Headway Case B detected at the kilometer 38+390 before Lejre, when two trains have the maximum speed (120 Km/h on left track, 160 Km/h on right track).

Scenarios	Track	Section	1st Train	2nd Train	Case	Technical Headway [sec]	Separate Tracks in Station	Headway Results [sec]
3	Left	(Roskilde) – Tølløse	IR4 Stop at Roskilde	IR4 Stop at Roskilde	A	105	Roskilde	78/105
	Right	(Roskilde) – Tølløse	IR4 Stop at Roskilde	IR4 Stop at Roskilde, Lejre (15s), Hvalsø (15s)	A	105	Roskilde	67/105

Table 44 – Headway Scenario 3 Results Overview

Here below is shown the train graph with the blocking time diagram of both IR4 trains at maximum speed at 78 seconds headway on left track and 67 seconds on right track (Figure 294).

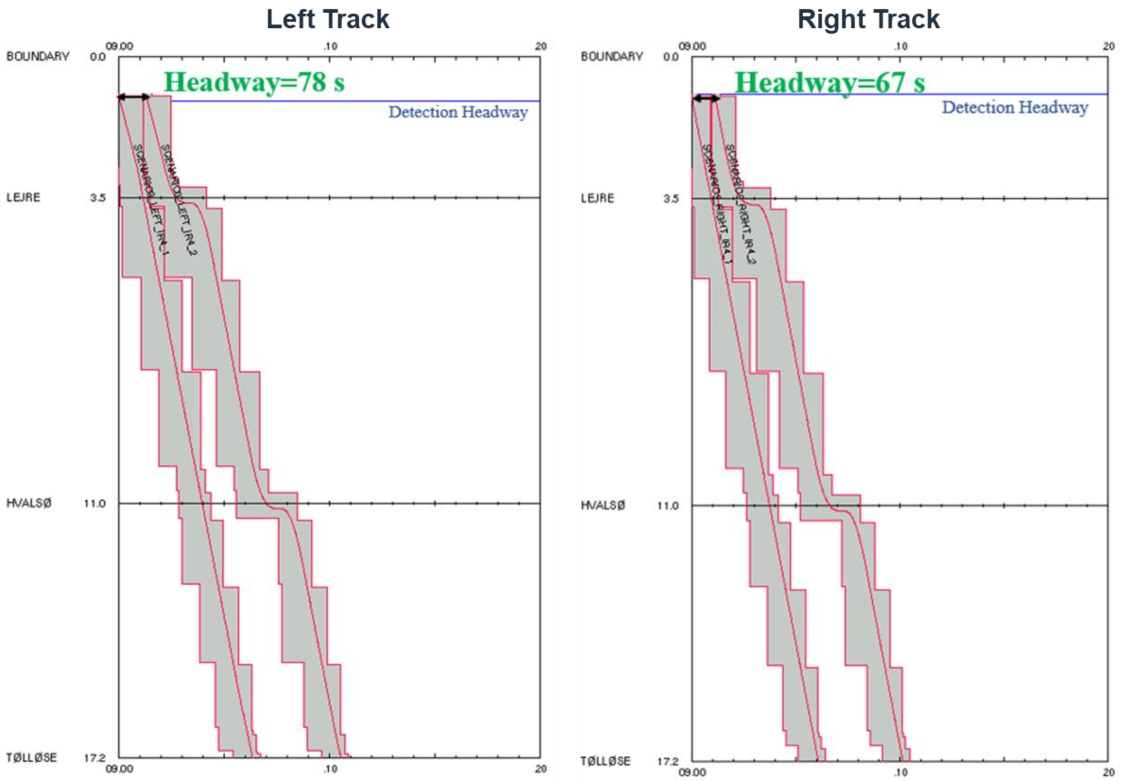


Figure 294 – Blocking time Case B (Roskilde) - Tølløse, IR4 train

As shown in the speed profile below the 2nd train running at 78 second headway for left track and at 67 seconds for right track, has no perturbations (Figure 295).

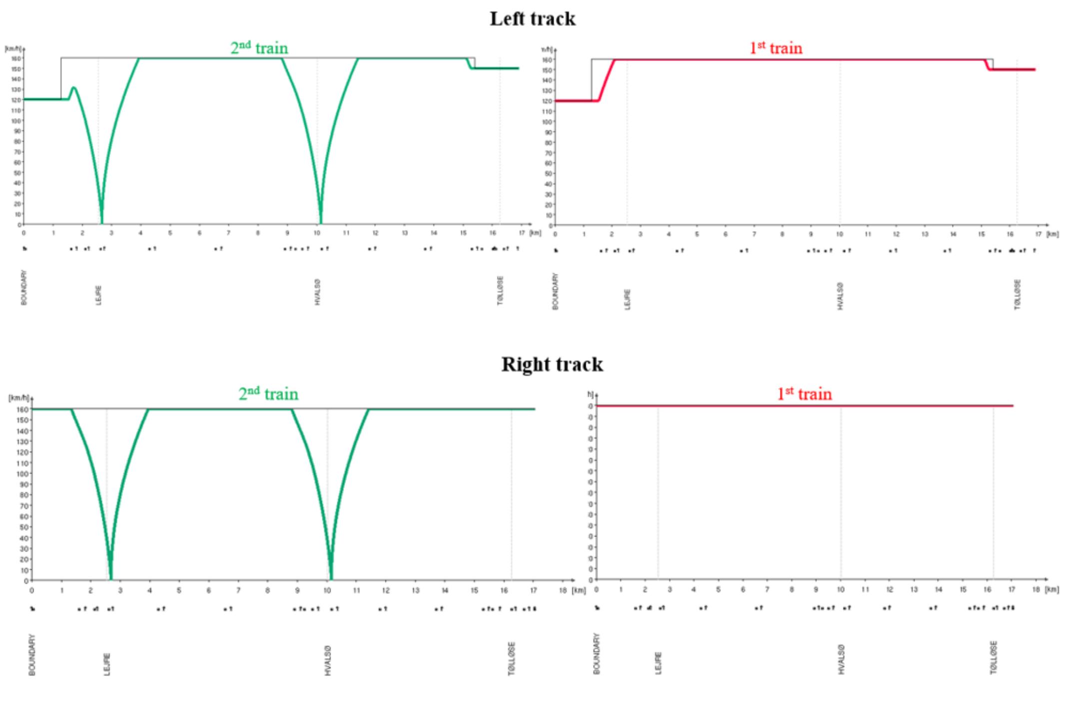


Figure 295 – Train Speed diagram Case B (Roskilde) - Tølløse, IR4 train

5.4.6.1 Scenario 4

In this scenario two IR4 trains runs from Tølløse to rollout boundary at Roskilde. The first train stops at Hvalsø, Lejre and Roskilde, and it is followed by a second train that stops in Roskilde (Figure 296, Table 45).

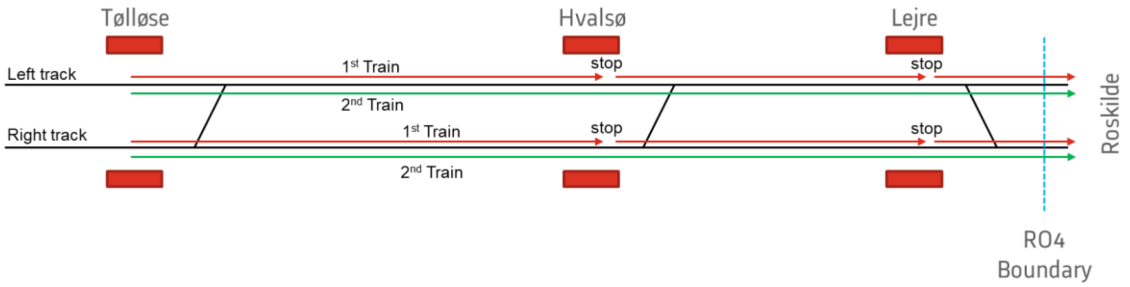


Figure 296 – Scenario 4: Tølløse to Roskilde use of the track

The speed profile of each train is compliant with the track speed profile (Cant Deficiency 150 mm), the entry speed on Tølløse is 160 Km/h on the left track and 150 km/h on the right track.

Headway is detected at the Marker Board Mrk-Lj-110 (kilometer 38+443) on the left track and at the Balise Bg-Lj-210 (kilometre 38+390) on the right track.

Scenarios	Track	Section	1st Train	2nd Train	Case	Technical Headway [sec]	Separate Tracks in Station	Headway Results [sec]
3	Left	Tølløse – (Roskilde)	IR4 Stop at IR4 Stop at Hvalsø (15s), Lejre (15s), Roskilde	IR4 Stop at Roskilde	B	105	Roskilde	109/105
	Right	Tølløse – (Roskilde)	IR4 Stop at IR4 Stop at Hvalsø (15s), Lejre (15s), Roskilde	IR4 Stop at Roskilde	B	105	Roskilde	95/105

Table 45 – Headway Scenario 4 Results Overview

Here below is shown the train graph with the blocking time diagram of both IR4 trains at maximum speed at 78 seconds headway on left track and 67 seconds on right track (Figure 297).

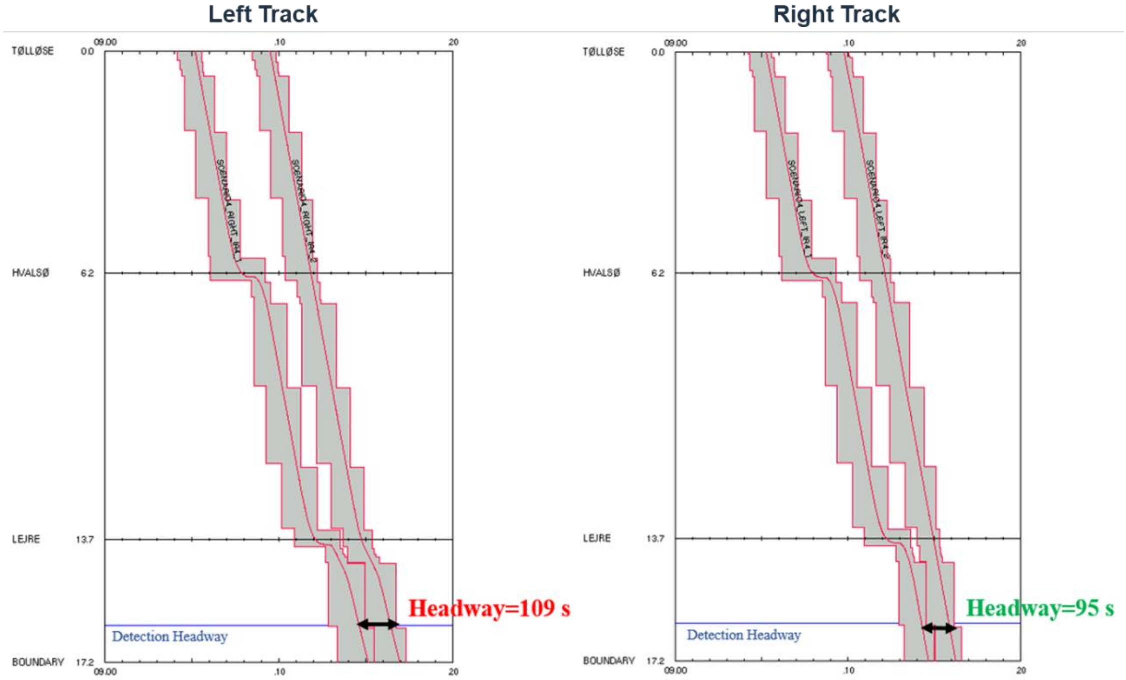


Figure 297 – Blocking time Case B Tølløse – Roskilde, IR4 train

As shown in the speed profile below the 2nd train running at 109 second headway for left track and at 95 seconds for right track, has no perturbations (Figure 298).

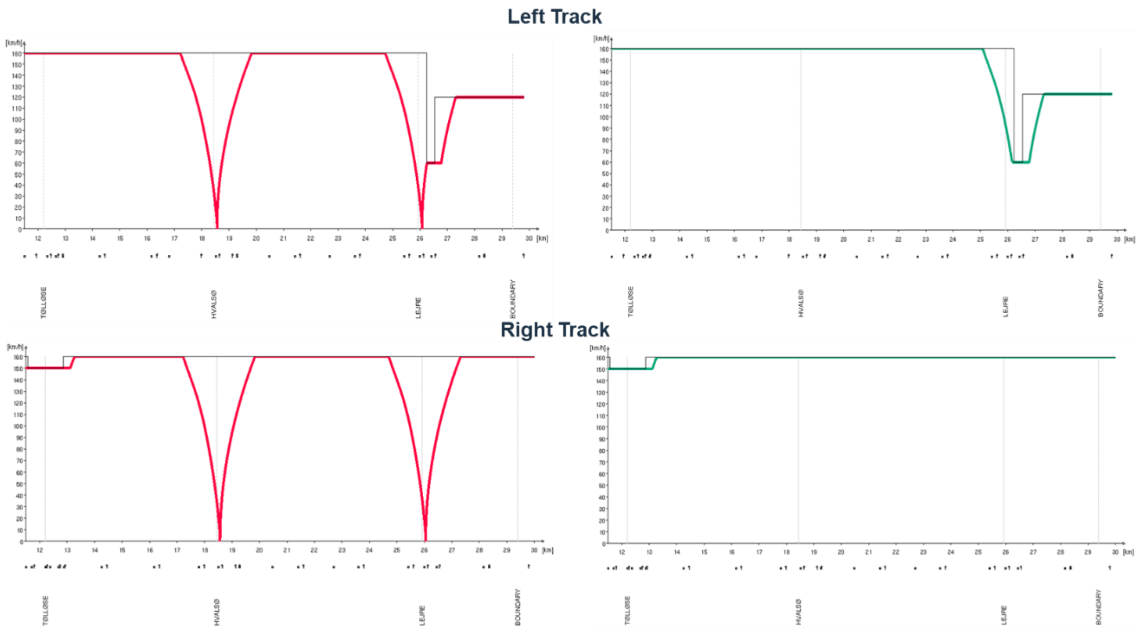


Figure 298 – Train Speed diagram Case B Tølløse – Roskilde, IR4 train

Scenario 4 for left track is not verified, this seems to be due to a speed restriction (160 → 60 → 120 Km/h) which is not present on the other travel direction for the same track and on the other track.

5.4.6.1 Scenario 5

In this scenario two IR4 trains run from Hvalsø to Holbaek. The first train stops at Tølløse (15s), Vipperod (15s) and on the overtaking track in Holbaek, and it is followed by a second train that stops on the main track in Holbaek (Figure 299, Table 46).

Figure 299 – Scenario 5: Halsvø to Holbæk use of the track

The speed profile of each train is compliant with the track speed profile (Cant Deficiency 150 mm).

Headway Case B is detected at slitting point in Holbæk.

Scenarios	Track	Section	1st Train	2nd Train	Case	Technical Headway [sec]	Separate Tracks in Station	Headway Results [sec]
3	Left	Hvalsø – Holbaek	IR4 Stop at Tø (15s), Pe (15s), Hk	IR4 Stop at Hk	B	105	Holbaek	89 / 105
	Right	Hvalsø – Holbaek	IR4 Stop at Tø (15s), Pe (15s), Hk	IR4 Stop at Hk	B	105	Holbaek	87 / 105

Table 46 – Headway Scenario 3 Results Overview

Here below is shown the train graph with the blocking time diagram of both IR4 trains at maximum speed at 89 seconds headway on left track and 87 seconds on right track (Figure 300).

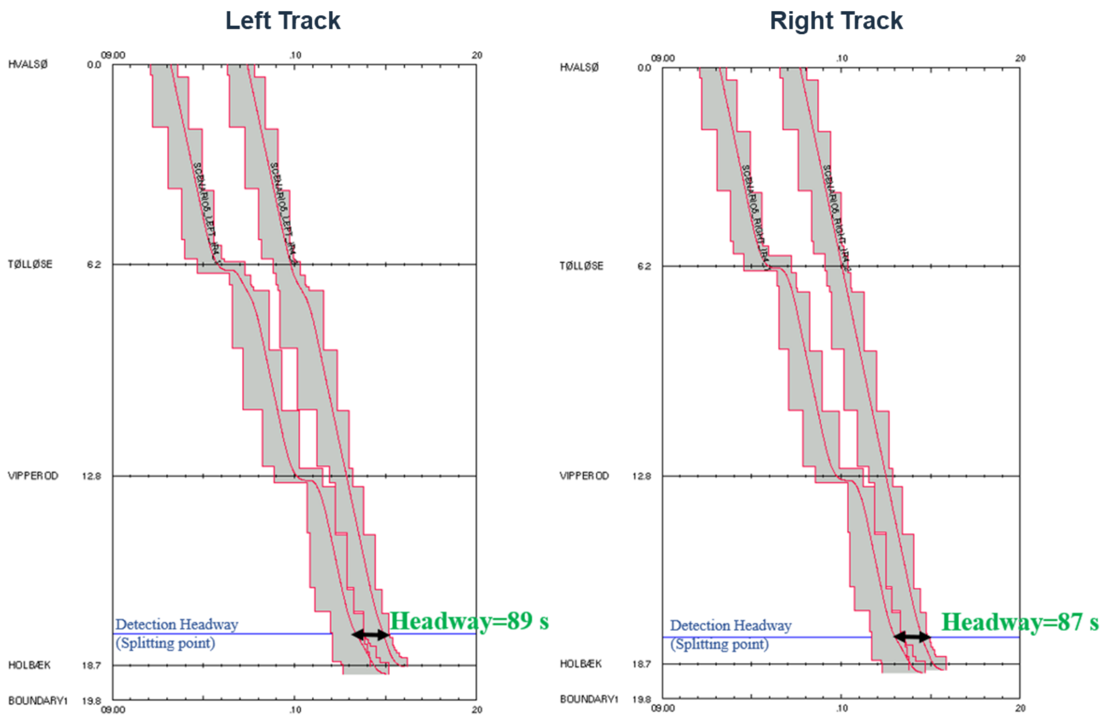


Figure 300 – Blocking time Case B Halsvø - Holbæk, IR4 train

As shown in the speed profile below the 2nd train running at 89 second headway for left track and at 87 seconds for right track, has no perturbations (Figure 301).

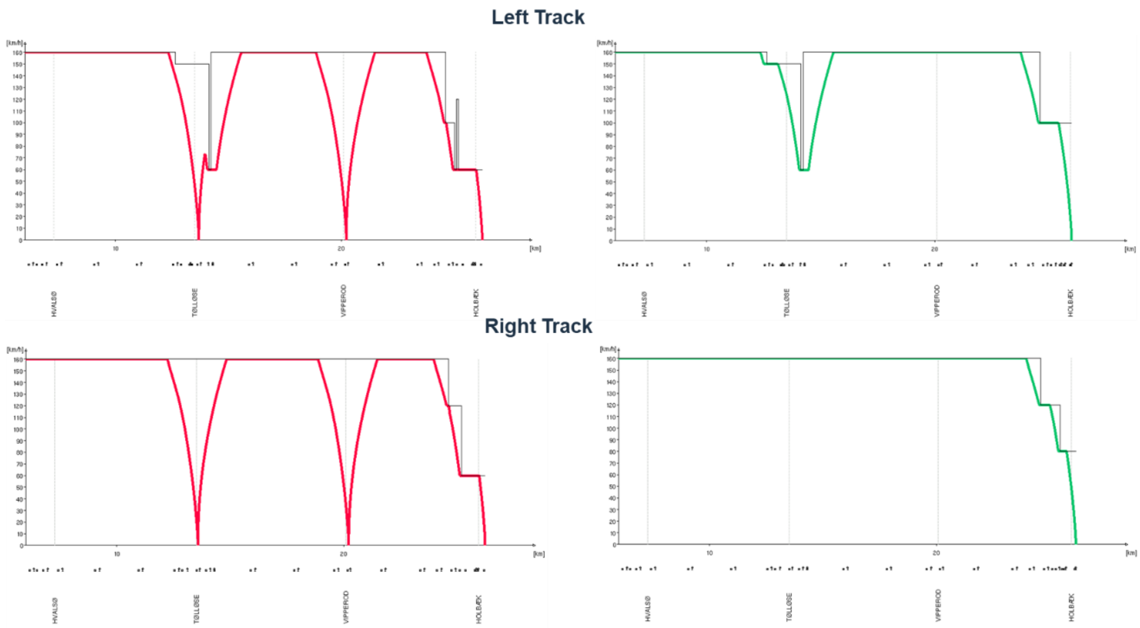


Figure 301 – Train Speed diagram Case B Halsvø - Holbæk, IR4 train

5.4.6.1 Scenario 6

In this scenario two IR4 trains run from Hvalsø to Holbaek. The first train departs on the main track in Holbaek while the second train starts on the overtaking track in Holbaek and stops at Vipperod (15s) and Tølløse (15s) (Figure 302, Table 47).

Figure 302 – Scenario 4: Tølløse to Roskilde use of the track

The speed profile of each train is compliant with the track speed profile (Cant Deficiency 150 mm).

Headway Case B is detected at the splitting point at Holbaek for both tracks.

Scenarios	Track	Section	1st Train	2nd Train	Case	Technical Headway [sec]	Separate Tracks in Station	Headway Results [sec]
3	Left	Holbaek – Hvalsø	IR4 228m, bp 180, stop at Holbaek	IR4 228m, bp 180, stop at Holbaek, Vipperod (15s), Tølløse (15s)	B	105 at start	Holbaek	79/105
	Right	Holbaek – Hvalsø	IR4 228m, bp 180, stop at Holbaek	IR4 228m, bp 180, stop at Holbaek, Vipperod (15s), Tølløse (15s)	B	105 at start	Holbaek	80/105

Table 47 – Headway Scenario 4 Results Overview

Here below is shown the train graph with the blocking time diagram of both IR4 trains at maximum speed at 79 seconds headway on left track and 80 seconds on right track (Figure 303).

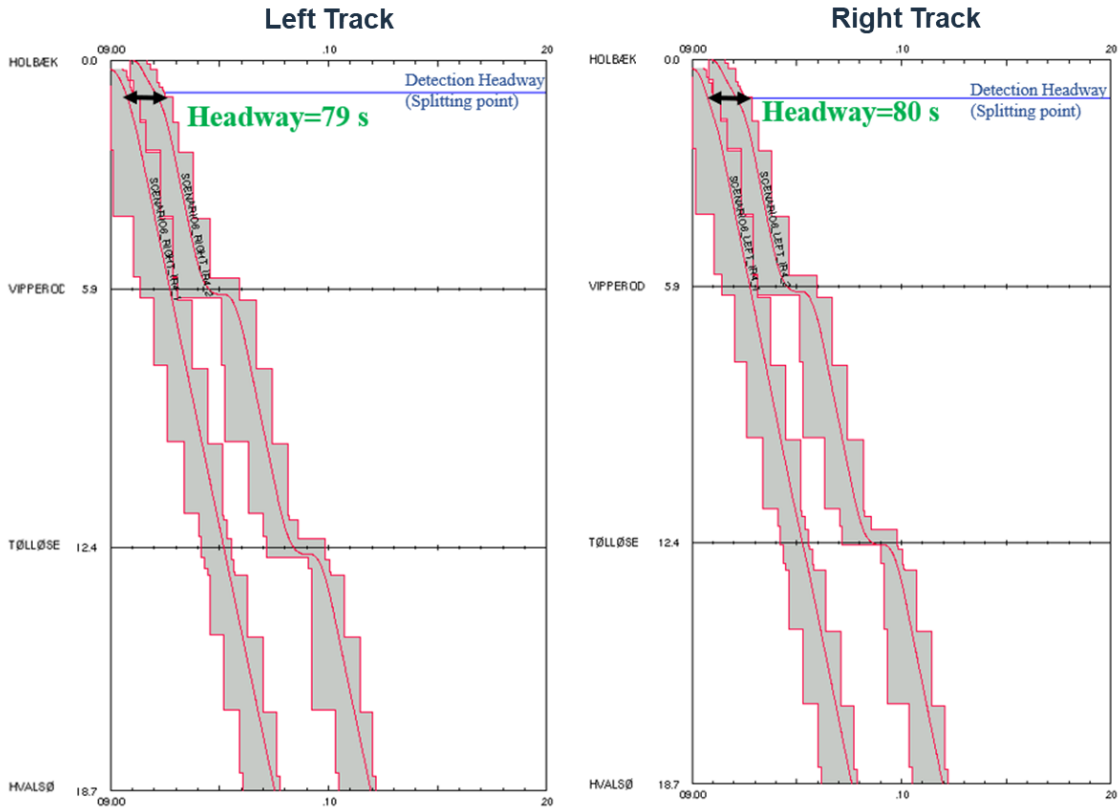


Figure 303 – Blocking time Case B Tølløse – Roskilde, IR4 train

As shown in the speed profile below the 2nd train running at 79 second headway for left track and at 80 seconds for right track, has no perturbations (Figure 304).

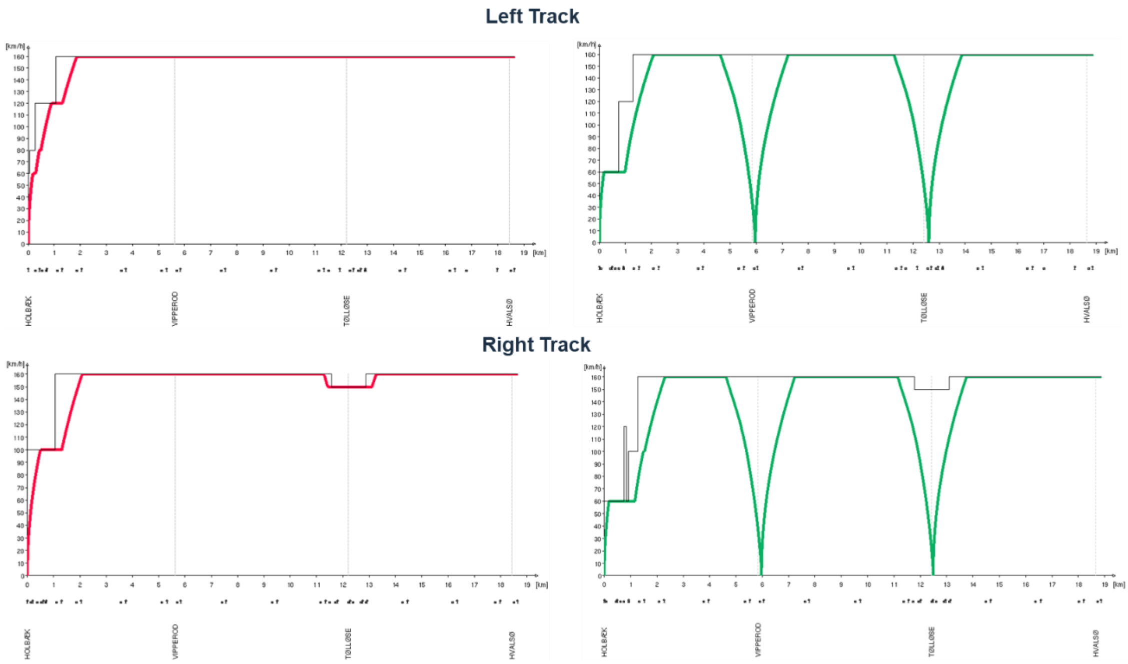


Figure 304 – Train Speed diagram Case B Tølløse – Roskilde, IR4 train

5.4.7. Project Conclusion

The proposed methodology is used to evaluate the first signalling equipment position, in terms of Marker Boards and Axle Counter, to fulfil the expected headway requirements and respect engineering rules, minimizing costs. It is supported by an analitichal method that allows to obtain consistent results. On the other hand, if obtained signalling layout doesn't fulfil each headway scenarios, it is possible to modify and re-design it, reiterating the procedure. In this why the methodology permits to the signalling engineer to analyse the results sensitivity by turning specific parameters related to infrastructure and trains, ensuring the fulfilment of operational and performance requirements applying a given headway in a commercial turn-key contract. The obtained results, in the case study of rollout 7 from Næstved to Nykøbing Falster in Denmark but also in rollout 8 from Lejre to Holbæk, are a robust signalling configuration which also provides a satisfying trade-off between total cost and network performance. So the application to the Danish case of study shows that it is possible to pursue a different objective that is not merely to get the maximum possible capacity for a given signalling system, but to evaluate the right trade-off between headway requirements, infrastructural constrains, operational constrains and technological constrains. These last are defined at the beginning of the process and the entire signalling layout is built based on these requirements, so the capacity of the railways lines is an implicit result.

5.5 Milan Metro Line 2 (Italy)

Line 2, is a subway line serving Milan, Italy, operated by ATM as part of the Milan Metro. It is also called the Green Line, as it is visually identified by green signs (Figure 305).

Figure 305 – The Green Line

The line runs from the southern to the north-eastern neighborhoods passing through the city centre, serving the north-eastern metropolitan area with two different branches. The line is 39.8 km long and has 35 stations. Line 2 is the longest line of the Milan Metro and is the only one running partially overground. The branch to Cologno Nord runs mostly on viaducts, while those to Assago and Gessate run on the surface (Figure 306).

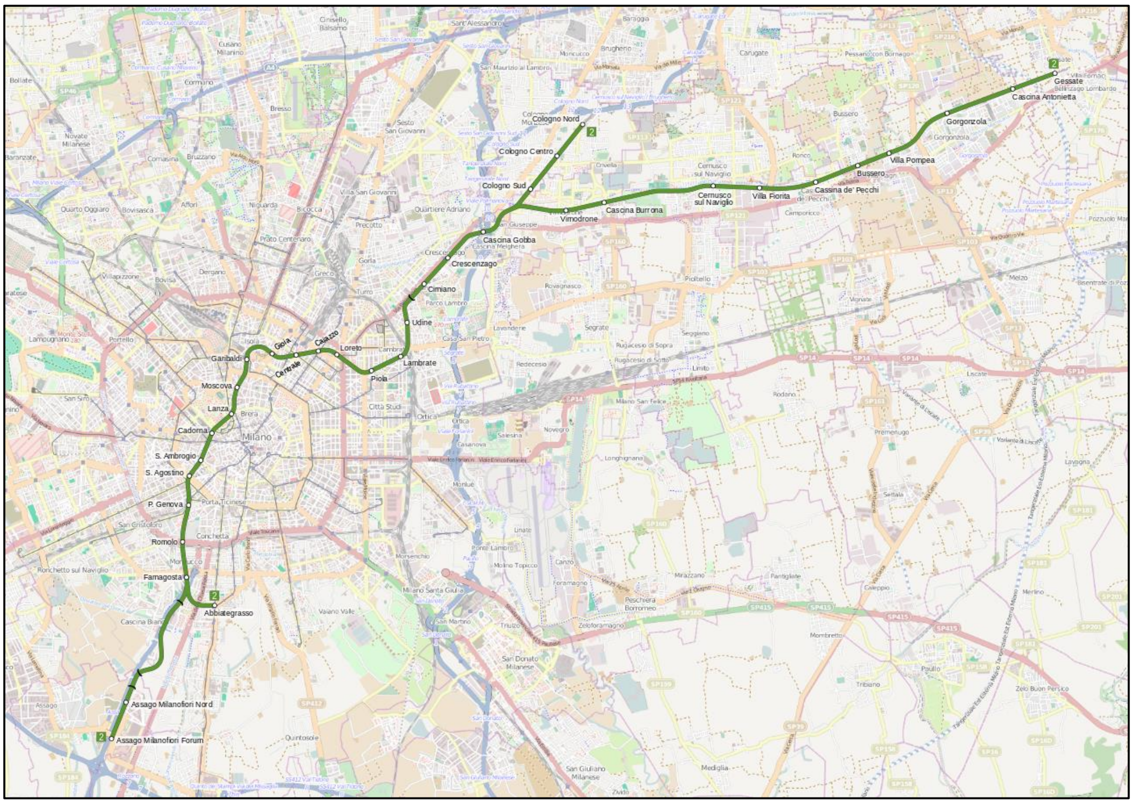


Figure 306 – Milano Metro Line 2 Map

5.5.1. Scope of the Simulation

The aim of the project is to calculate the performance of the new moving block signalling system (CBTC) through the simulation of train traffic on the Milan Metro Line 2. In particular, the purpose of the simulation activities is to:

- verify the future signalling system in mobile block so that it can be determine limits and advantages;
- identify, where possible, the need for action on the infrastructure and operating conditions which could significantly improve the operation of the line even in degraded and/or poor conditions.

The simulation activity was divided into several phases: initially the mainline sections, the terminal stations and the forks were evaluated and then the evaluation of the total movements on the whole line has been done.

5.5.2. Lines Overview

Figure 307 shows the line schema. The central section runs from Cascina Gobba to Famagosta while forks at both ends develop as follow: the North branch runs from Cologno Sud to Cologno Nord, the North-East branch runs from Vimodrone to Gessate, the South-East branch consists of the Abbiategrasso station and the South branch runs from Assago Milanofiori Nord to Assago Milanofiori Forum.

Figure 307 – Milan Metro Line 2 Schema

5.5.3. Simulation Model Assumption

Here below the modelling assumptions related to the input used for the simulation are described.

5.5.3.1 Line Topology

The network layout is modelled in OpenTrack tool with a sequence of nodes and links.

Each edge is characterized by the following features:

- gradient (based on ATM plano-altimetric profile);
- no tunnel if is an outside edge;
- tunnel single smooth if is an inside tunnel edge;
- none information about curve radius;
- loop (flagged for all edges, to allow a continue communication between trains);

- overlap (flagged only for overlap edges);
- speed for train speed type and both directions, according to track speed profile.

The signals types used in OpenTrack, are:

- Main Signal;
- Stopping position.

5.5.3.2 Overlap

No overlaps are present.

5.5.3.3 Speed Profile

The speed profiles used for the Line M2 simulations allow the achievement of a maximum speed of 85 km/h.

The calculation of curve speed restrictions was evaluated by the following formula (Viganò, 2014):

$$V = 3{,}6\sqrt{\left(a_{nc} + \frac{h}{153}\right)R}$$

where:

- a_{nc} is the unmatched acceleration, assumed to be 1,00 m/s^2;
- h is the track cant deficiency;
- R is the radius of curvature.

Referring to the schematic plan of the line, the permissible speed on the switches was derived from the document (RFI, 1960) in Table 48.

Switch Type	Speed
S.60 UNI/170/0.12	38 km/h
S.60 UNI/250/0.12	46 km/h
S.60 UNI/250/0.092	46 km/h
S.60 UNI/400/0.094	60 km/h
S.60 UNI/400/0.074	60 km/h

Table 48 – Permissible Speed on Switch.

5.5.3.4 Rolling Stock

On the line there is only one type of rolling stock called Meneghino (Figure 308).

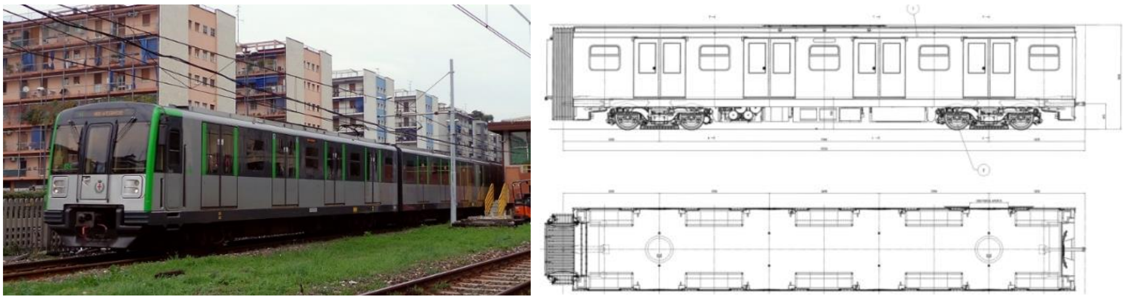


Figure 308 – Meneghino Train

The constructive and kinematic parameters of the trains are summarized in Table 49, Figure 309 and Figure 310. A maximum average deceleration of 1.0 m/s^2 has been used, that is, a braking without the aid of electric braking and in the absence of skids. All values are provided by ATM.

Parameter	Value
Load	293 t
Length	106 m
Max. Speed	90 km/h
Max. Tractive Effort	355 KN
Davis Formula (Air Resistance)	R = A + B*v + C*v2 (A = 3,300; B = 0,02422; C = 0,000552)
Resistance Factor (OT default value)	3,2999
Rotating Mass Factor (OT default value)	1,10
Adhesion (OT default value)	Normal (125%)
Engine	Electric Engine

Table 49 – Meneghino technical data.

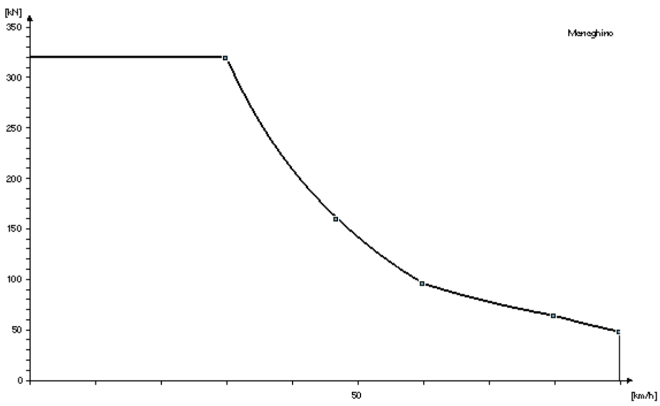


Figure 309 – Meneghino Traction Force.

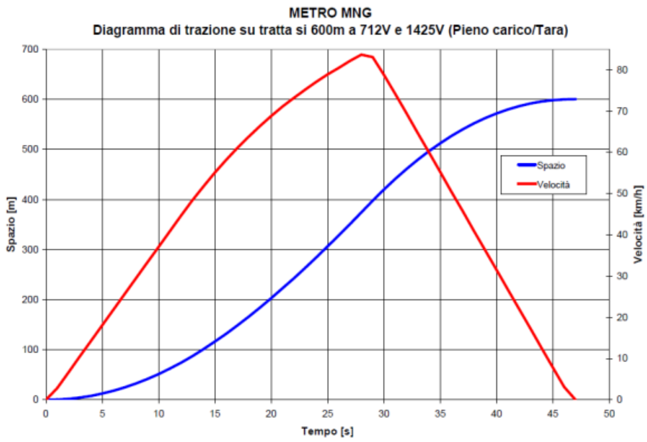


Figure 310 – Meneghino Traction Diagram.

5.5.3.1 CBTC Braking Curve

According to ATM requirements, all simulations shall be performed using the Comfort (C) braking curve with constant deceleration of -1 m/s^2.

The braking curves and stopping distances of the trainsets, provided by the ATM, are based on the normal adhesion conditions and in flat conditions (0% gradient); the simulations are also carried out on slopes (slope profile other than 0) with the same braking curves.

Simulations are performed using the gradient correction factor (Opentrack parameter). The value of the parameter is 0,01 $m/s^2/‰$.

5.5.3.2 Dwell Time

The dwell time at stations has been defined as the time required for loading and unloading passengers (Table 50).

Station	Dwell Time [s]	Station	Dwell Time [s]
Assago M. Forum	25	Udine	25
Assago M. Nord	25	Cimiano	40
Abbiategrasso	25	Crescenzago	25
Famagosta	25	C.na Gobba	25
Romolo	40	Cologno Sud	25
Porta Genova	40	Cologno Centro	25
S. Agostino	25	Cologno Nord	25
S. Ambrogio	25	Vimodrone	25
Cadorna FNM	40	C.na Burrona	25
Lanza	25	Cernusco S/N	25
Moscova	25	Villa Fiorita	25
Garibaldi FS	40	Cascina de' Pecchi	25
Gioia	40	Bussero	25
Centrale FS	40	Villa Pompea	25
Caiazzo	25	Gorgonzola	25
Loreto	40	Cascina Antonietta	25
Piola	40	Gessate	25
Lambrate FS	40		

Table 50 – Stations Dwell Time.

5.5.3.3 Train Movements

Based on the schematic plan of the line, here below are reported the assumption made to perform the simulation:

- The simulation has been carried out assuming the full efficiency of the trains;
- Peak-time operation (maximum number of trains on line) has been simulated, therefore the limited routes to Cascina Gobba and Famagosta or the "soft" hour in which there are fewer trains on line have not been considered;
- For each terminal station, a sequence of the turnback manoeuvres that the trains have to carry out has been defined to be able to sort the incoming frequency and the restart from the platform;

- The sequence of the trains at the fork of Famagosta and Cascina Gobba in peak hours is alternated in the two divergent directions;
- The smaller length of the branches of Abbiategrasso and Cologno Nord than the branches of Assago Forum and Gessate, is compensated by the initial entry of trains with an additional delay so as to ensure the arrival of trains in order to comply with the headway defined for the mainline;
- At terminal stations:
    - trains departing from Cologno Nord (odd platform) arrive at Assago M. Forum (odd platform);
    - trains departing from Abbiategrasso (even platform) arrive at Gessate (even platform);
    - trains departing from Gessate (odd platform) arrive at Abbiategrasso (odd platform);
    - trains departing from Assago M. Forum (even platform) arrive in Cologno Nord. In this case, since the station is the subject of change bench at peak time, the arrival at the docks is alternating.
- The turnaround time at the terminal stations in the case of a single driver on board and with the automatic retrocession system (ATB) disabled, is at least 90 seconds;
- The turnaround time at the terminal stations in the case of automatic retrocession system (ATB) enabled, is at least 15 seconds;
- At the fork of C.na Gobba the trains directed to Gessate will pass on track 1, those directed to Cologno Nord on track 2. To Crescenzago the coming trains from Gessate and Cologno Nord will pass on track 3.

5.5.4. Metro Line 2 Simulation Results

The simulations were carried out in moving block mode (CBTC) evaluating the most critical points of the line, which was divided into the following different logs (Figure 311):

- Mainline;
- Terminal Station;
- Forks;
- Loop.

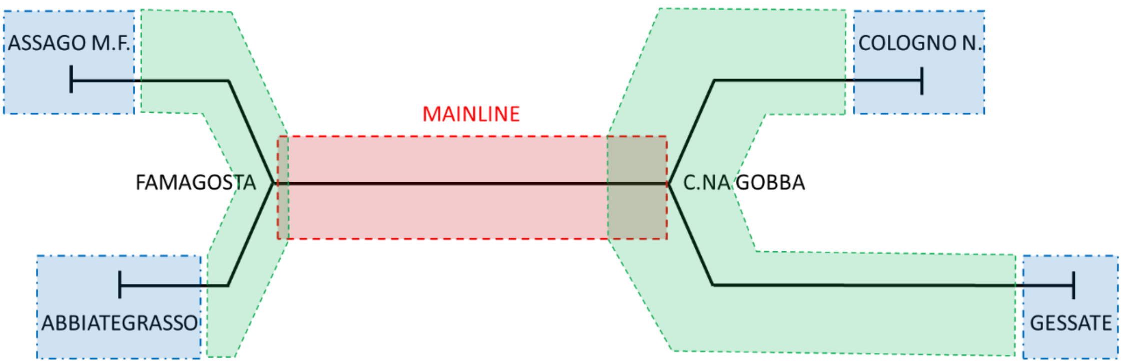


Figure 311 – Line 2 Simulation Steps Map.

5.5.4.1 Mainline

In this simulation, a single Meneghino train has been tested on the four basic routes (Assago Forum - Cologno Nord, Cologno Nord - Assago Forum, Abbiategrasso - Gessate, Gessate - Abbiategrasso) with the maximum speed of the 85km/h line. This simulation is useful to calculate the journey time of the four routes, the commercial speed and the train course without any kind of influence (this trend will be used to verify the possible disturbance caused by the insertion of additional trains).

Figure 312 and Figure 313 show the train graphs of the four train runs, while Figure 314, Figure 315, Figure 316, Figure 317 show the different running profiles, which allow you to understand the kinematics of the train and to identify the speed restrictions. Finally, in Figure 318, Figure 319, Figure 320 and Figure 321 it is possible to appreciate the minimum headway between pairs of trains that cover the different routes.

The simulations on the different routes generated the following data:

Interstation	Journey Time	Commercial Speed	Headway
Assago MF – Cologno N.	38min 49s	34,0 km/h	77 s
Cologno N. – Assago MF	38min 32s	34,4 km/h	78 s
Abbiategrasso – Gessate	49min 53s	36,0 km/h	77 s
Gessate – Abbiategrasso	49min 35s	36,6 km/h	78 s

Table 51 – Mainline Output.

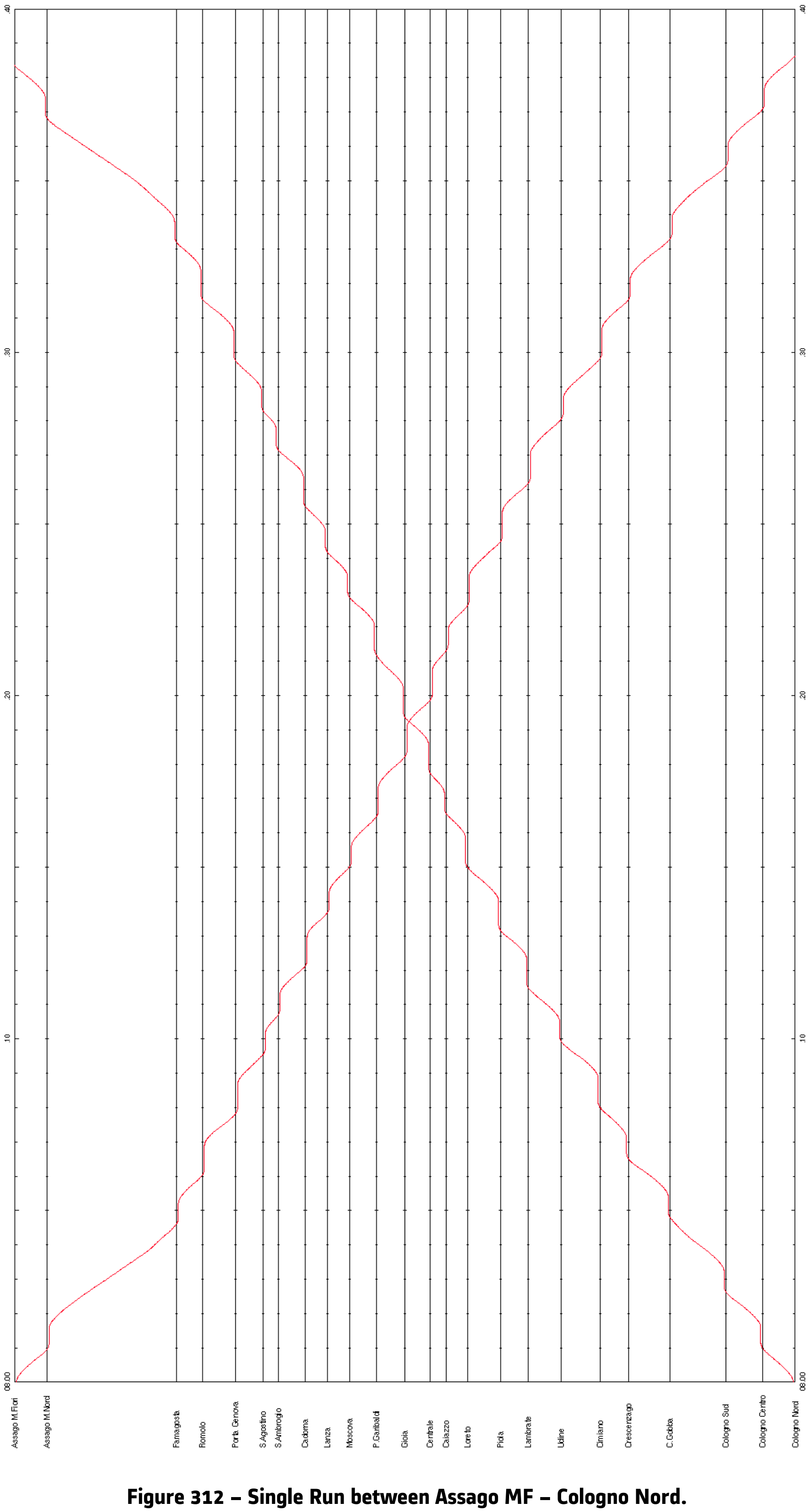


Figure 312 – Single Run between Assago MF – Cologno Nord.

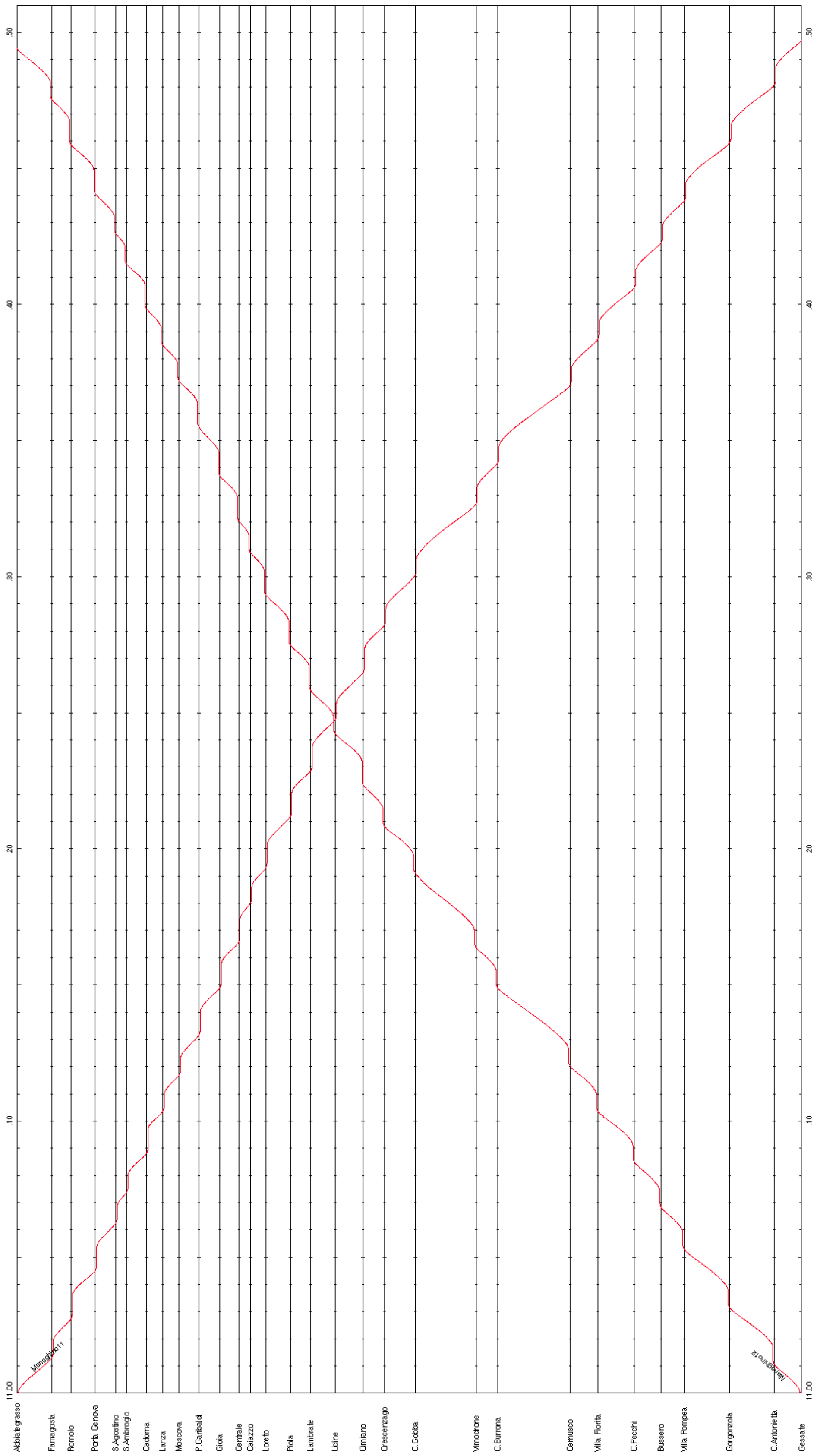


Figure 313 – Single Run between Abbiategrasso – Gessate.

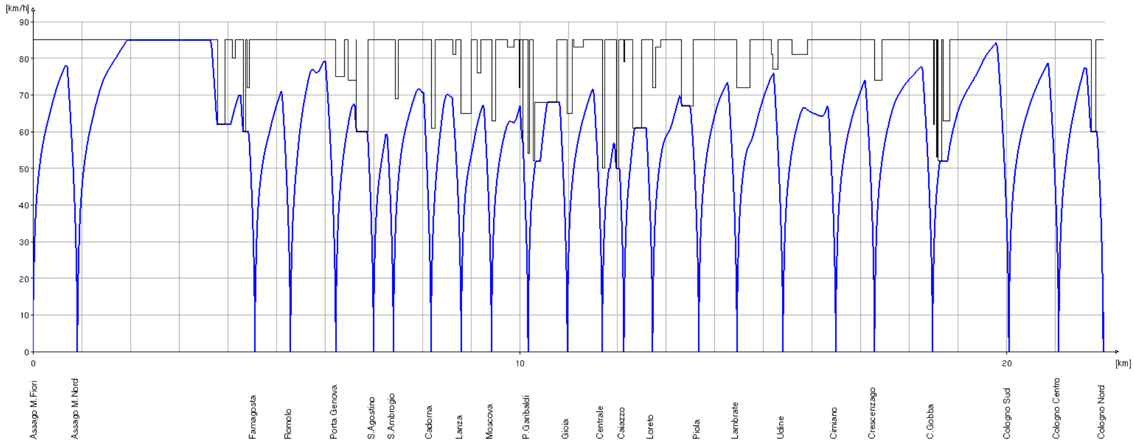


Figure 314 – Running profile between Assago MF – Cologno Nord.

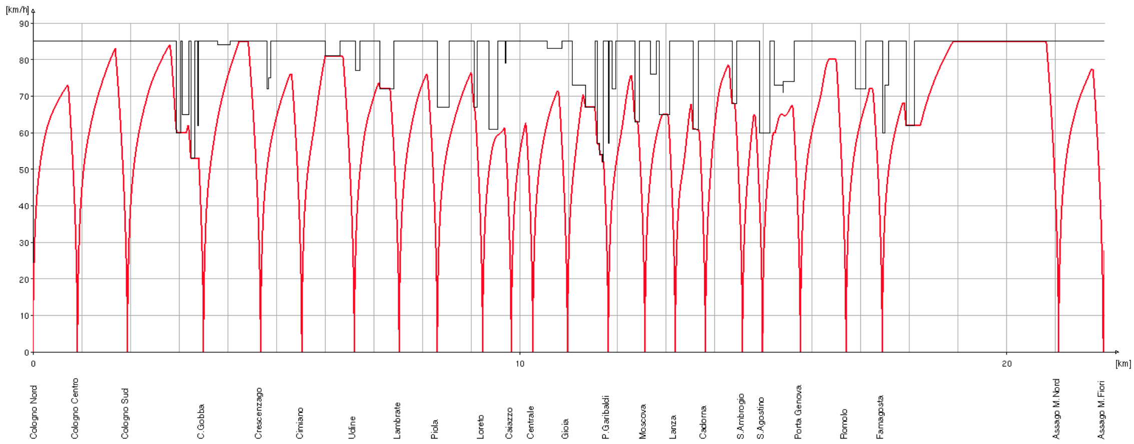


Figure 315 – Running Profile between Cologno Nord – Assago M.F.

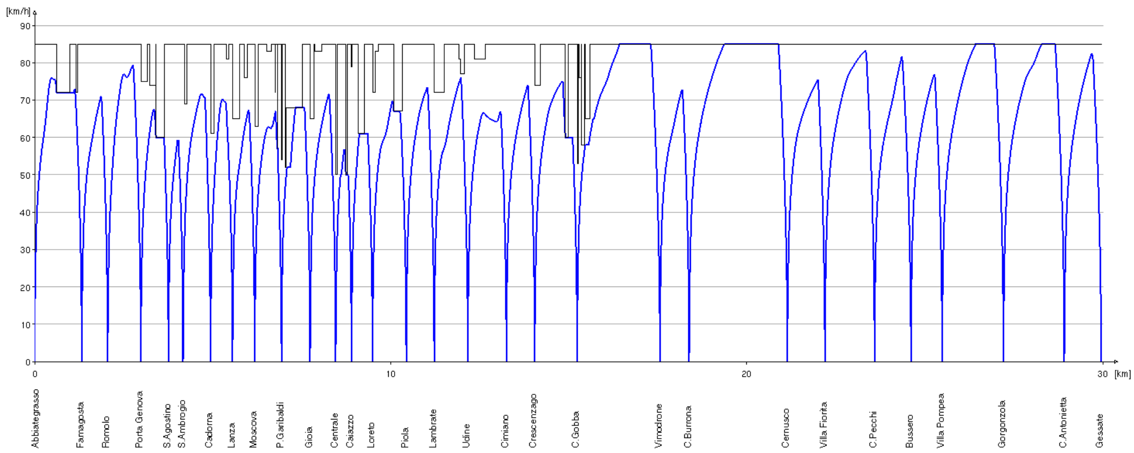


Figure 316 – Running Profile between Abbiategrasso – Gessate.

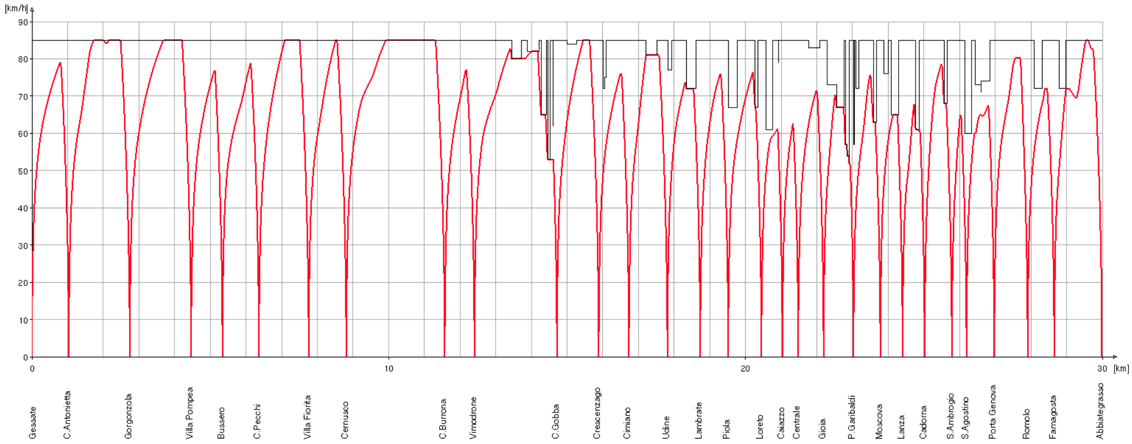


Figure 317 – Running Profile between Gessate – Abbiategrasso.

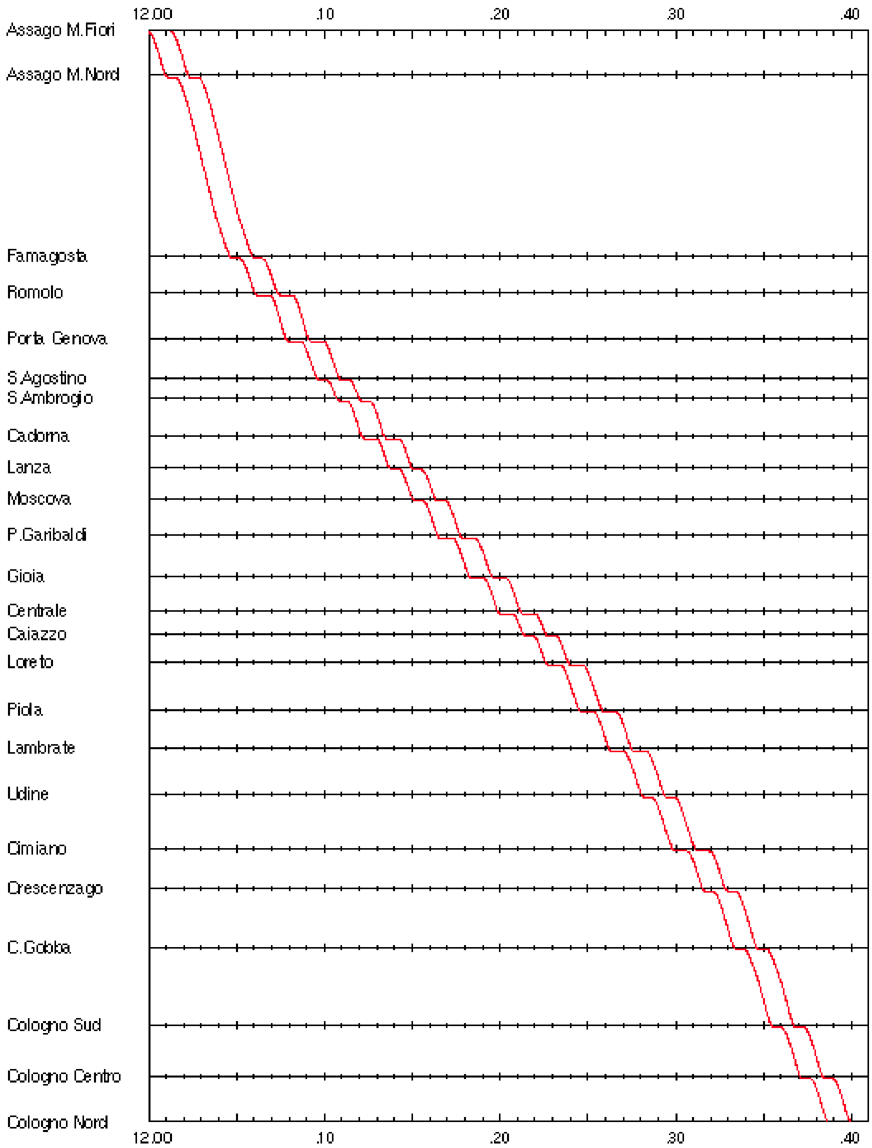


Figure 318 – Headway betwwen Assago MF – Cologno Nord.

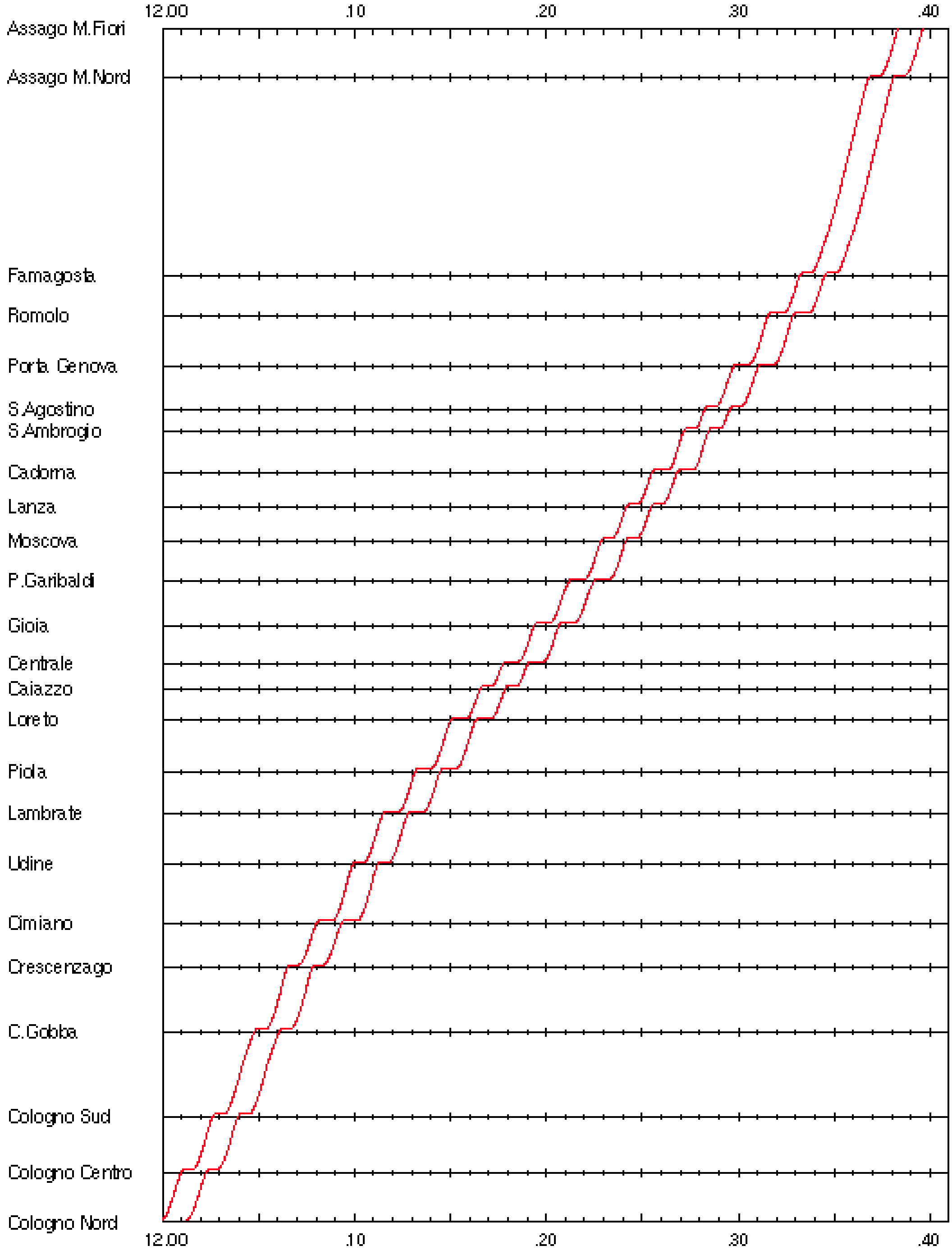


Figure 319 – Headway between Cologno Nord – Assago M.F.

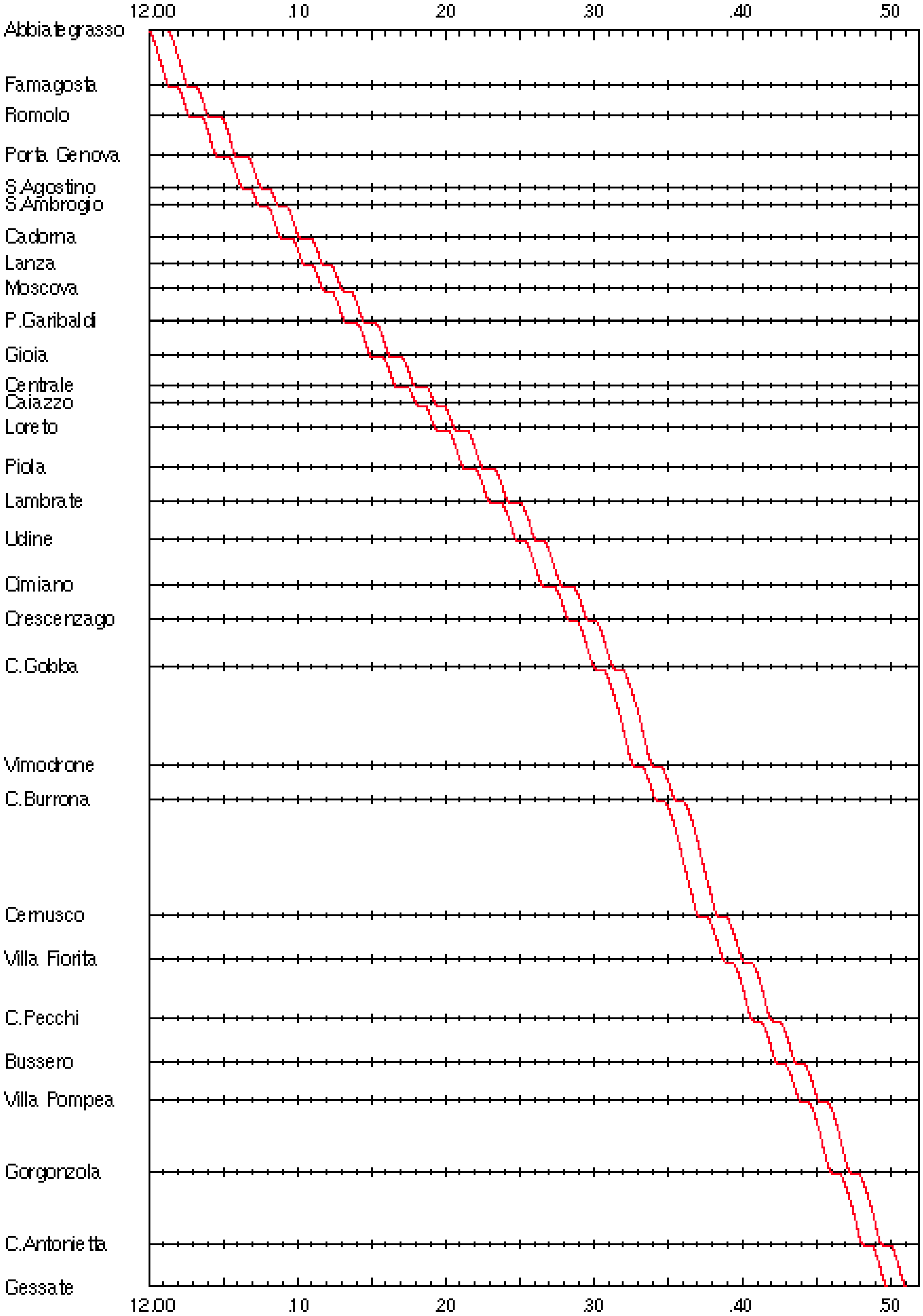


Figure 320 – Headway between Abbiategrasso – Gessate.

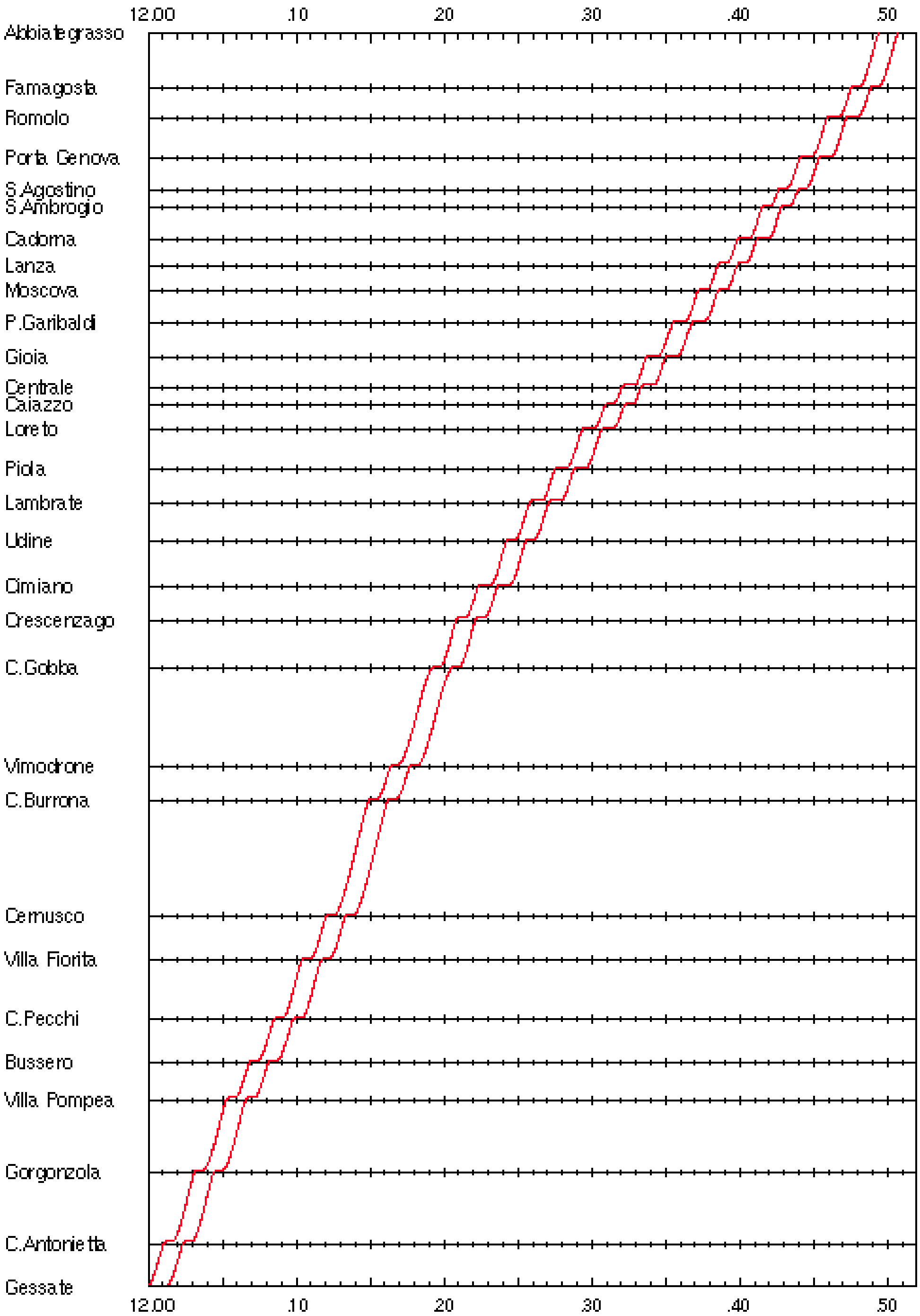


Figure 321 – Headway between Gessate – Abbiategrasso.

5.5.4.2 Famagosta Fork in diverging direction

Figure 322 shows the management of the Famagosta junction in the direction of Assago Nord and Abbiategrasso.

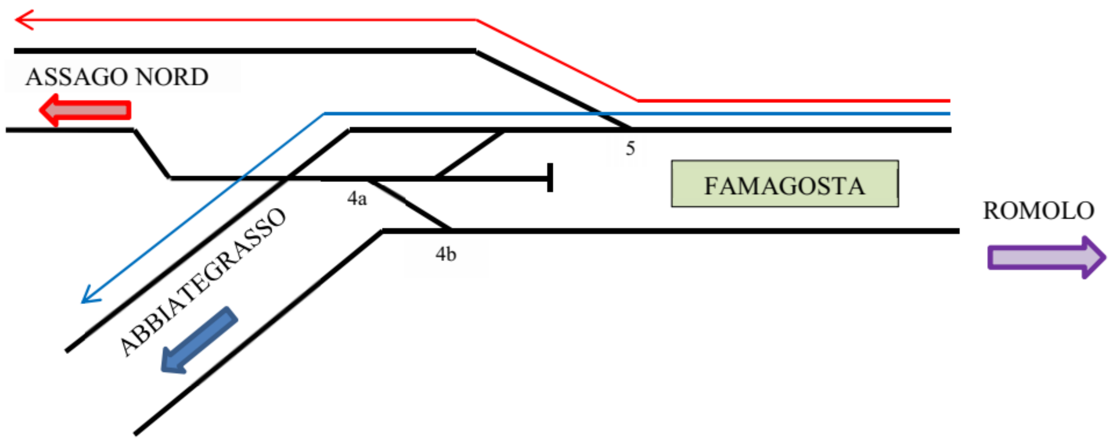


Figure 322 – Famagosta Fork: Diverging Configuration

In this simulation the operation of 8 Meneghino trains coming from Romolo has been tested, which are evenly distributed on the two main directions Assago M.F. and Abbiategrasso.

Considering the 78 s headway in the mainline, the Famagosta fork must be able to handle the incoming traffic. Figure 323 shows how the fork can manage the run of a train every 78 seconds, thus being a non-critical point of the infrastructure.

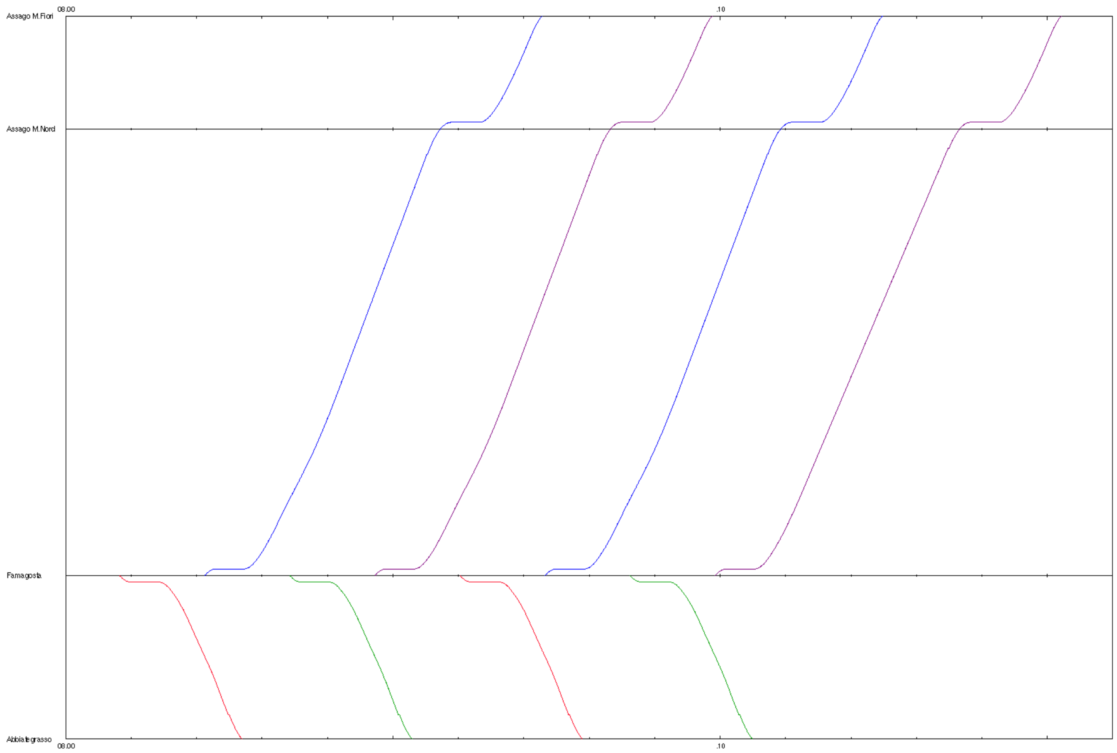


Figure 323 – Train Graph Famagosta Fork in Diverging Configuration.

5.5.4.3 Famagosta Fork in converging direction

Figure 324 shows the management of the Famagosta junction in the direction of Assago Nord and Abbiategrasso.

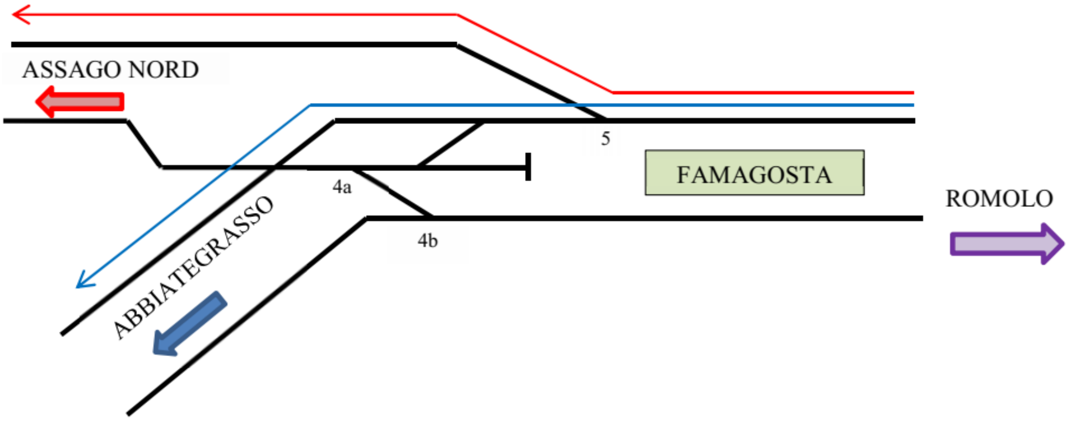


Figure 324 – Famagosta Fork: Converging Configuration

In this simulation the operation of 8 Meneghino trains from the line leaders of Assago and Abbiategrasso was tried out in order to meet the junction of Famagosta.

Considering the 78 s cadencing in the mainline, the Famagusta Junction must be able to handle the incoming traffic. Figure 325 shows how the junction can manage the passage of a train every 78 seconds, thus being a non-critical point of the infrastructure; In addition, to ensure this value in mainline it is necessary that trains depart reciprocally from their respective line heads with an offset of 199 s.

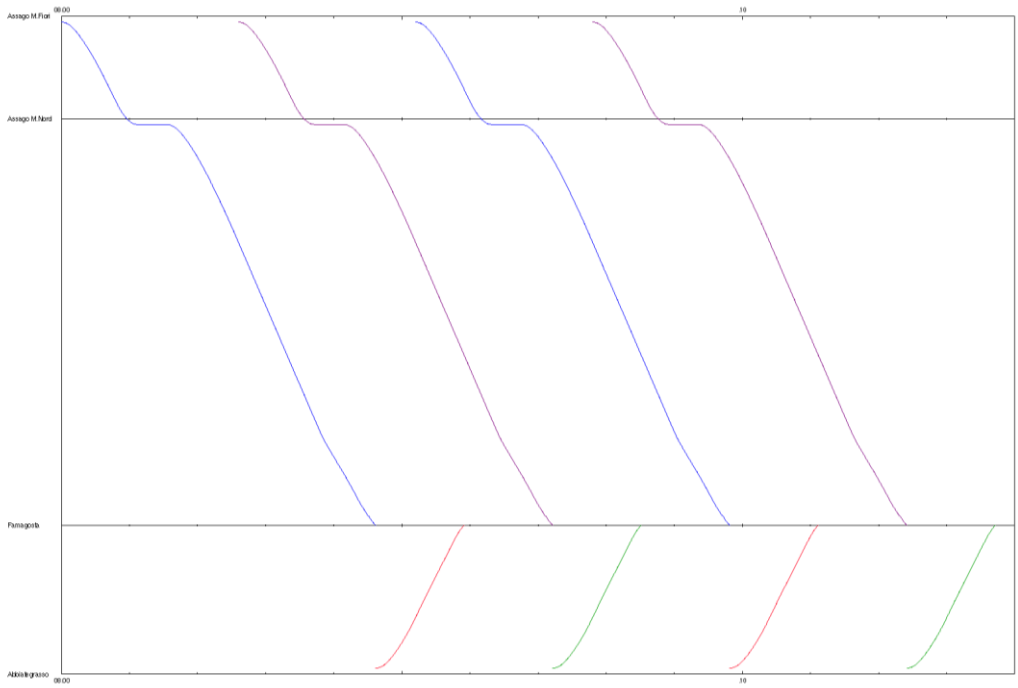


Figure 325 – Train Graph Famagosta Fork in Converging Configuration.

5.5.4.4 Cascina Gobba Fork in diverging direction

Figure 326 shows the management of the junction of C.na Gobba in the direction of Cologno and Gessate.

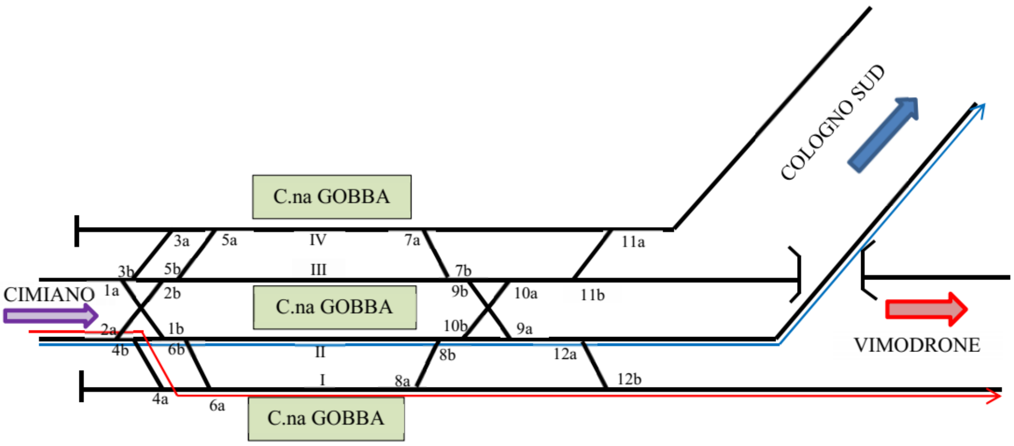


Figure 326 – Cascina Gobba Fork: Diverging Configuration

In this simulation, the operation of 8 Meneghino trains from Cimiano has been tested, which are evenly distributed over the two main directions Cologno and Gessate.

Considering the rate of 78 s in the mainline, the Cascina Gobba Junction must be able to handle the incoming traffic. Figure 327 shows how the junction can manage the passage of a train every 78 seconds, thus being a non-critical point of infrastructure.

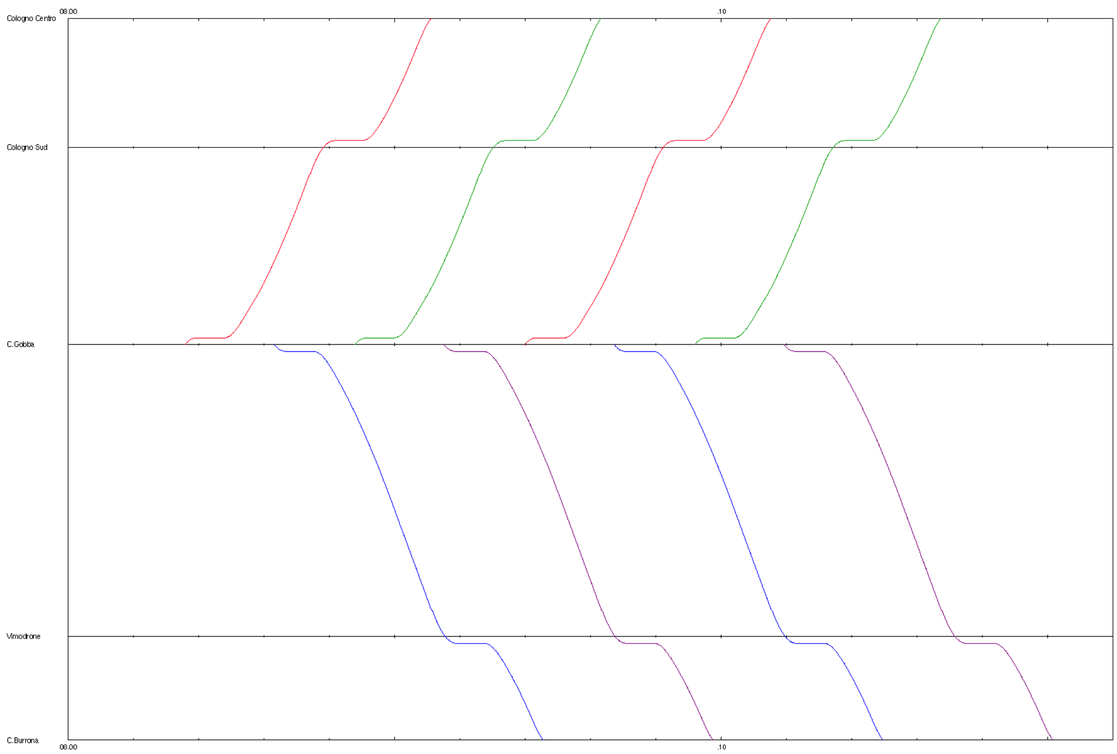


Figure 327 – Train Graph Cascina Gobba Fork in Diverging Configuration.

5.5.4.5 Cascina Gobba Fork in converging direction

Figure 328 shows the management of the junction of C.na Gobba in the converging direction, that is from the leaders of Cologno and Gessate towards C.na Gobba.

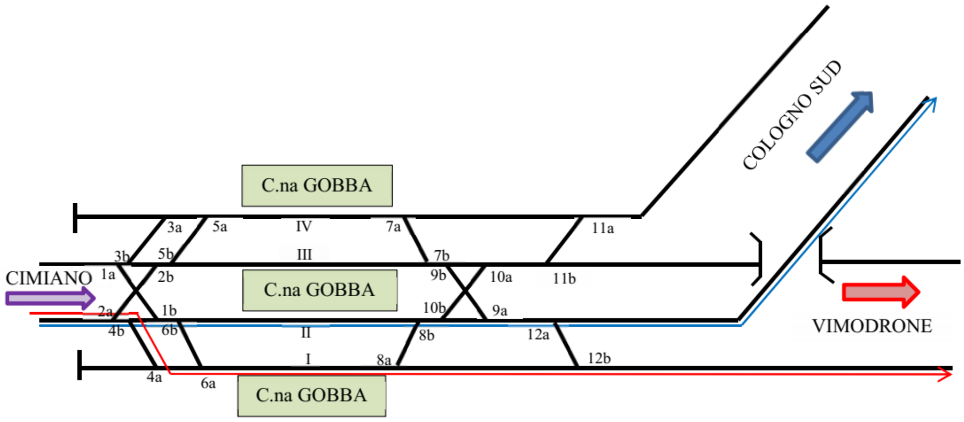


Figure 328 – Cascina Gobba Fork: Converging Configuration

In this simulation, the operation of 8 Meneghino trains from the Cologno and Gessate lines was tried and distributed equally in order to meet the junction of C.na Gobba.

Considering the 78 s cadencing in the mainline, the Famagusta Junction must be able to handle the incoming traffic. Figure 329 shows how the junction can manage the passage of a train every 78 seconds, thus being a non-critical point of the infrastructure; In addition, to ensure this value in mainline it is necessary that trains depart reciprocally from their respective line heads with an offset of 955 s.

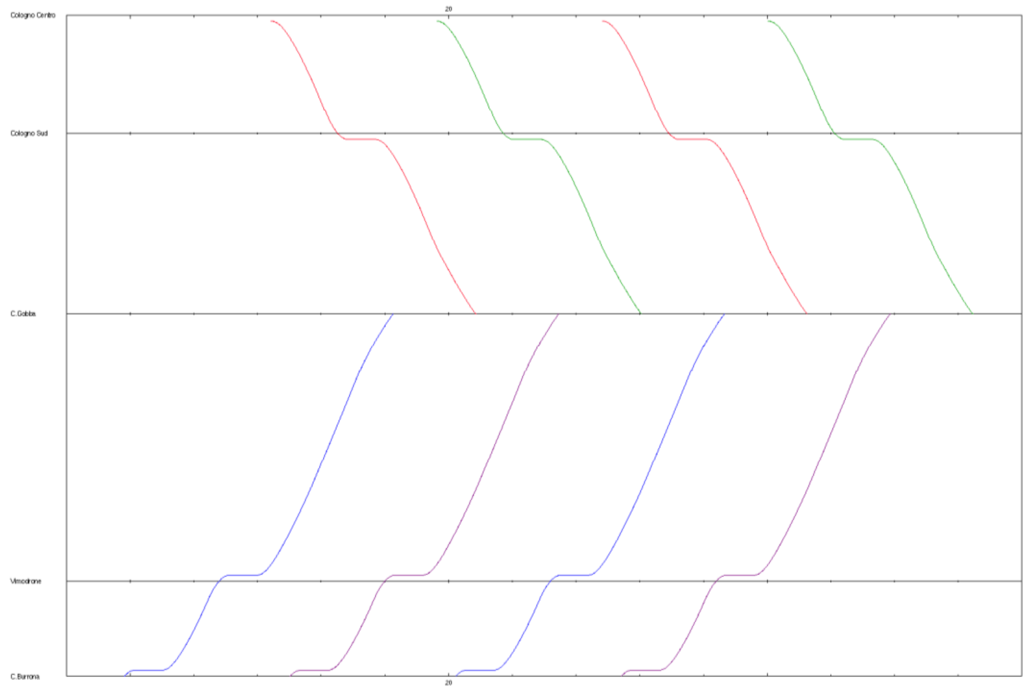


Figure 329 – Train Graph Cascina Gobba Fork in Converging Configuration.

5.5.4.6 Assago Milano Fiori Terminal Station

Figure 330 shows the management of Assago M.F.'s Terminus. In the following paragraphs, the different simulations in the Best Case scenario will be illustrated in both turnback configurations, with and without ATB system.

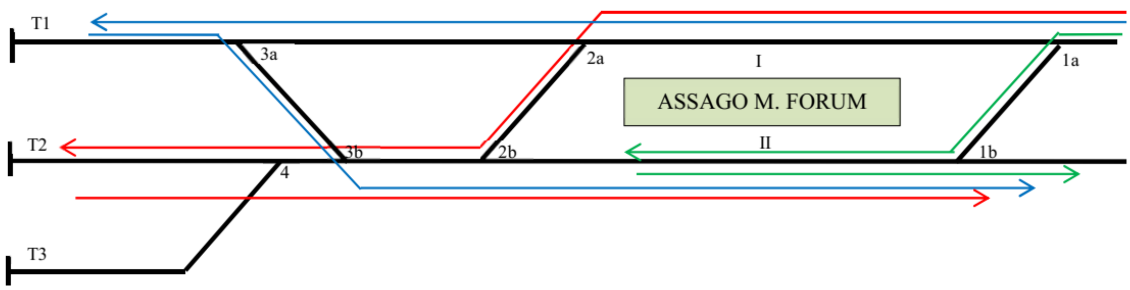


Figure 330 – Turnback in Assago M.F Station

With ATB enabled, to ensure the same headway in arrival and exit from the terminus, the dwell time at turnback will be respectively of 15 and 24 seconds. Considering the rate of 78 s in the mainline, then 156 s in the branches, the Assago terminal station is able to manage the incoming traffic as shown in Figure 331 thus resulting in a non-critical point of the infrastructure.

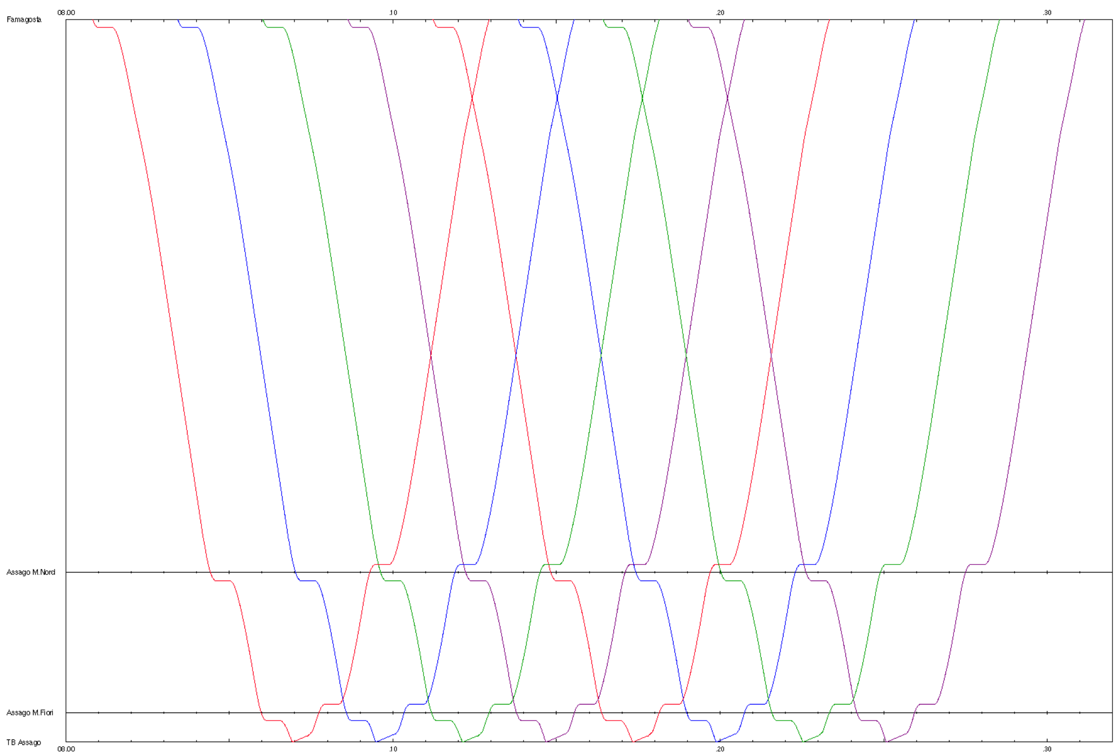


Figure 331 – Turnback in Assago with ATB enabled.

Without ATB, to ensure the same frequency in arrival and exit from the terminus, , the dwell time at turnback will be respectively of 90 and 99 seconds. Considering the rate of 78 s in the mainline, then 156 s in the branches, the Assago terminal station is able to manage the incoming traffic as shown in Figure 332 thus resulting in a non-critical point of the infrastructure.

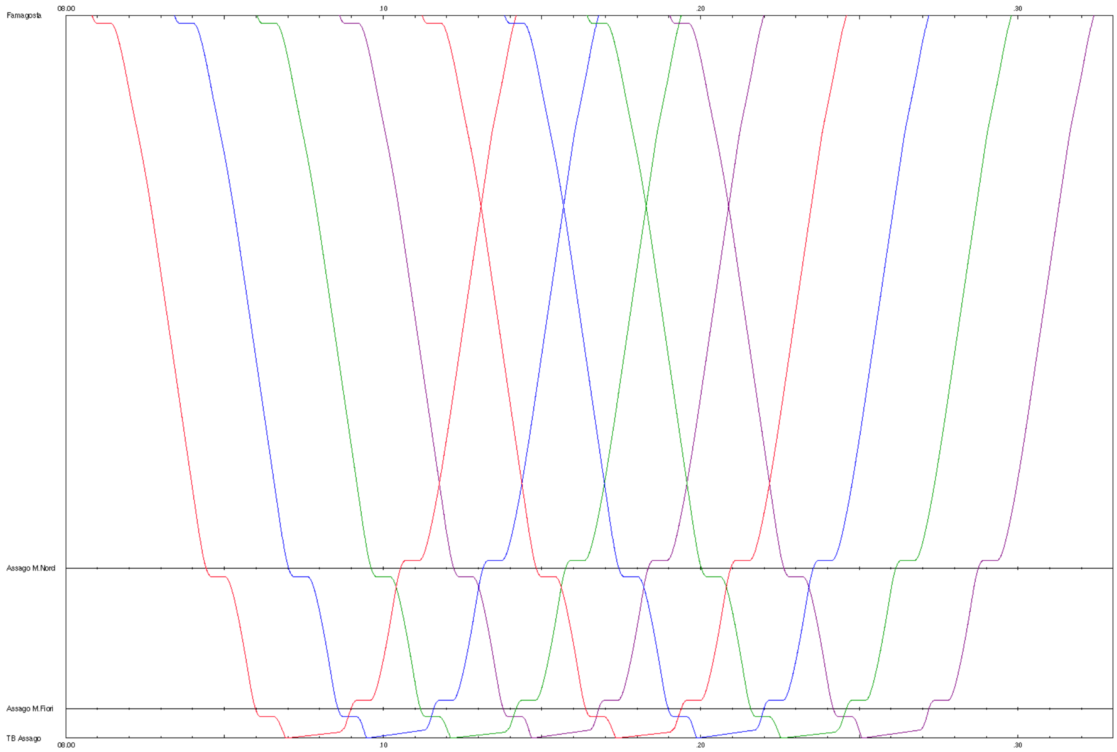


Figure 332 – Turnback in Assago with ATB disabled.

5.5.4.7 Abbiategrasso Terminal Station

Figure 333 shows the management of Abbiategrasso's Terminus. In the following paragraphs, the different simulations in the Best Case scenario will be illustrated in both turnback configurations, with and without ATB system.

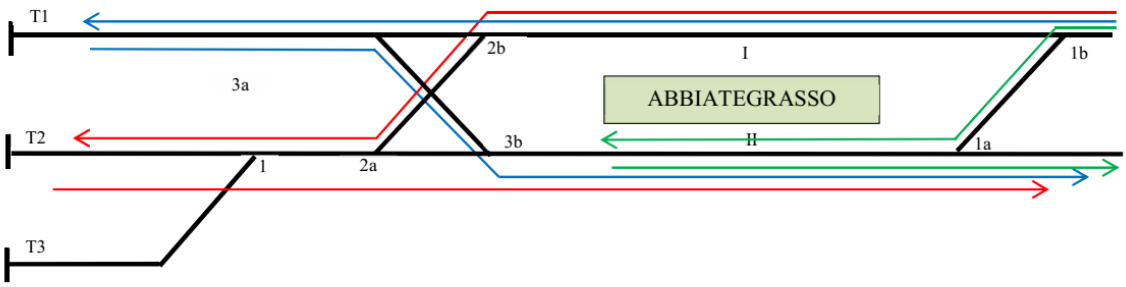


Figure 333 – Turnback in Abbiategrasso Station

With ATB enabled, to ensure the same headway in arrival and exit from the terminus, the dwell time at turnback will be respectively of 15 and 25 seconds. Considering the rate of 78 s in the mainline, then 156 s in the branches, the Abbiategrasso terminal station is able to manage the incoming traffic as shown in Figure 334 thus resulting in a non-critical point of the infrastructure.

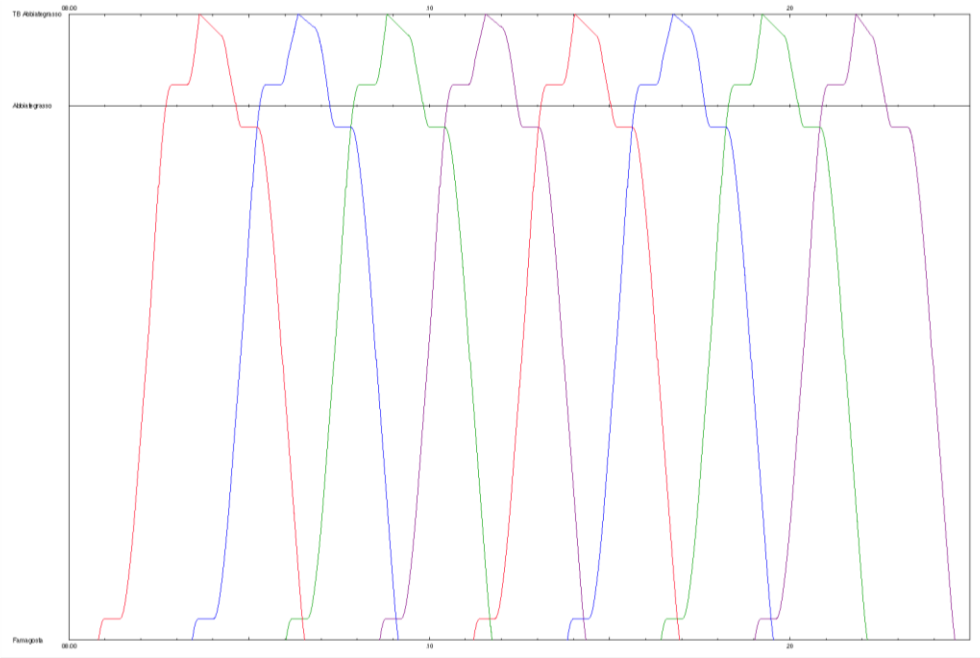


Figure 334 – Turnback in Abbiategrasso with ATB enabled.

Without ATB, to ensure the same frequency in arrival and exit from the terminus, , the dwell time at turnback will be respectively of 90 and 100 seconds. Considering the rate of 78 s in the mainline, then 156 s in the branches, the Abbiategrasso terminal station is able to manage the incoming traffic as shown in Figure 335 thus resulting in a non-critical point of the infrastructure.

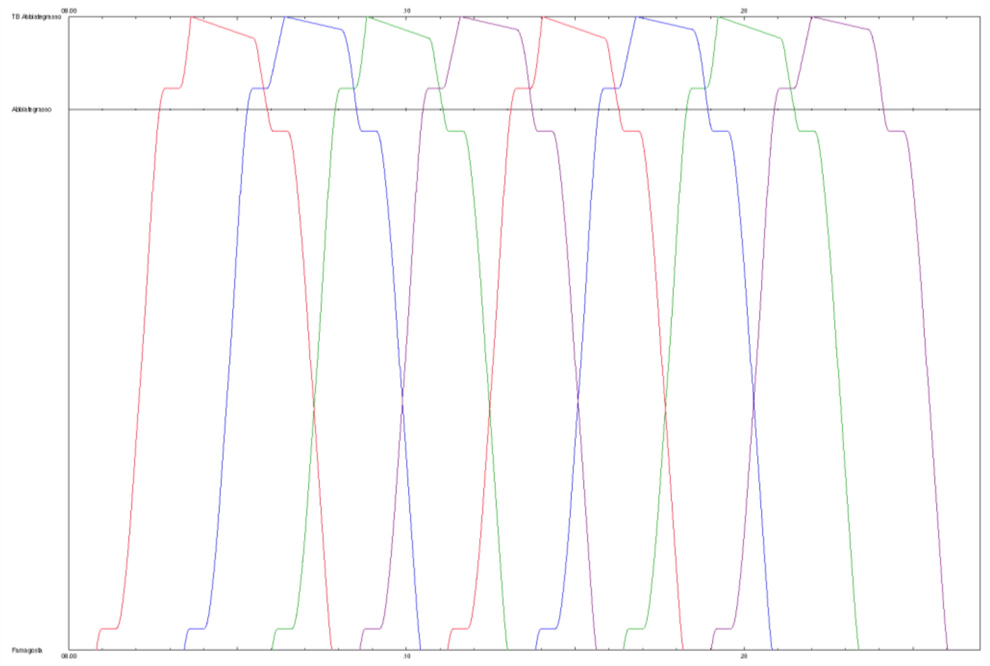


Figure 335 – Turnback in Abbiategrasso with ATB disabled.

5.5.4.8 Cologno Nord Terminal Station

Figure 336 shows the management of Cologno Nord's Terminus. In the following paragraphs, the different simulations in the Best Case scenario will be illustrated in both turnback configurations, with and without ATB system.

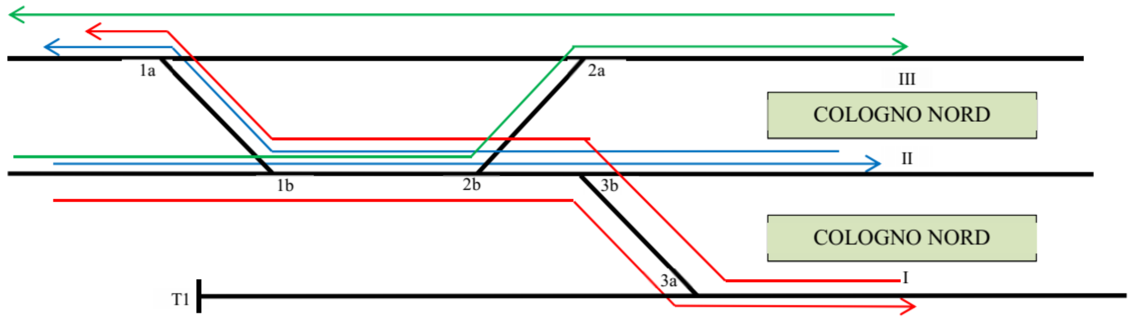


Figure 336 – Turnback in Cologno Nord Station

With ATB enabled, to ensure the same headway in arrival and exit from the terminus, the dwell time at turnback will be respectively of 15 and 16 seconds. Considering the rate of 78 s in the mainline, then 156 s in the branches, the Cologna Nord terminal station is able to manage the incoming traffic as shown in Figure 337 thus resulting in a non-critical point of the infrastructure.

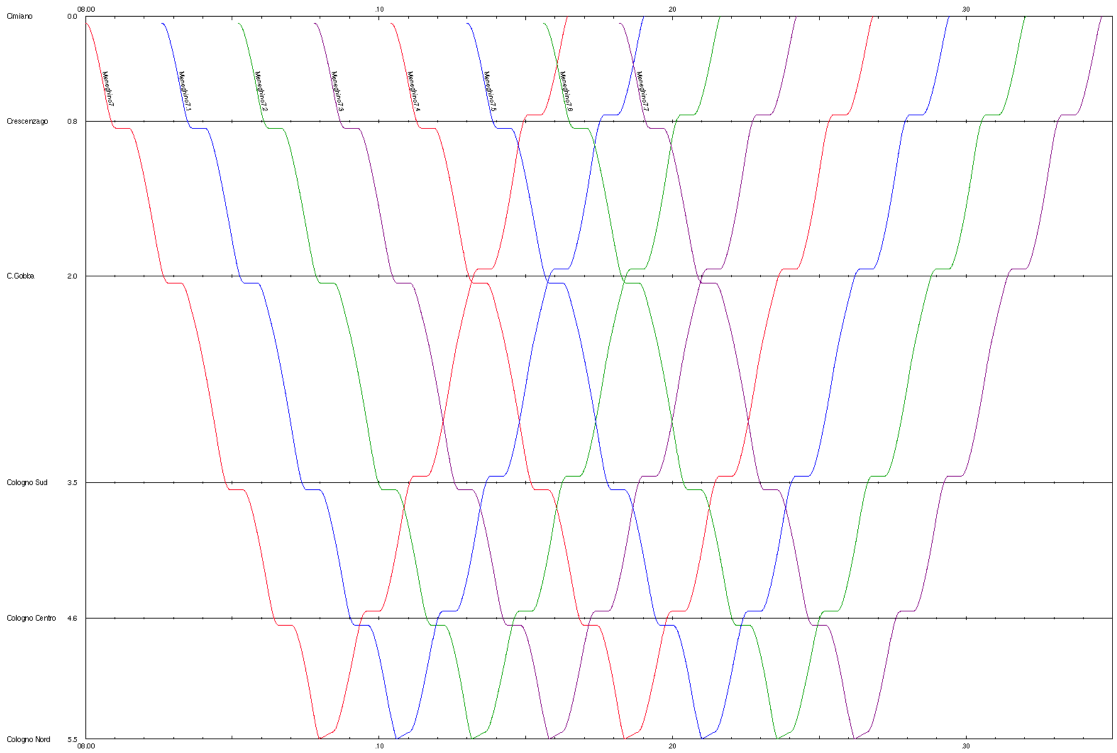


Figure 337 – Turnback in Cologno Nord with ATB enabled.

Without ATB, to ensure the same frequency in arrival and exit from the terminus, , the dwell time at turnback will be respectively of 90 and 91 seconds. Considering the rate of 78 s in the mainline, then

156 s in the branches, the Cologno Nord terminal station is able to manage the incoming traffic as shown in Figure 338 thus resulting in a non-critical point of the infrastructure.

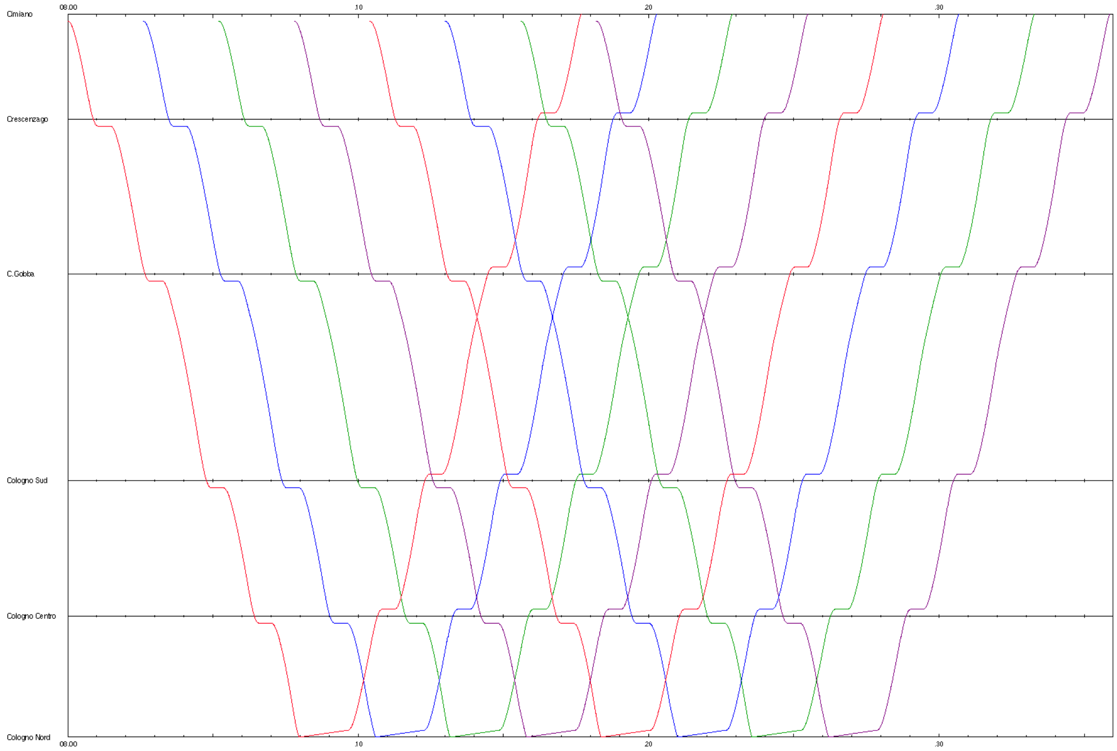


Figure 338 – Turnback in Colognpo Nord with ATB disabled.

5.5.4.9 Gessate Terminal Station

Figure 339 shows the management of Gessate's Terminus. In the following paragraphs, the different simulations in the Best Case scenario will be illustrated in both turnback configurations, with and without ATB system.

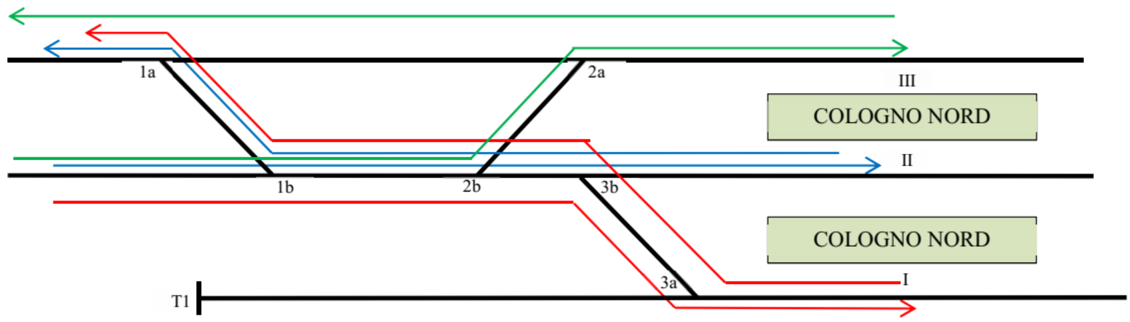


Figure 339 – Turnback in Gessate Station

With ATB enabled, to ensure the same headway in arrival and exit from the terminus, the dwell time at turnback will be respectively of 15 and 17 seconds. Considering the rate of 78 s in the mainline, then 156 s in the branches, the Gessate terminal station is able to manage the incoming traffic as shown in Figure 340 thus resulting in a non-critical point of the infrastructure.

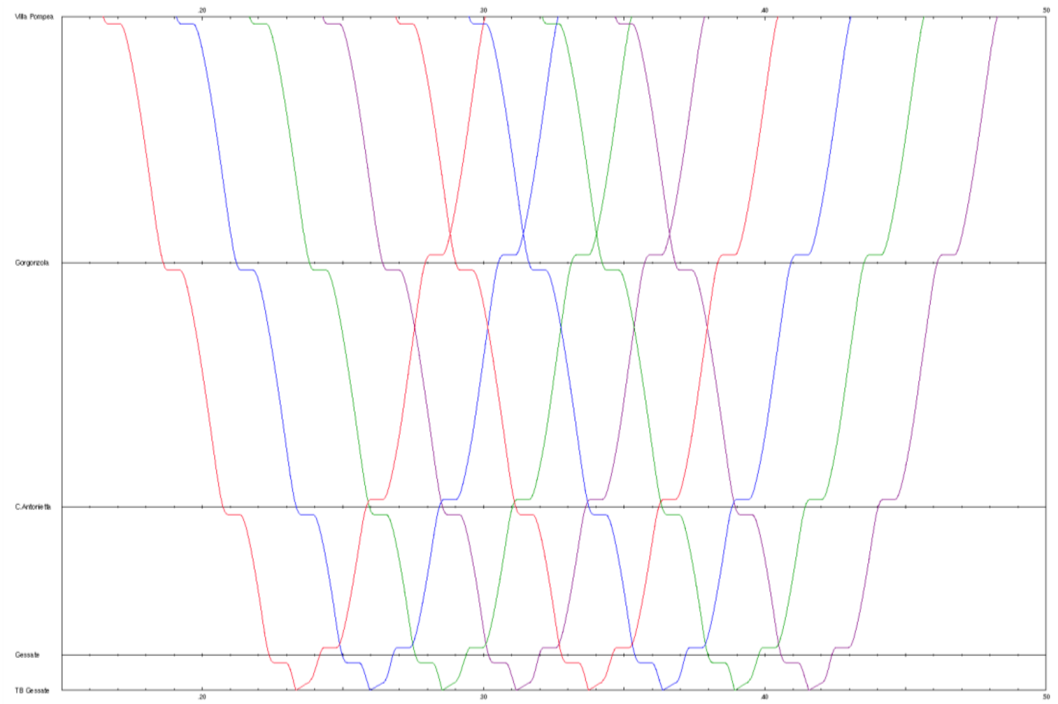


Figure 340 – Turnback in Gessate with ATB enabled.

Without ATB, to ensure the same frequency in arrival and exit from the terminus, , the dwell time at turnback will be respectively of 90 and 92 seconds. Considering the rate of 78 s in the mainline, then 156 s in the branches, the Gessate terminal station is able to manage the incoming traffic as shown in Figure 341 thus resulting in a non-critical point of the infrastructure.

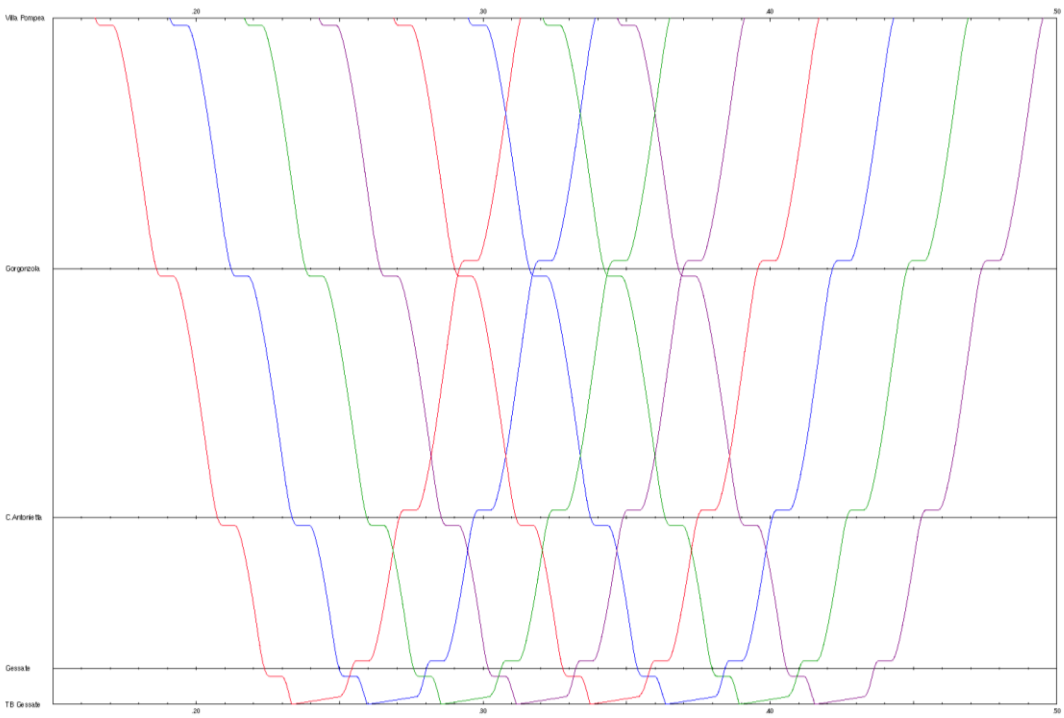


Figure 341 – Turnback in Gessate with ATB disabled (Best Case)

5.5.4.10 Loops

The following paragraph illustrates a simulation of the operation on the entire line in a time window of 3 hours (8:00 - 11:00) generated in order to evaluate the possible conflicts and the maximum number of trains running simultaneously.

In accordance with paragraph 5.5.3, assuming alternating turnback movements, 4 different loops have been identified:

- Loop 1: Assago M.F. Terminal T1 - Cologno N. even track (red line) (Figure 342);
- Loop 2: Abbiategrasso Terminal T1 - Gessate Terminal T2 (blue line) (Figure 342);
- Loop 3: Assago M.F. Terminal T2 - Cologno N. odd track (green line) (Figure 343);
- Loop 4: Abbiategrasso Terminal T2 - Gessate Terminal T1 (purple line) (Figure 343).

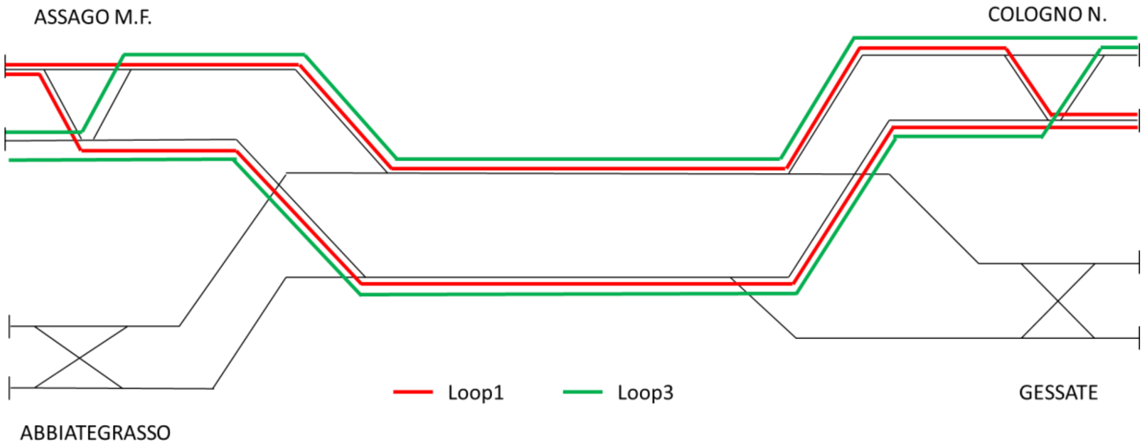


Figure 342 – Loop 1 and 3 between Assago M.F. – Cologno N.

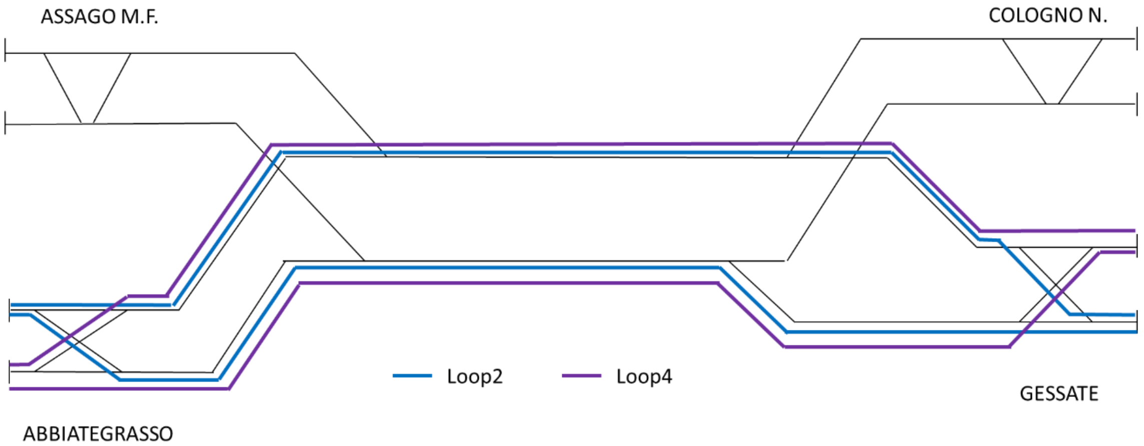


Figure 343 – Loop 3 and 4 between Abbiategrasso – Gessate.

The simulation has been successful as it can be noted that all trains maintain a headway of 78 seconds in all platforms. In addition, it appears that the trend of the first train is identical to that of the next, which shows that there is no interference between trains and/or disruption to their respective gears (Figure 344, Figure 345, Figure 346).

Journey times and commercial speeds are identical to single train simulation.

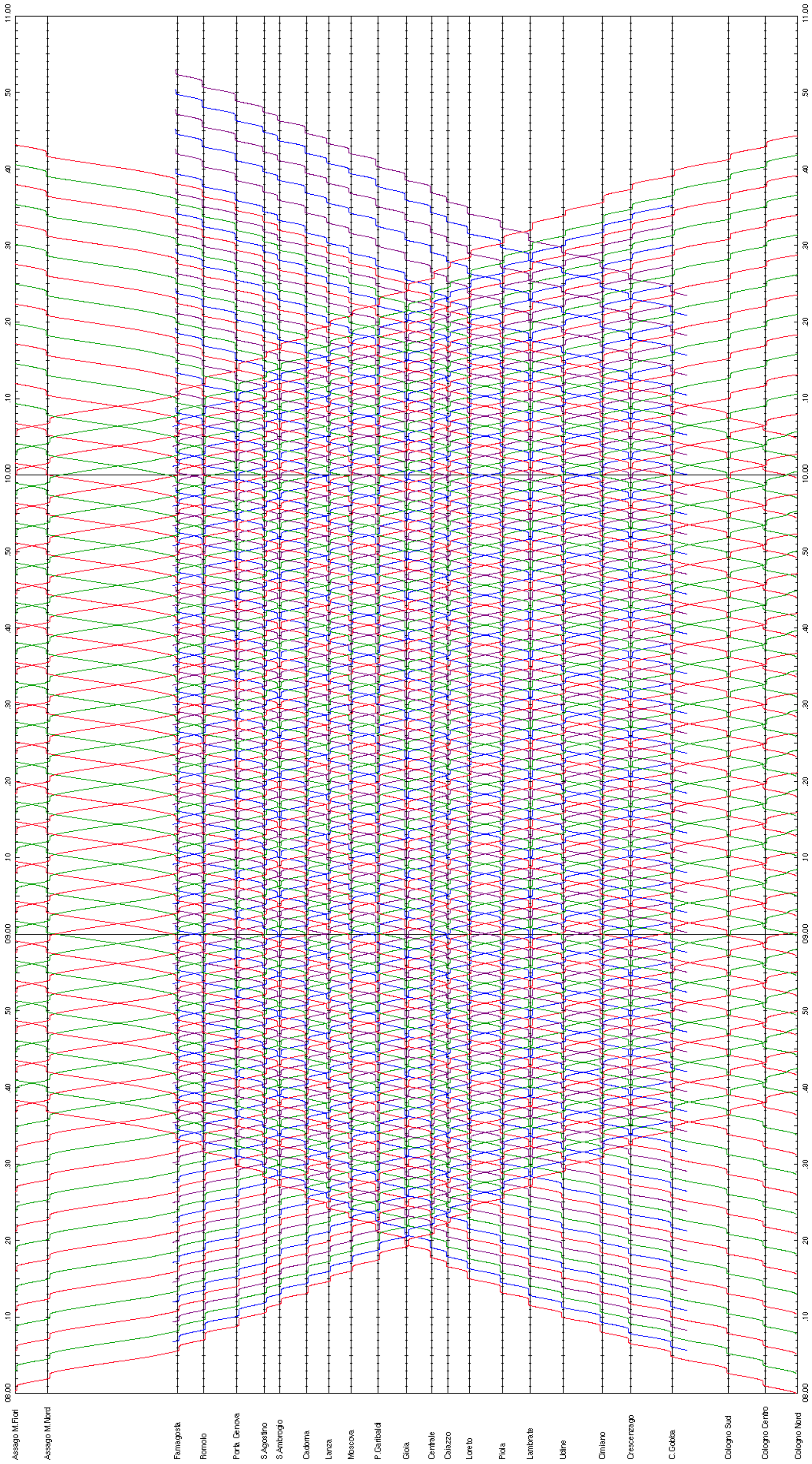


Figure 344 – Simulation Output between Assago M.F. – Cologno N.

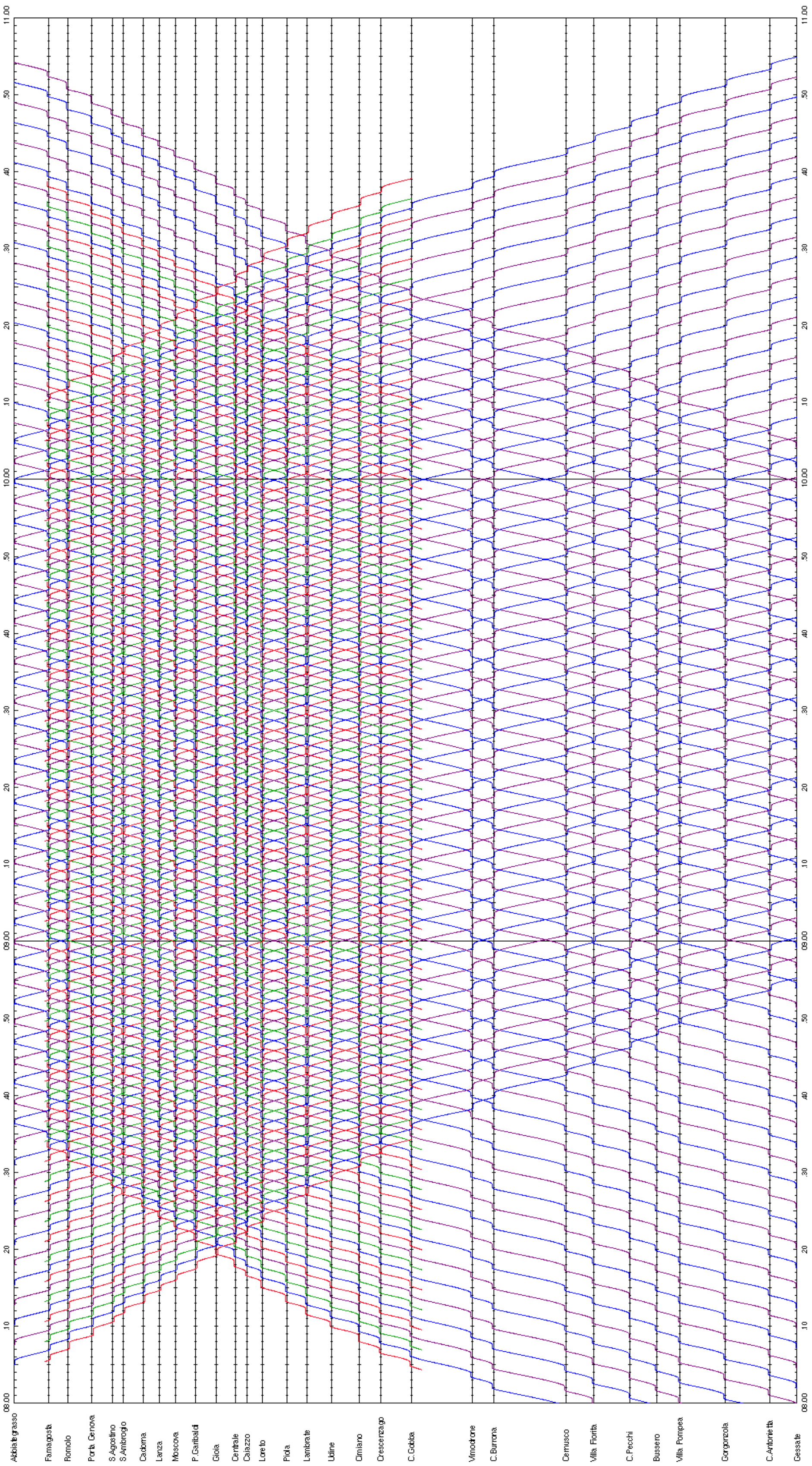


Figure 345 – Simulation Output between Abbiategrasso – Gessate.

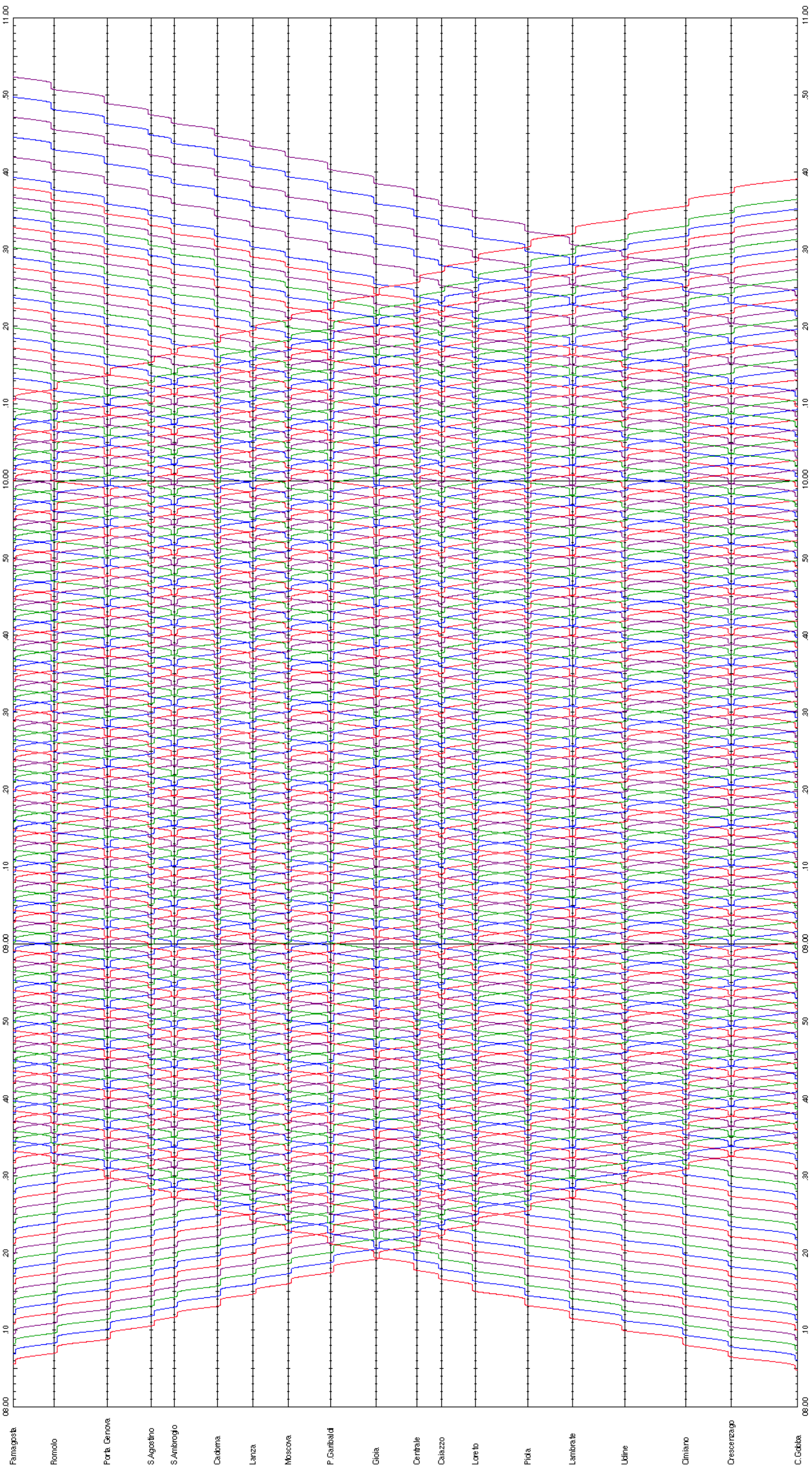


Figure 346 – Simulation Output between Famagosta – C.na Gobba.

5.5.5. Project Conclusion

Downstream of the simulations carried out, it can be definitively stated that the line can manage a headway of 78 seconds in the central section (Famagosta - Cascina Gobba) and 156 seconds in the 4 branches.

The train frequency allows the running of trains without any interference maintaining an average commercial speed (arithmetic average of commercial speeds on the 4 routes Assago Forum - Cologno Nord, Cologno Nord - Assago Forum, Abbiategrasso - Gessate, Gessate - Abbiategrasso) of 35,30 Km/h.

It is clear that the journey times of the 4 branches are different from each other so it will be the task of the ATS subsystem to manage departures from turnback to ensure spacing and a regular headway.

5.6 Node of Rome (Italy)

Metropolitan traffic scenario in the big hubs highlights simultaneously the need for specialized traffic flows and traffic promiscuity, for specific daily temporal slots. This requires the implementation of technical and functional integrations on current infrastructures and on their traffic control systems, which, safeguarding the characteristics of current traffic flows, implements an integrated system that allows to increase the traffic capacity inside big urban nodes and to obtain distance recoveries as a result of specific operational critical issues. The Italian Railway Infrastructure Manager has decided to satisfy the high capacity demand of railway traffic through the adoption of the High-Density European Traffic Management System (HD-ERTMS). The main characteristics of the system are:

- ETCS Baseline 3 optimized train braking curve with parameters sent from the ground equipment;
- Static Speed Profile (SSP) of diverging track managed in proximity of switch point instead of signals;
- Mixed traffic operation between ERTMS train (virtual subsection) and non-ERTMS train (real section);
- Parametrization of Interlocking (IXL) and Radio Block Center (RBC) timers for optimization of free track detection in exit itineraries with release speed maximizations;
- Configuration of the release speed calculated on board train on virtual sections;
- Virtual Block Sections optimization in line and station;
- Upgrading of GSM-R network and use of GPRS on ground and on board.

The strategy adopted to decongest the main urban nodes of the network must be applied with extreme caution considering the implementation and management complexity of the migration phase from the current signalling system to HD-ERTMS.

5.6.1. Scope of the Simulation

The aim of the simulation activities are the analysis of HD-ERTMS features and mode of operation, and the evaluation of benefits that can be gained from the implementation of this new signalling system in an urban node.

The HD-ERTMS system has been applied to the node of Rome in order to requalify its train spacing distancing system, superimposing the current lineside signaling system, that is the automatic block system with four codified currents, to the innovative HD- ERTMS system.

5.6.2. Node Overview

Different lines will be impacted by the installation of HD-ERTMS technology (Figure 347):

- Roma Casilina – Roma Ciampino (red line);
- Roma Tiburtina – Roma Monte Mario (blue line);
- Roma Monte Mario – Cesano di Roma (yellow line).

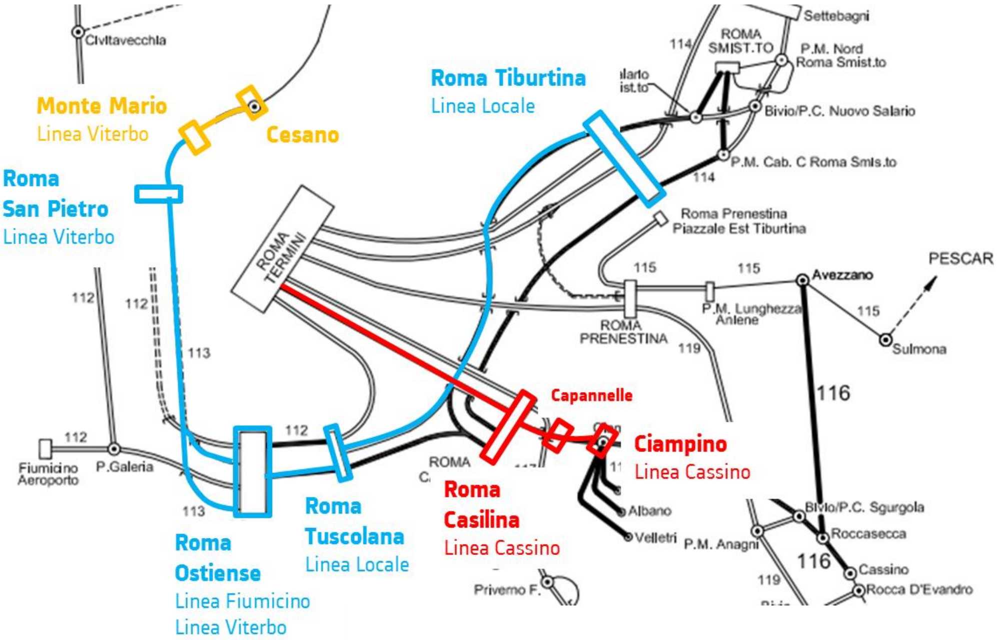


Figure 347 – Rome Node.

The traffic flow analysis has showed that the average number of daily running trains is equal to 394, subdivided in (Table 52):

- 188 trains in the Roma Casilina – Ciampino HD corridor;
- 206 trains in the Roma Tiburtina – Roma Ostiense – Roma Monte Mario HD corridor.

HD-ERTMS corridors	Train Type		
	Regional	Intercity	Freight
Casilina – Roma Ciampino	181 (96 %)	1 (1 %)	6 (3 %)
Tiburtina – Roma Monte Mario – Cesano	206 (100 %)	0	0

Table 52 – Traffic flows analysis.

Currently on the lines object of study there are the headways reported in Table 53.

Line	Odd Track	Even Track
Ostiense – Tiburtina	5’00’’	5’00’’
Ostiense - Cesano	5’00’’	4’00’’
Casilina – Roma Ciampino	5’00’’	5’00’’

Table 53 – Actual headway on different Rome urban corridors.

5.6.3. The Signalling System

A requalification of the train spacing distancing system is started in Rome railway node, in order to superimpose the HD-ERTMS system (L2) to the existing lateral signaling system (automatic block system with four codified currents).

Currently, in the node of Rome, there are lines with the following characteristic:

- line speed rank B;
- block sections of variable length between 900 and 1350 m;
- signals with yellow blinking aspects.

These characteristic changes the sequence of signal aspects and codes that the train can catch respect to the traditional case; here it is:

- code 270, which is associated with green aspects and means proceed without restrictions;
- code 180, which is associated with the signal, always looking green, which is located more than 2700 m from a red aspects signal. It relays a code 270 before the preceding signal;
- code 180, which is associated with the flashing yellow aspects, which is located less than 2700 m from a red aspect. It relays a code 180 before the preceding signal;
- code 75, which is associated with the yellow aspects. It precedes a section of occupied block in which no signal is picked up, identified with AC (absence code). The length of the section in which current coded is running with code 75 shall always be greater than or equal to 900 m;
- code AC, absence of code.

The presence of two yellow signals is due to the distance between the yellow signal and the red one; when the length of the block section is less than 1350 m the yellow signal must be repeated twice.

In this particular case, the minimum distance between the trains is therefore equal to $D = 4L + l$ where D is the distance between the trains, L is the length of the block section and l is the length of the train (Figure 348a).

The future line setup with the new HD-ERTMS system will include the definition of virtual sections, shorter of the existing block sections (Figure 348b), in agreement with the Italian Infrastructure owner in which every virtual section will have lengths in the range approximately from 350 to 450 m (Table 54) (Senesi et al., 2014).

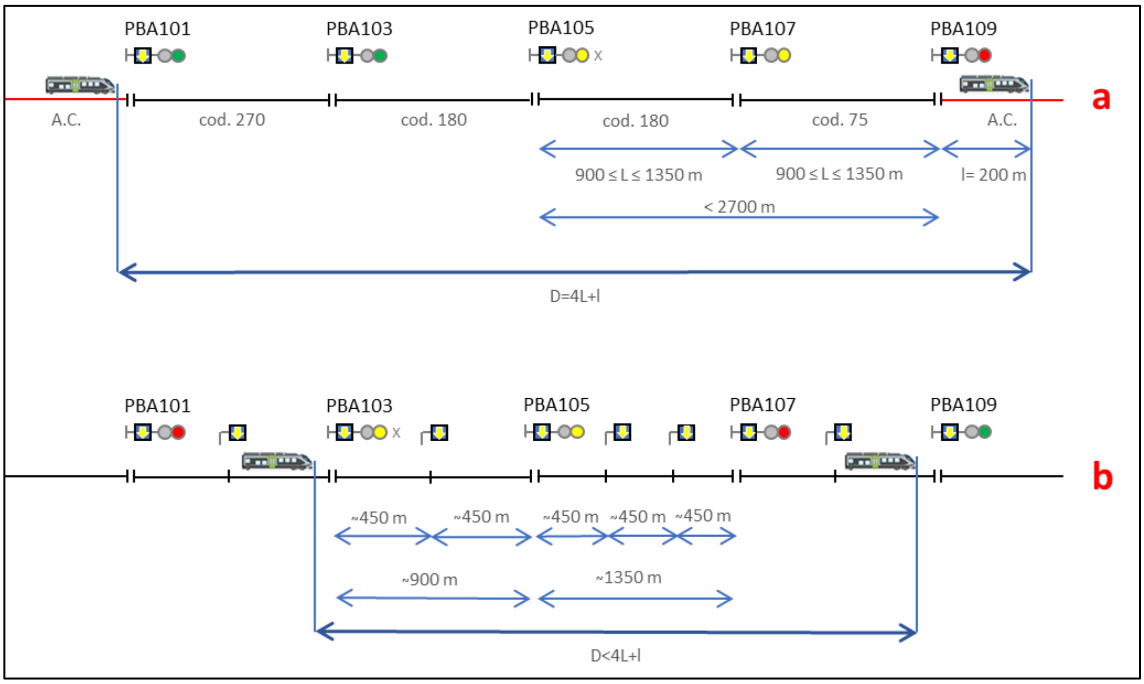


Figure 348 – Section length with traditional signalling system (a) and HD-ERTMS system in the node of Rome (b)

Section Length	Virtual section #1	Virtual section #2	Virtual section #3	Virtual section #4
700 m	350 m	350 m		
800 m	350 m	450 m		
900 m	450 m	450 m		
1050 m	350 m	350 m	350 m	
1150 m	350 m	350 m	450 m	
1250 m	350 m	450 m	450 m	
1350 m	450 m	450 m	450 m	
1400 m	350 m	350 m	350 m	350 m

Table 54 – Virtual section lengths.

The minimum distance between the trains (T_H) will be determined considering the various components of the Blocking Time Model relative to ERTMS L2 (Büker et al., 2019; Verkehrswisswnschaftliches Institut, 2008).

5.6.4. Simulation Model Assumption

Here below the modelling assumptions related to the input used for the simulation are described.

5.6.4.1 Line Topology

The network layout is modelled in OpenTrack tool with a sequence of nodes and links.

Each edge is characterized by the following features:

- gradient (based on ATC Diagram gradient profile);
- no tunnel if is an outside edge;
- tunnel single smooth if is an inside tunnel edge;
- none information about curve radius;
- loop/ Radio ETCS (flagged for all edges, to allow a continue communication between track and train);
- overlap (flagged only for overlap edges);
- speed for train speed type and both directions, according to track speed profile.

The signals types used in OpenTrack, are:

- Main/Distant Signal (home, block or exit signal for Marker Boards);
- Stopping position (stop head signal at platform for passenger train).

Each Marker Board, in OpenTrack, is set as track speed only (based on track speed profile).

Moreover in OpenTrack model all the edges are flagged with loop/ Radio (ETCS), and the rolling stocks are flagged with loop/ Radio telegram; this means that there is a continuous communication between track and train, each train is modelled with ETCS Braking deceleration value, that is applied to all the network.

5.6.4.2 Overlap

Overlap has been set as 20 m.

5.6.4.3 Speed Profile

Line speeds along HD corridors are derived from the RFI line dossier.

From the analysis, different speed profiles are identified for each corridor in Table 55, Table 56 and Table 57.

Velocità di linea (km/h)	Progressive chilometriche	Sistema di riferimento	Località di servizio
125	2+513	Ro Term.	Segnale di Protezione Casilina (PBA403)
	4+257	Ro Term.	Roma Casilina
150	4+257	Ro Term.	Roma Casilina
	13+000	Ro Term.	Cippo
110	13+000	Ro Term.	Cippo
	13+920	Ro Term.	Ciampino

Table 55 – Speed Profile: Roma Casilina – Capannelle - Ciampino

Velocità di linea (km/h)	Progressive chilometriche	Sistema di riferimento	Località di servizio
110	13+920	Ro Term.	Ciampino
	13+000	Ro Term.	Cippo
150	13+000	Ro Term.	Cippo
	4+257	Ro Term.	Roma Casilina
90	4+257	Ro Term.	Roma Casilina
	2+556	Ro Term.	Segnale di Uscita Casilina (PBA402)

Table 56 – Speed Profile: Ciampino – Capannelle – Roma Casilina

Velocità di linea (km/h)	Progressive chilometriche	Sistema di riferimento	Località di servizio
65	4+505	Ro Term.	Roma Tiburtina
	3+082	Ro Term.	Roma Tuscolana
70	6+692	Ro Term.	Roma Ostiense
	2+000	VT	Cippo
75	2+000	VT	Cippo
	4+280	VT	Roma San Pietro
70	4+280	VT	Roma San Pietro
	6+000	VT	Cippo
85	6+000	VT	Cippo
	20+000	VT	Cippo
95	20+000	VT	Cippo
	22+000	VT	Cippo
105	22+000	VT	Cippo
	25+000	VT	Cippo
90	25+000	VT	Cippo
	27+640	VT	Cesano di Roma

Table 57 – Speed Profile: Roma Tiburtina – Roma Ostiense – Cesano di Roma

5.6.4.4 Interlocking Routes

In addition to the infrastructure elements, interlocking routes are needed to model train runs. Due to the complexity of the infrastructure and the two superimposed signalling system, it is needed to distinguish two kind of element: the high-density section placed in line and the high-density itinerary located inside a station area. Both elements are defined from one signal to a following signal. Each of them is characterized by a different route setting time (reserve time) and a release time.

Route Setting time for HD Section

Sections can be defined as the following:

- HD section defined between real signal (PBA) and virtual signal (Marker Board);
- HD section defined between two virtual signals (Marker Board).

The route setting time calculation for HD section bounded by physical signal (PBA) and MB is described below (Figure 349).

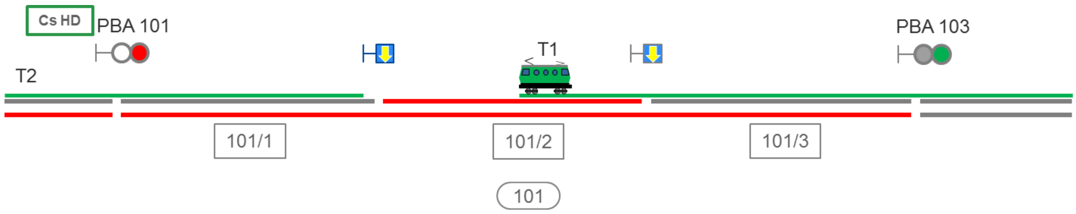


Figure 349 – Reserve Time for HD section bounded by physical signal (PBA) and MB.

Defined the 3 conditions leading to the generation of consent by RBC (Cs HD), such as:

- RBC detect PBA 101 at red aspect;
- Presence of a connected train upstream of PBA 101;
- The HD section downstream of PBA 101 is free (101/1);

and defined the instant t_0 as the instant of receiving the position report from the T_1 train, the time contributions from the t_0 moment for the extension of the MA on the HD 101/1 section for the T_2 train are:

- 0.5 second for position report processing by RBC and consent generation;
- 0.5 seconds for IXL processing and transmission time;
- 1.5 seconds for IXL that switches on the white “X” lamp of the signal PBA101;
- 1.5 seconds for acquisition of the control of the “X” of the PBA101 signal lamp in RBC;
- 1 seconds for RBC processing and transmission time;
- 2 seconds for GSMR transmission delay;
- 0.5 seconds for upgrade and extensions of MA onboard.

Summing all the contributions gives a value of 7.5 seconds, to which are added a further 2.5 seconds of tolerance, resulting in a final value of 10 seconds.

The route setting time calculation for HD section bounded by two virtual signal (MB) is described below (Figure 350).

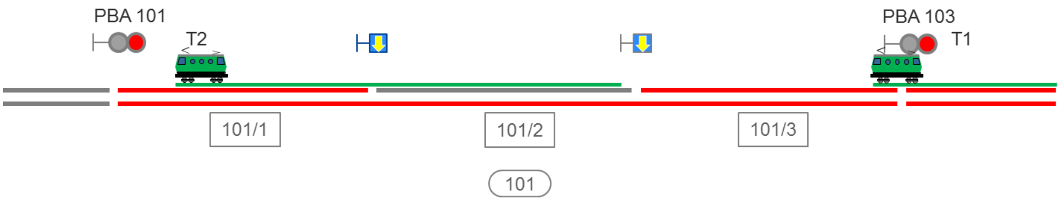


Figure 350 – Reserve Time for HD section bounded by two virtual signal (MB).

Defined the instant t_0 as the instant of receiving the position report from the T_1 train, the time contributions from the t_0 moment for the extension of the MA on the HD 101/2 section for the T_2 train are:

- 0.5 second for position report processing by RBC and consent generation;
- 2 seconds for GSMR transmission delay;
- 0.5 seconds for upgrade and extensions of MA onboard.

Summing all the contributions gives a value of 3 seconds, to which are added a further 1 second of tolerance, resulting in a final value of 4 seconds.

Route Setting time for HD Itinerary

Station itinerary can be defined as the following:

- HD itinerary defined between real signal (S01) and virtual signal (Marker Board):
  - with need for point movement;
  - without need for point movement;
- HD itinerary defined between two virtual signals (Marker Board):
  - with need for point movement;
  - without need for point movement.

The route setting time calculation related to the case of HD route delimited by physical signal (S01) and Marker Board is described below, assuming that it is in the case without a switch to be moved (Figure 351).

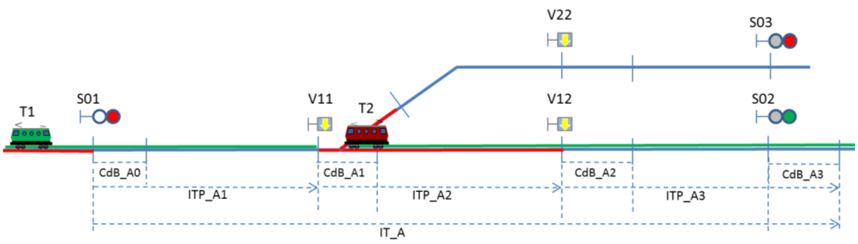


Figure 351 – Reserve Time for HD itinerary (ITP_A1) bounded by physical signal (S01) and MB.

Defined the instant t_0 as the instant in which the HD itinerary (ITP_A1) is free, the temporal contributors from the instant t_0 for the extension of the MA on the HD itinerary (ITP_A1) for the T_1 train are:

- 1.5 second for remote control processing and transmission (TBC);
- 3 seconds for HD itinerary creation by IXL (TBC) and transmission to RBC;
- 1 second for RBC processing and transmission time to IXL;
- 1.5 seconds for IXL that switches on the white "X" lamp of the signal PBA101;
- 1.5 seconds for acquisition of the control of the "X" of the PBA101 signal lamp in RBC;
- 1 seconds for RBC processing and transmission time;
- 2 seconds for GSMR transmission delay;
- 0.5 seconds for upgrade and extensions of MA onboard.

Summing all the contributions gives a value of 12 seconds, to which are added a further 3 seconds of tolerance, resulting in a final value of 15 seconds.

In the case of HD itinerary delimited by physical signal (S01) and Marker Board, with switches to be moved, the only contribution that is modified is the HD itinerary creation by IXL and transmission to RBC, which is assigned a time equal to 10 seconds, which includes the actual 4 seconds of movement of the switch.

The result is that the sum of all the contributions gives a value of 19 nominal seconds, to which are added a further 3 seconds of tolerance, obtaining a final value equal to 22 seconds.

The route setting time calculation related to the case of HD route delimited by two virtual signal (MB) is described below, assuming that it is in the case without a switch to be moved (Figure 352).

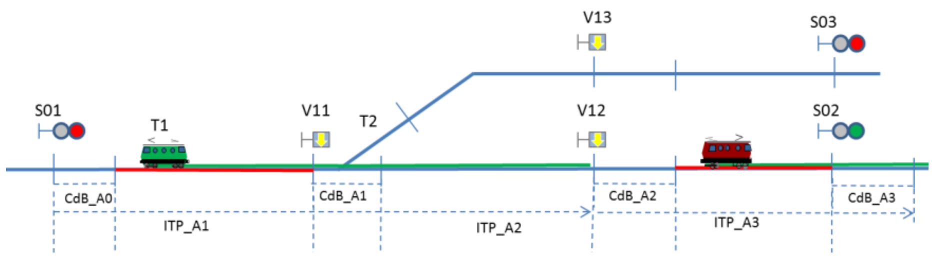


Figure 352 – Reserve Time for HD itinerary (ITP_A2) bounded by two virtual signal (MB).

Defined the instant t_0 as the instant in which the HD itinerary (ITP_A2) is free, the temporal contributors from the instant t_0 for the extension of the MA on the HD itinerary (ITP_A2) for the T_1 train are:

- 1.5 second for remote control processing and transmission (TBC);
- 3 seconds for HD itinerary creation by IXL (TBC) and transmission to RBC;
- 0.5 second for RBC processing and transmission;
- 2 seconds for GSMR transmission delay;
- 0.5 seconds for upgrade and extensions of MA onboard.

Summing all the contributions gives a value of 7.5 seconds, to which are added a further 1.5 seconds of tolerance, resulting in a final value of 9 seconds.

In the case of HD itinerary delimited by two virtual signals (MB), with switches to be moved, the only contribution that is modified is the HD itinerary creation by IXL and transmission to RBC, which is assigned a time equal to 10 seconds, which includes the actual 4 seconds of movement of the switch.

The result is that the sum of all the contributions gives a value of 14.5 nominal seconds, to which are added a further 1.5 seconds of tolerance, obtaining a final value equal to 16 seconds.

Route Release Time

The section clearing (based on release groups, according to signalling characteristics) is assumed in 5 seconds.

In Table 58 the system response times of route setting and release time of the described cases are synthesized.

	Section		**Itinerary**	
Route Setting Time (s)	PBA-MB	MB-MB	S01-MB	MB-MB
with point movement	\	\	15	9
without point movement	10	4	22	16
Release Time (s)	5	5	5	5

Table 58 – System response times.

5.6.4.5 Rolling Stock

The study area of the Rome node is almost entirely covered by a regional flow. For this reason, during the simulation phase it was decided to identify a regional train as representative train.

The train used for the simulations is a theoretical train with characteristics similar to the Coradia Meridian train (Figure 353).

Figure 353 – Coradia Meridian Train

The Coradia Meridian train, 200 m length, is composed by 2 trains sets coupled, each length 100 m. Table 59 reports the technical data.

Parameter	Value
Load	180 t
Adherence load (Not influence, covered by tractive effort / speed diagram)	90 t (50% of total weight)
Length	100 m
Max. Speed	160 km/h
Max. Tractive Effort	190 KN
Max. Acceleration	0,85 m/s²
Resistance Factor (OT default value)	3,2999
Rotating Mass Factor (OT default value)	1,06
Adhesion (OT default value)	Normal (125%)
Engine	Electric Engine

Table 59 – Coradia Meridian single train set data.

In Figure 354 the Coradia Meridian traction force diagram is shown.

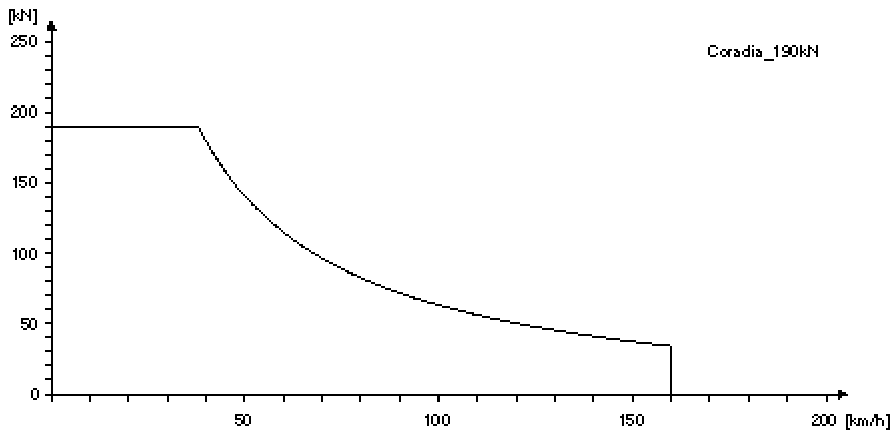


Figure 354 – Coradia Meridian Traction Force.

Considering the final composition of 2 train sets, Table 60 reports the Coradia Meridian train technical data.

Parameter	Value
Train Type	IC/ Fast Train
Load	360 t
Length	200 m
Davis Formula (Air Resistance)	R= A + B*v+ C*v^2 (A= 1,500; B= 0,0030; C= 0,00085)
Curve Resistance (Roeckl Formula)	Not Applied
Braked Weight Percentage (BWP)	135% (Not Relevant for Deceleration function Default ETCS)
Deceleration function	Default (ETCS)

Table 60 – Coradia Meridian technical data.

5.6.4.1 ETCS Braking Curve

In accordance to the RFI requirements, for the simulations the Indication braking curve was used, with overlap 20 m as it provides a more conservative results than overlap 50 m.

The braking curve has been calculated using the ERA braking curves tool v.3.0 (ERA, 2018), for lambda trains with a percentage braking mass (PMF) of 115, as per requirement.

The national values defined by RFI as values for the ETCS L2 system superimposed on the existing signalling system, defined in the Table 61, were inserted in the ERA model.

Description	Parameter	Value
Modification of adhesion factor by driver	Q_NVDRIVER_ADHES	Not allowed
Shunting mode speed limit	V_NVSHUNT	30km/h
Staff Responsible mode speed limit	V_NVSTFF	30km/h
On Sight mode speed limit	V_NVONSIGHT	30km/h
Limited Supervision mode speed limit	V_NVLIMSUPERV	150 km/h
Unfitted mode speed limit	V_NVUNFIT	0 km/h
Release Speed	V_NVREL	15 Km/h
Distance to be used in Roll Away protection, Reverse movement protection and Standstill supervision	D_NVROLL	2 m
Use service brake when braking to a target	Q_NVSRBKTRG	NO

Description	Parameter	Value
Permission to use service brake in target speed monitoring	Q_NVSBTSMPERM	NO
Permission to release emergency brake	Q_NVEMRRLS	Immediate release
Permission to use guidance curves	Q_NVGUIPERM	NO
Permission to use the service brake feedback	Q_NVSBFBPERM	NO
Permission to inhibit the compensation of the speed measurement inaccuracy	Q_NVINHSMICPERM	NO
Speed limit for triggering the override function	V_NVALLOWOVTRP	0 Km/h
Override speed limit to be supervised when the “override” function is active	V_NVSUPOVTRP	30 Km/h
Distance for train trip suppression when override function is triggered	D_NVOVTRP	200 m
Max. time for train trip suppression when override function is triggered	T_NVOVTRP	60 s
Change of driver ID permitted while running	M_NVDERUN	Yes
System reaction if radio channel monitoring time limit expires (T-Contact)	M_NVCONTACT	Service Brake
Maximum time since creation in the RBC of last received telegram.	T_NVCONTACT	7 sec
Distance to be allowed for reversing in Post Trip mode	D_NVPOTRP	20 m
Max permitted distance to run in Staff Responsible mode	D_NVSTFF	∞
Default location accuracy of a balise group	Q_NVLOCACC	5 m
Weighting factor for available wheel/rail adhesion	M_NVAVADH	0
Confidence level for emergency brake safe deceleration on dry rails	M_NVEBCL	99,9999999% (-9)
Train length step used for the integrated correction factor Kr_int	L_NVKRINT	0 m 25 m 50 m 100 m

Description	Parameter	Value
Train length dependent integrated correction factor Kr_int	M_NVKRINT*	0,70 0,80 0,95 1,00
Speed step used for the integrated correction factor Kv_int	V_NVKVINT	Passenger: 0 km/h 55 km/h 105 km/h Freight: 0 km/h 55 km/h 105 km/h
Speed dependent integrated correction factor Kv_int	M_NVKVINT*	Passenger: 0,68 0,72 0,74 Freight: 0,64 0,68 0,70
Integrated correction factor for brake build up time	M_NVKTINT	1
Maximum deceleration value under reduced adhesion conditions (1)	A_NVMAXREDADH1	1.0 m/s^2
Maximum deceleration value under reduced adhesion conditions (2)	A_NVMAXREDADH2	0.7 m/s^2
Maximum deceleration value under reduced adhesion conditions (3)	A_NVMAXREDADH3	0.7 m/s^2
Lower deceleration limit to determine the set of Kv_int to be used	A_NVP12	3.10 m/s^2
Upper deceleration limit to determine the set of Kv_int to be used	A_NVP23	3.15 m/s^2

Table 61 – Parameters used inside ERA Braking Tool.

To obtain simulations as close to reality as possible, it was decided to derive two different braking curves:

- Roma Casilina - Ciampino: from 143 km/h to 0 km/h, overlap 20 m (Figure 355);
- Rome Tiburtina - Ostiense - Cesano: from 80 to 0 km/h, overlap 20 m (Figure 356);

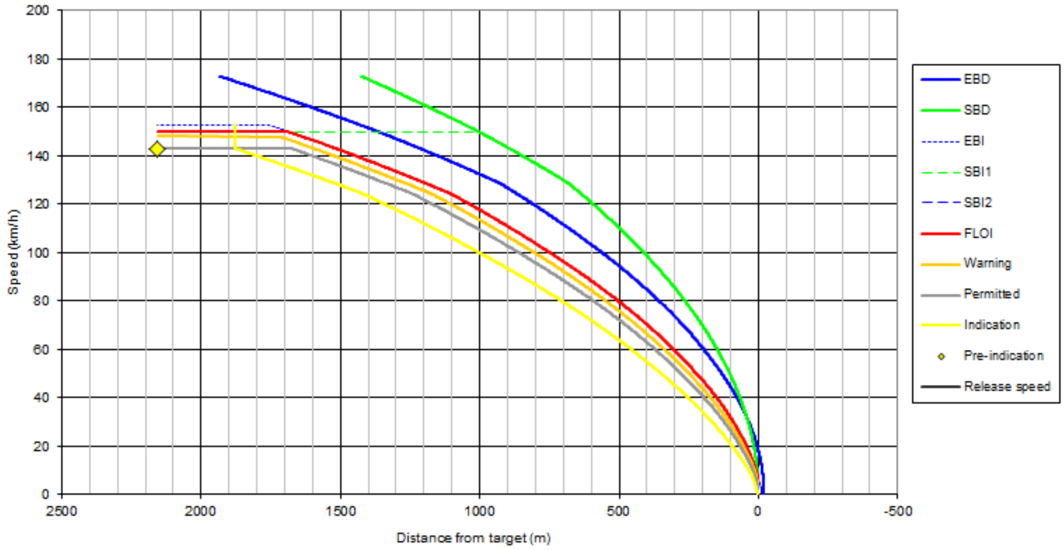


Figure 355 – Roma Casilina – Ciampino corridor braking curve, overlap 20 m.

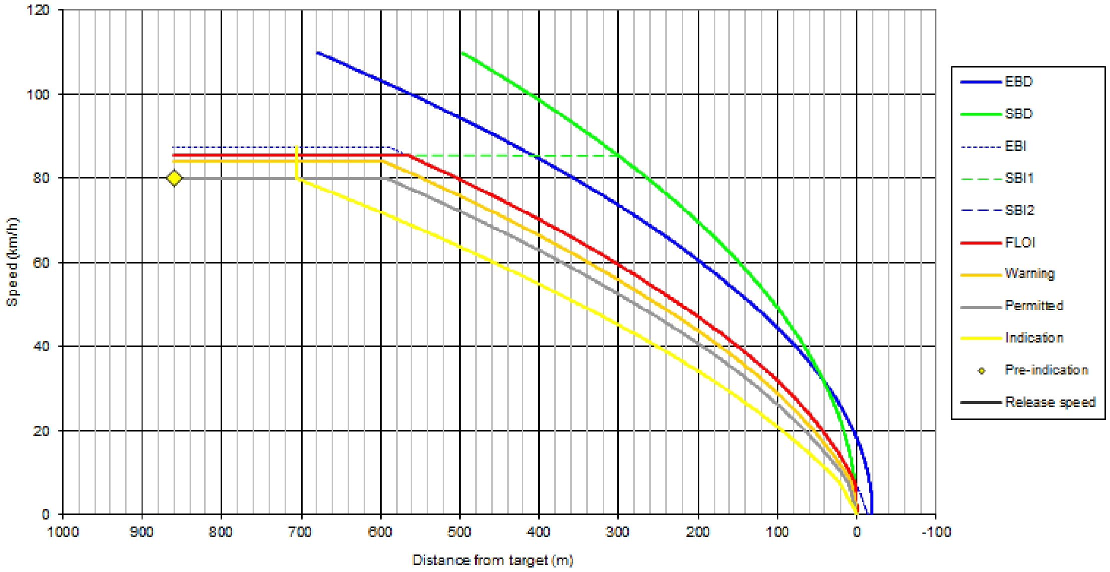


Figure 356 – Rome Tiburtina - Ostiense – Cesano corridor, overlap 20 m.

5.6.5. Headway Simulation Results

The line capacity has been analyzed applying the simulation methodology reported in Vignali et al. (2020). In this study it was not necessary to design the initial section of the line because it's an input data provided by the Italian Infrastructure manager (Table 54).

The following different configurations have been analyzed:

- Traditional Italian signalling system (BAcc) (Figure 357a);
- RFI HD Solution, that is the HD-ERTMS system suggested by the Italian railway infrastructure manager, with virtual block sections length reported in Table 1 (Figure 357b);
- HD Solution #1: following the previous configuration, this condition introduces an optimization of quantity and length of subsections. Sections equal or longer than 1350 m have been divided into three/four virtual sections, while sections between 900 and 1150 m have been divided into two/three virtual sections. Virtual sections are 450 to 500 meters long in both cases (Figure 357c);
- HD Solution #2: similar to HD Solution #1, the following configuration propose another sections layout. Sections equal or longer than 1350 m have been divided into four/five virtual sections, while sections between 900 and 1150 m have been divided into two/three virtual sections. For this layout, virtual sections are 300 to 400 meters long (Figure 357d);
- HD Solution #3: this solution is a combination of the previous ones designed to reduce the ratio between line impact factor (number of track equipment) and performances. Virtual sections length can change between 300 up to 700 meters long in both cases (Figure 357e).

Solution #1 and #2 are purely theoretical solutions, while Solution #3 is designed with the aim of reaching the same headway values of the previous solutions using the minimum number of virtual sections based on the simulations conducted, resulting in a decrease in the material to be installed.

For each solution, couple of chasing train, arrival/departure station track, type of service was defined to be able to compute the minimum achievable headway using as a reference the UIC Code 406 timetable compression method (UIC, 2013).

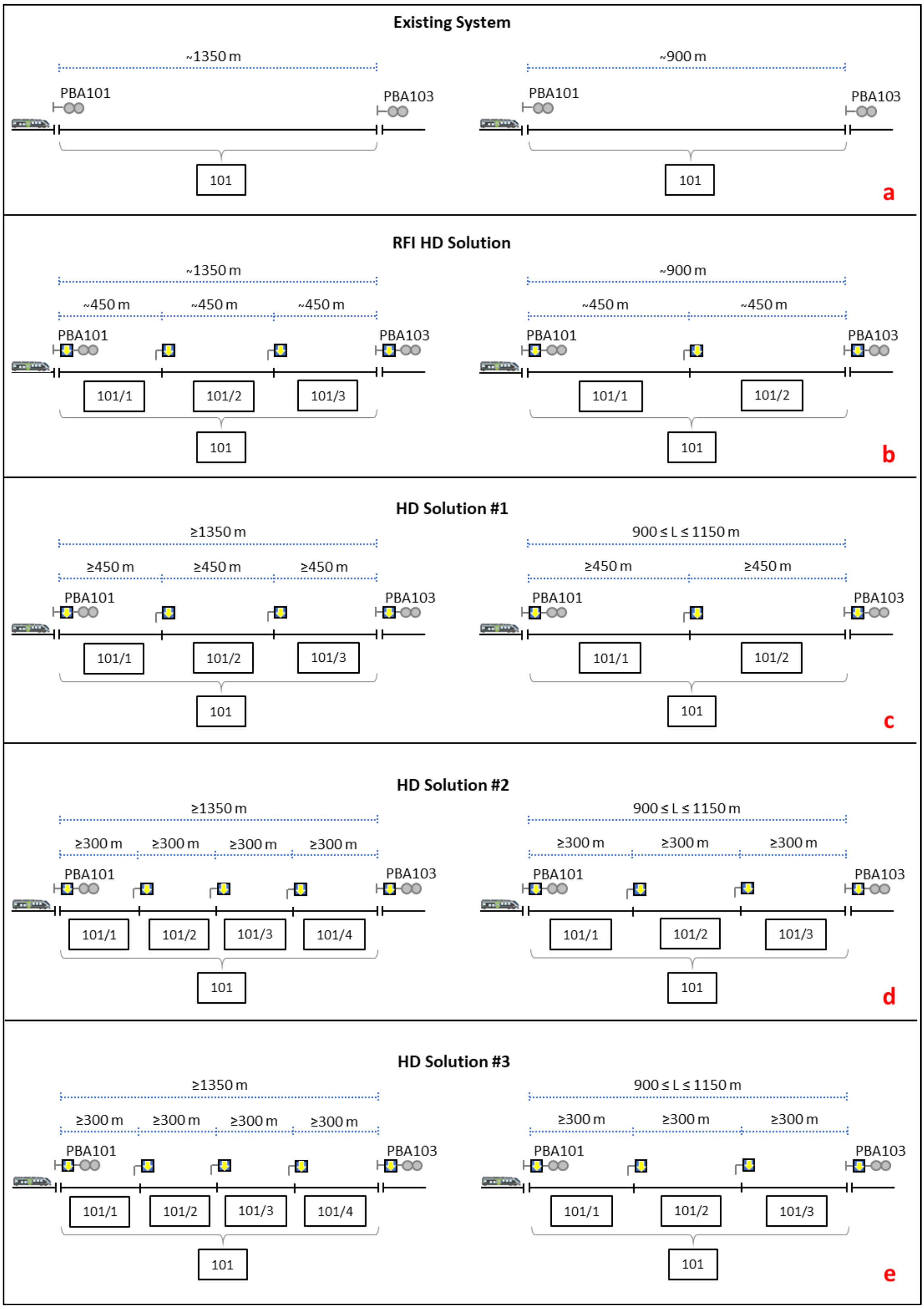


Figure 357 – Different proposal solution for the case study.

5.6.5.1 Roma Casilina – Capannelle – Ciampino Corridor

For the section Roma Casilina - Capannelle - Ciampino the following proposals are defined:

- RFI HD Solution (HD sections and HD routes from 450/500 m) equipped with 26 MB;
- HD Solution #1 (HD sections and HD routes from 450/500 m) equipped with 25 MB;
- HD Solution #2 (HD sections and HD routes from 350/400 m) equipped with 37 MB;
- HD Solution #3 (HD sections from 450/500 m and HD itinerary from 300/350 m) equipped with 28 MB.

The simulated scenario is an existing operating scenario and is representative as it simulates the operation of the urban service FL4. In fact, it is described by the following train sequence:

- Transit from Roma Casilina, on the same track (track VI);
- 60 seconds stop at Capannelle, on the same track (track II);
- 60 seconds stop at Ciampino, on separate tracks (tracks IV and III).

The minimum achievable headway is reported in Figure 358.

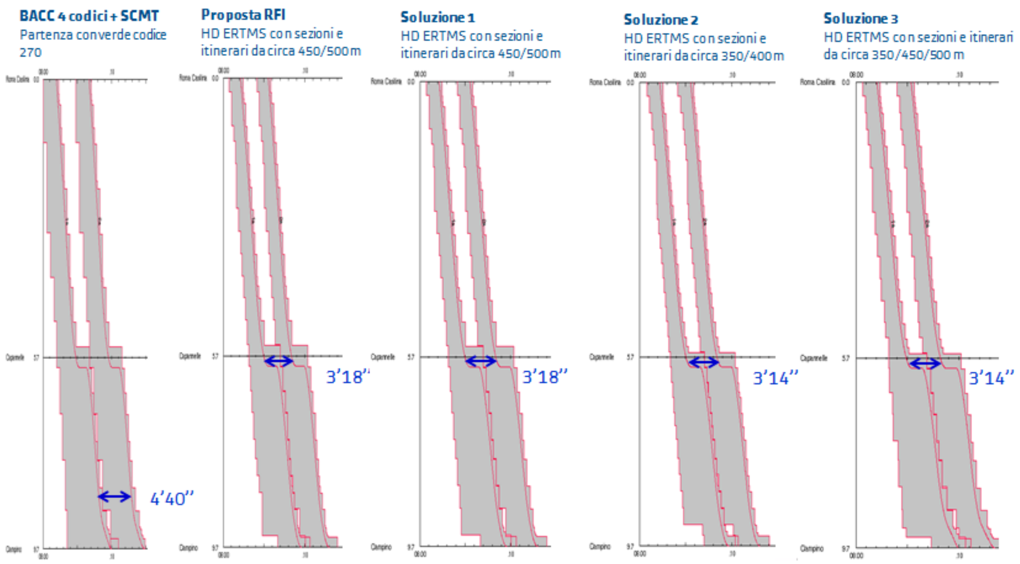


Figure 358 – Roma Casilina – Capannelle – Ciampino Corridor minimum headway.

5.6.5.2 Ciampino – Capannelle – Roma Casilina Corridor

For the section Roma Casilina - Capannelle - Ciampino the following proposals are defined:

- RFI HD Solution (HD sections and HD routes from 450/500 m) equipped with 29 MB;
- HD Solution #1 (HD sections and HD routes from 450/500 m) equipped with 25 MB;
- HD Solution #2 (HD sections and HD routes from 350/400 m) equipped with 35 MB;
- HD Solution #3 (HD sections from 450/500 m and HD itinerary from 300/350 m) equipped with 27 MB.

The simulated scenario is an existing operating scenario and is representative as it simulates the operation of the urban service FL4. In fact, it is described by the following train sequence:

- 60 seconds stop at Ciampino, on separate tracks (tracks II and I);
- 60 seconds stop at Capannelle, on the same track (track I);
- Transit to Roma Casilina (track V).

The minimum achievable headway is reported in Figure 359.

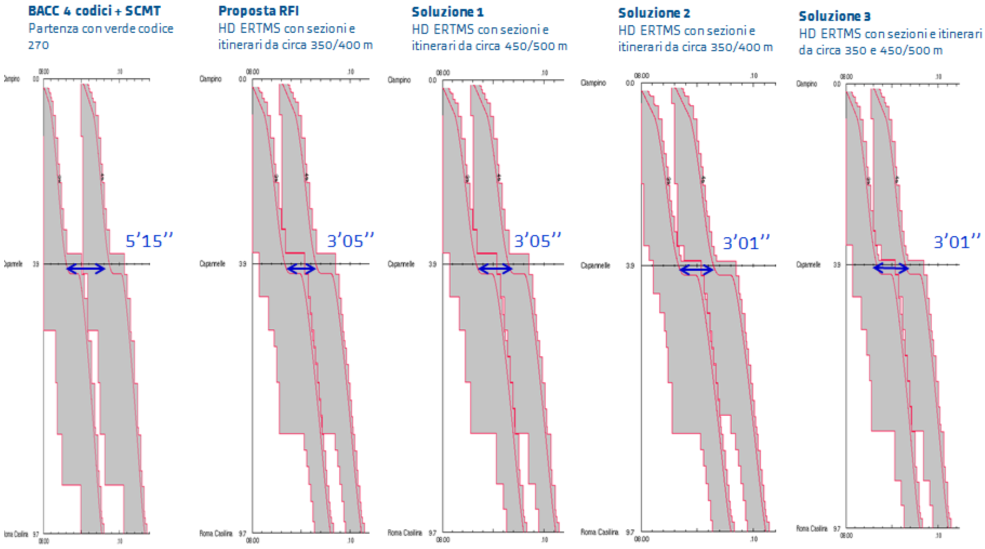


Figure 359 – Roma Casilina - Capannelle - Ciampino minimum headway.

5.6.5.3 Roma Tiburtina – Roma Tuscolana – Roma Ostiense Corridor

For the section Roma Tiburtina – Roma Tuscolana – Roma Ostiense the following proposals are defined:

- HD Solution #1 (HD sections and HD routes from 450/700 m) equipped with 17 MB;
- HD Solution #2 (HD sections and HD routes from 350/450 m) equipped with 23 MB;
- HD Solution #3 (HD sections and HD routes from 350/550 m) equipped with 20 MB.

The simulated scenario is an existing operating scenario and is representative as it simulates the operation of the urban service FL1 and FL3. In fact, it is described by the following train sequence:

- 60 seconds stop at Roma Tiburtina, on different tracks (track V and III);
- 60 seconds stop at Roma Tuscolana, on the same track (track V);
- 60 seconds stop in Roma Ostiense, on different tracks (Track XII and XIII).

The minimum achievable headway is reported in Figure 360.

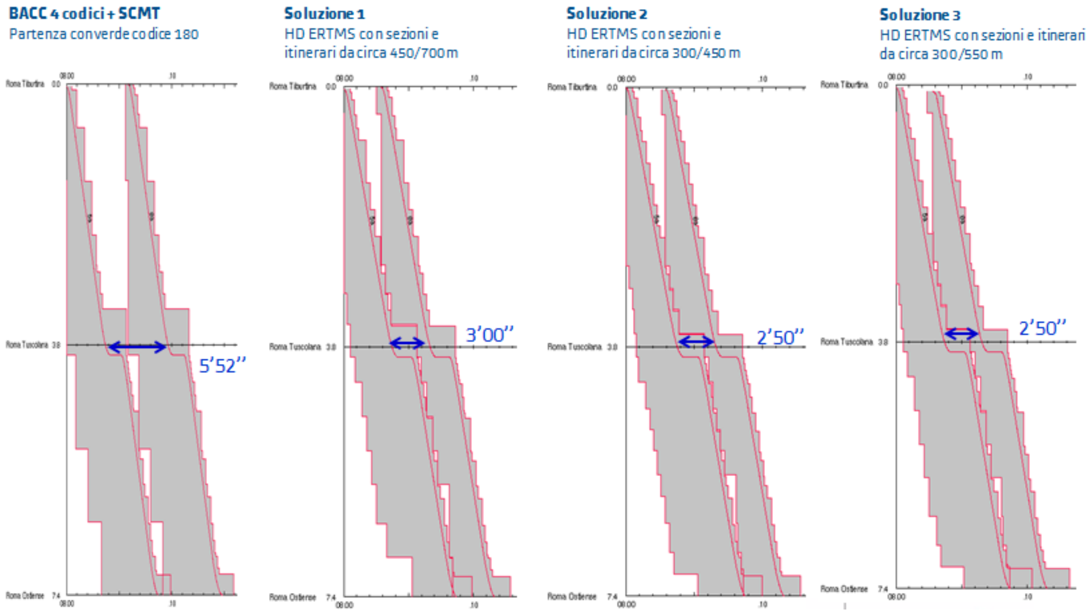


Figure 360 – Roma Tiburtina – Roma Tuscolana – Roma Ostiense minimum headway.

5.6.5.4 Roma Ostiense – Roma Tuscolana – Roma Tiburtina Corridor

For the section Roma Ostiense – Roma Tuscolana – Roma Tiburtina the following proposals are defined:

- HD Solution #1 (HD sections and HD routes from 450/700 m) equipped with 15 MB;
- HD Solution #2 (HD sections and HD routes from 350/450 m) equipped with 22 MB;
- HD Solution #3 (HD sections and HD routes from 350/550 m) equipped with 19 MB.

The simulated scenario is an existing operating scenario and is representative as it simulates the operation of the urban service FL3 and FL1. In fact, it is described by the following train sequence:

- 60 seconds stop at Roma Ostience, on different tracks (track X and XI);
- 60 seconds stop at Roma Tuscolana, on the same track (track IV);
- 60 seconds stop in Roma Tiburtina, on different tracks (track III and V).

The minimum achievable headway is reported in Figure 361.

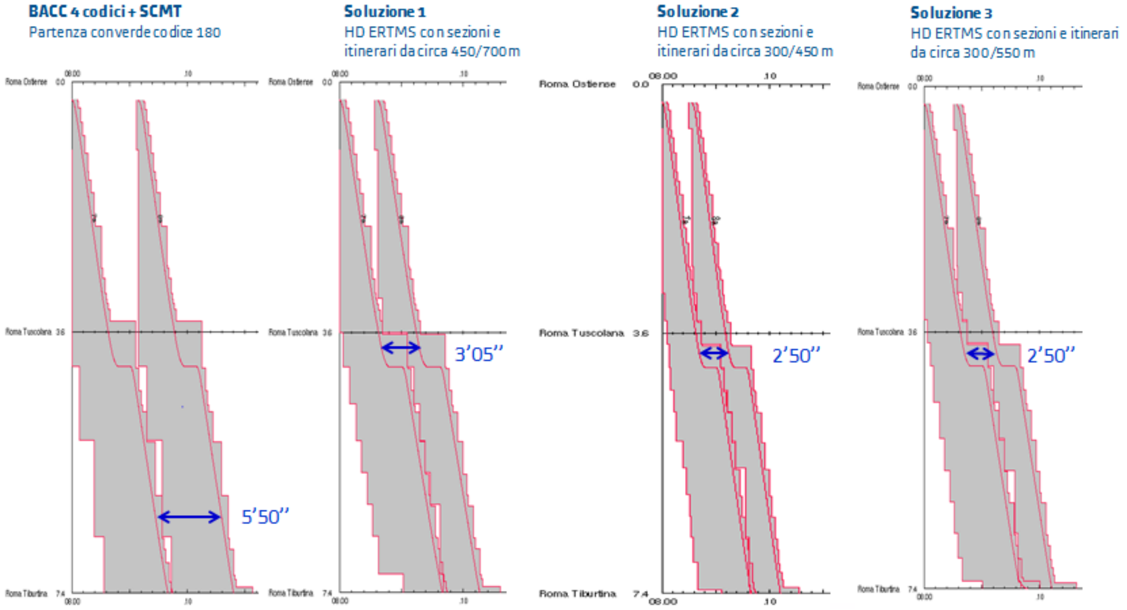


Figure 361 – Roma Ostiense – Roma Tuscolana – Roma Tiburtina minimum headway.

5.6.5.5 Roma Ostiense – Roma Monte Mario Corridor

For the section Roma Ostiense – Roma Monte Mario the following proposals are defined:

- HD Solution #1 (HD sections and HD routes from 450/700 m) equipped with 23 MB;
- HD Solution #2 (HD sections and HD routes from 300/450 m) equipped with 34 MB;
- HD Solution #3 (HD sections and HD routes from 300/500 m) equipped with 33 MB.

The simulated scenario is an existing operating scenario and is representative as it simulates the operation of the urban service FL3. In fact, it is described by the following train sequence:

- both train stops 60 seconds in Roma Ostiense, Roma Trastevere, Quattro Venti, Roma San Pietro, Valle Aurelia, Appiano, Roma Balduina, Gemelli, Monte Mario on the same track.

The minimum achievable headway is reported in Figure 362.

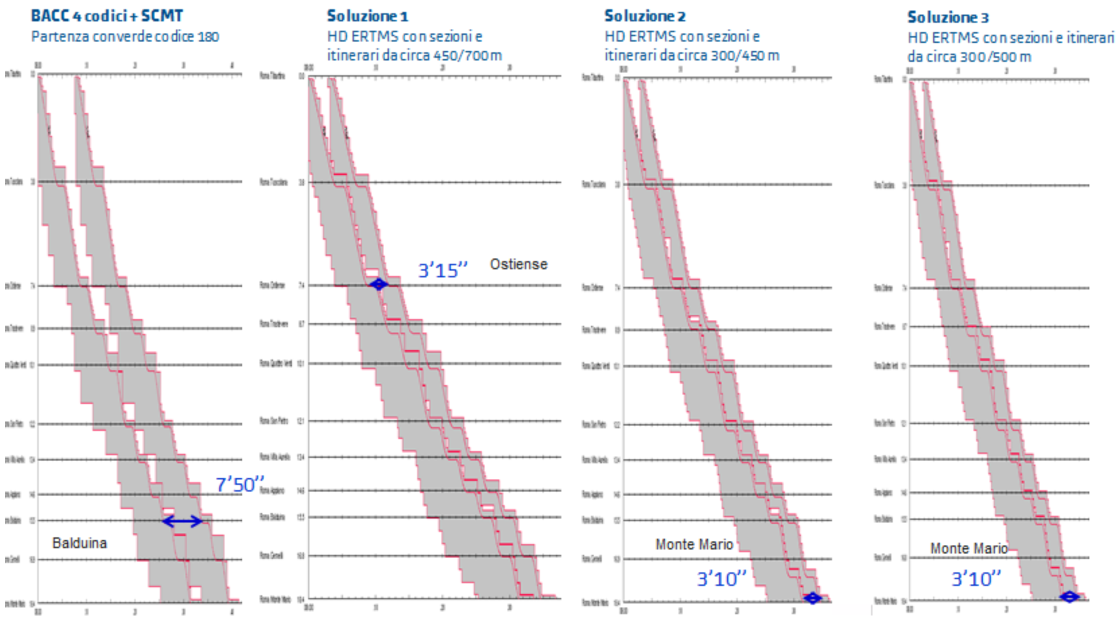


Figure 362 – Roma Ostiense – Roma Monte Mario minimum headway.

5.6.5.6 Roma Monte Mario – Roma Ostiense Corridor

For the section Roma Monte Mario – Roma Ostiense the following proposals are defined:

- HD Solution #1 (HD sections and HD routes from 450/700 m) equipped with 23 MB;
- HD Solution #2 (HD sections and HD routes from 300/450 m) equipped with 34 MB.

The simulated scenario is an existing operating scenario and is representative as it simulates the operation of the urban service FL3. In fact, it is described by the following train sequence:

- both train stops 60 seconds to Monte Mario, Gemelli, Roma Balduina, Appiano, Valle Aurelia, Roma San Pietro, Quattro Venti, Roma Trastevere, Roma Ostiense (then proceed with the stop also to Roma Tuscolana and Roma Tiburtina.

The minimum achievable headway is reported in Figure 363.

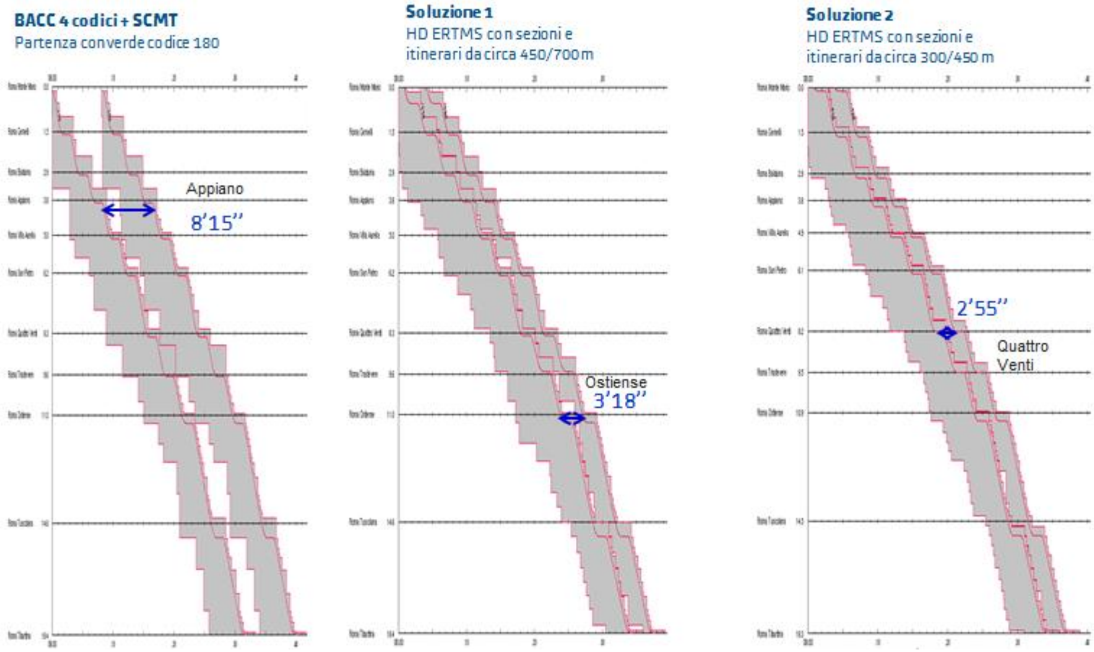


Figure 363 – Roma Monte Mario – Roma Ostiense minimum headway.

5.6.5.7 Roma Monte Mario – Cesano di Roma Corridor

For the section Roma Monte Mario – Roma Ostiense the following proposals are defined:

- HD Solution #1 (HD sections and HD routes from 450/700 m) equipped with 37 MB;
- HD Solution #2 (HD sections and HD routes from 300/450 m) equipped with 55 MB;
- HD Solution #3 (HD sections and HD routes from 300/550 m) equipped with 47 MB.

The simulated scenario is an existing operating scenario and is representative as it simulates the operation of the urban service FL3. In fact, it is described by the following train sequence:

- both train stops 60 seconds to Monte Mario, Roma San Filippo Neri, Ottavia, Ipogeo degli Ottavi, La Giustiniana, La Storta, Olgiata, Cesano di Roma.

The minimum achievable headway is reported in Figure 364.

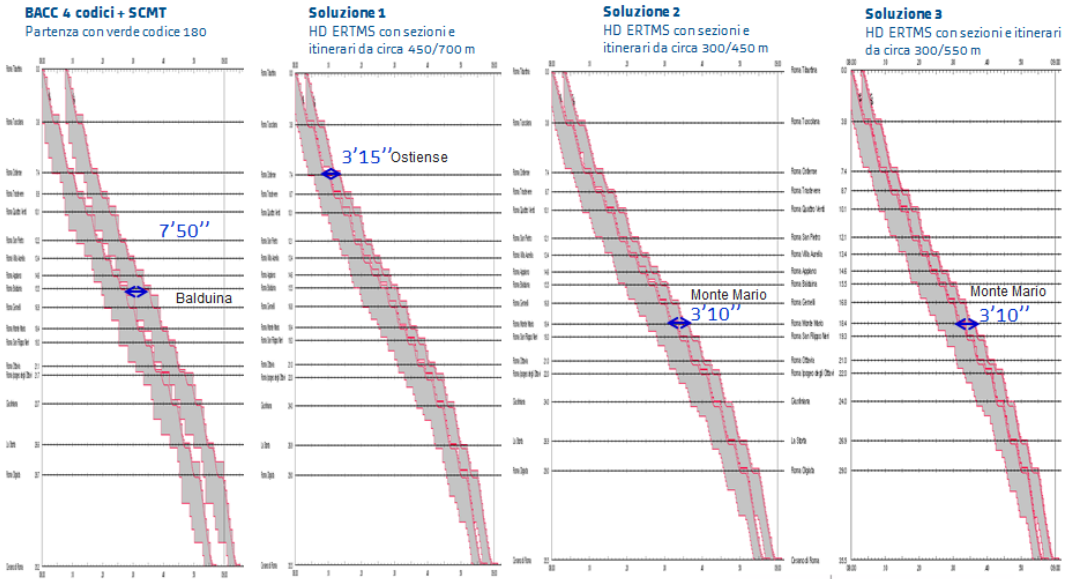


Figure 364 – Roma Monte Mario – Cesano di Roma minimum headway

5.6.5.8 Cesano di Roma – Roma Monte Mario Corridor

For the section Roma Monte Mario – Roma Ostiense the following proposals are defined:

- HD Solution #1 (HD sections and HD routes from 450/700 m) equipped with 36 MB;
- HD Solution #2 (HD sections and HD routes from 300/450 m) equipped with 52 MB;
- HD Solution #3 (HD sections and HD routes from 300/550 m) equipped with 43 MB.

The simulated scenario is an existing operating scenario and is representative as it simulates the operation of the urban service FL3. In fact, it is described by the following train sequence:

- both train stops 60 seconds to Cesano di Roma, Olgiata, La Storta, La Giustiniana, Ipogeo degli Ottavi, Ottavia, Roma San Filippo Neri, Monte Mario (then proceed with the stop also to Roma Tuscolana and Roma Tiburtina).

The minimum achievable headway is reported in Figure 365.

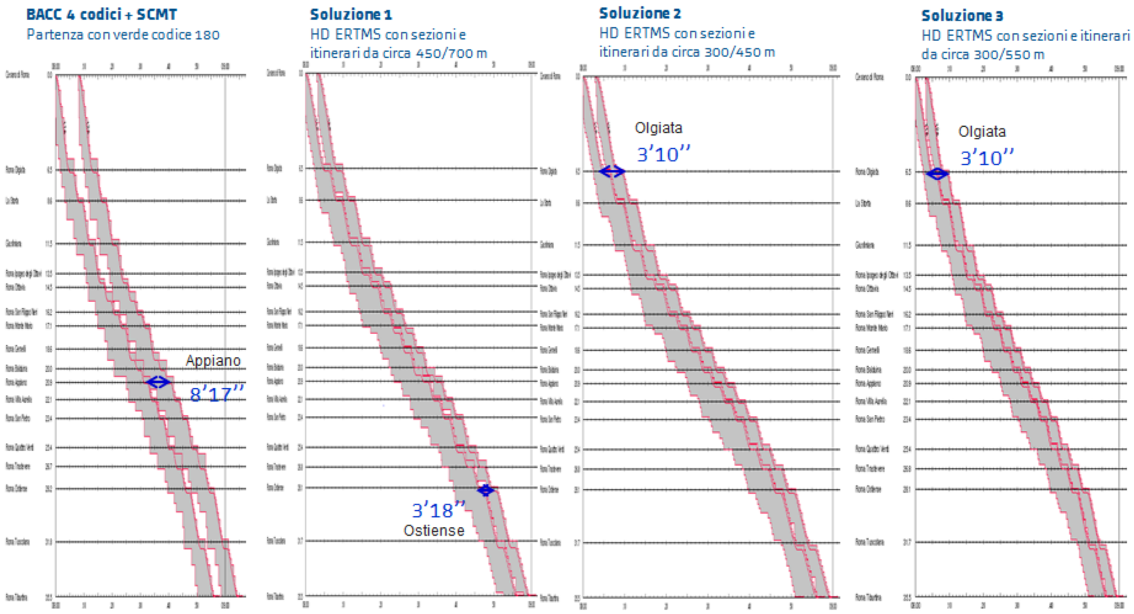


Figure 365 – Roma Monte Mario – Roma Ostiense minimum headway

Summary, in Table 62 are reported the results of minimum headway for every corridor.

Line (odd track)	BAcc	RFI HD Solution	HD Solution #1	HD Solution #2	HD Solution #3
Ciampino - Casilina	5’15’’	3’05’’	3’05’’	3’01’’	3’01’’
Tiburtina - Ostiense	5’56’’	\	3’15’’	2’55’’	2’55’’
Ostiense – Monte Mario	7’50’’	\	3’15’’	3’10’’	3’10’’
Monte Mario - Cesano	7’50’’	\	3’15’’	3’10’’	3’10’’
Line (even track)	**BAcc**	**RFI HD Solution**	**HD Solution #1**	**HD Solution #2**	**HD Solution #3**
Casilina – Ciampino	4’40’’	3’18’’	3’18’’	3’14’’	3’14’’
Ostiense – Tiburtina	5’50’’	\	3’14’’	2’53’’	2’53’’
Monte Mario – Ostiense	8’15’’	\	3’18’’	2’55’’	\
Cesano – Monte Mario	8’17’’	\	3’18’’	3’10’’	3’10’’

Table 62 – Headway results for odd and even track of each HD corridor.

5.6.6. Strengthening the Operational Program

From the flow analysis, considering all trains that circulate during a representative working day from 6:00 to 21:00, it is possible to identify the various services with the respective frequency of travel. After that, assuming to realize the HD-ERTMS system (solution #3) applied to two HD corridors (Roma Casilina – Ciampino and Roma Tiburtina – Cesano di Roma corridor) using only train equipped with HD-ERTMS technologies, it is possible to generate an enhanced operational program taking into account the following assumptions:

- existing regional and suburban services with double frequency compared to the existing one;
- number of regional free courses unchanged;
- the operational plan must be conflict-free;
- peak hour from 17:00 to 18:00.

5.6.6.1 Roma Casilina – Ciampino Corridor

For the route Roma Casilina - Ciampino, through the analysis of flows, the largest flow is detected at the afternoon peak time (17:00 - 18:00) and the services that affect the corridor are regional trains towards Frosinone/Cassino/Campobasso and urban services FL4 and FL6.

The enhanced operational plan in this section is characterized by:

- Frequency of the FL4 service at 30 minutes, compared to the current 60 minutes, to/from:
  - Velletri;
  - Albano Laziale;
  - Frascati;
- Frequency of the FL4 service at 30 minutes, compared to the current 60 minutes, to/from:
  - Colleferro/ Frosinone;

The analysis conducted for each station is described below, with the results.

Roma Casalina

Roma Casilina station is a place of movement and therefore is characterized by only transits.

In Figure 366, the transit times in Rome Casilina (Ciampino direction) are reported on the left from 17:00 to 18:00 of the existing services (FL4, FL6 and regional), while on the right are defined the transit times made available by strengthening the program of operation, with ERTMS HD system.

In addition, it can be noted that the number of regional unstretched tracks is kept unchanged.

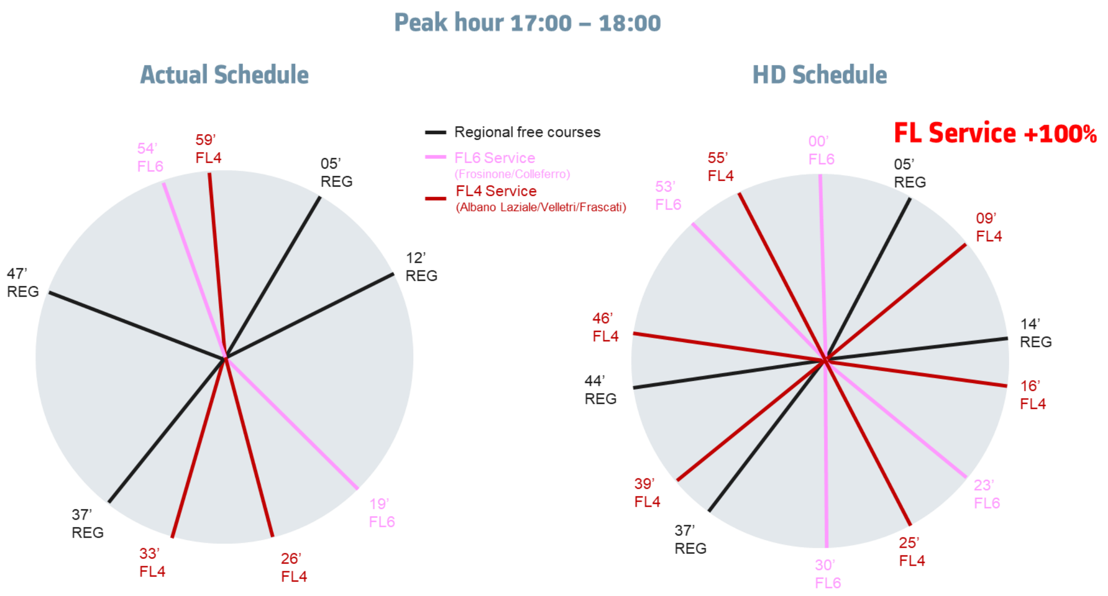


Figure 366 – Roma Casilina (transit to Ciampino): existing and HD service from 17:00 to 18:00

As described above, in Figure 367 the transit times for Roma Casilina (direction Roma Termini) from 17:00 to 18:00 of the existing services are to the left, while to the right are defined the transit times made available by strengthening the program of operation.

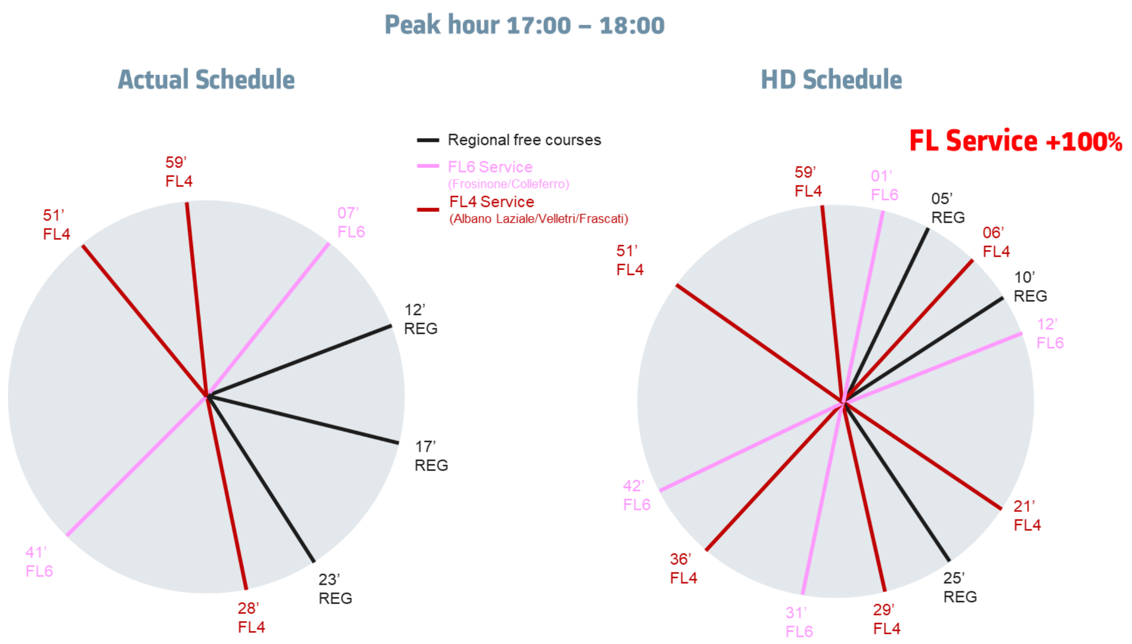


Figure 367 – Roma Casilina (transit to Roma Termini): existing and HD service from 17:00 to 18:00

Ciampino

Ciampino station, unlike Roma Casilina, is a passenger station.

In Figure 368, is reported on the left the arrival times from Roma Casilina from 17:00 to 18:00 of the existing services (FL4, FL6 and regional), while on the right the times made available by strengthening the program of operation, with ERTMS HD system.

Also, in this case the number of regional tracks not cadenced is maintained unchanged.

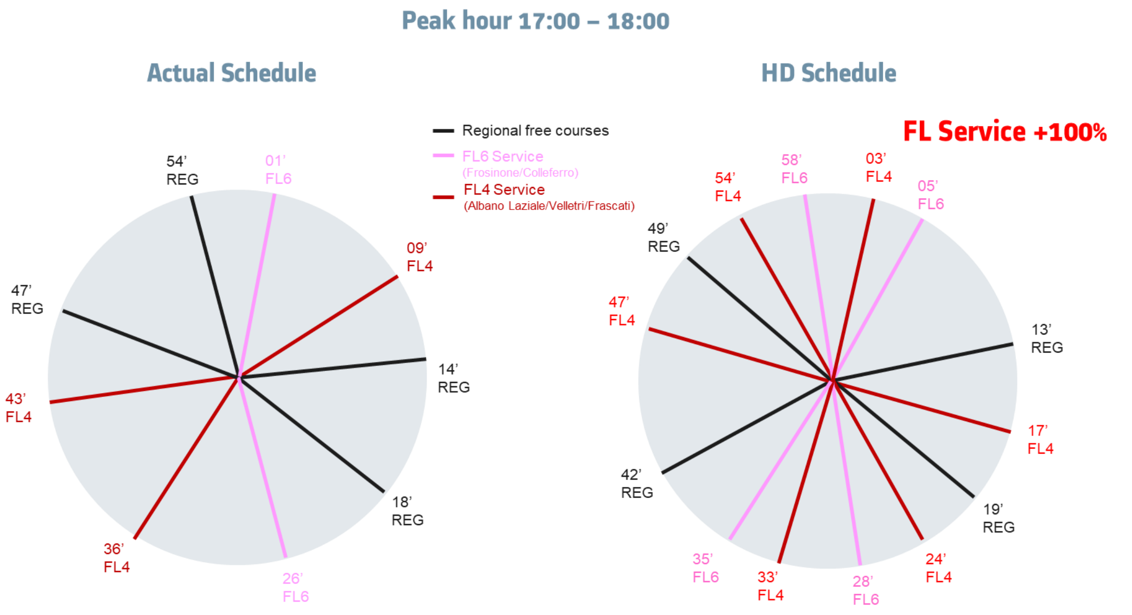


Figure 368 – Ciampino (arrival from Casilina): existing and HD service from 17:00 to 18:00

Below in Figure 369, the departure times for Roma Casilina are shown on the left from 17:00 to 18:00 of the existing services (FL4, FL6 and regional), while on the right the times made available by strengthening the program of operation, with ERTMS HD system.

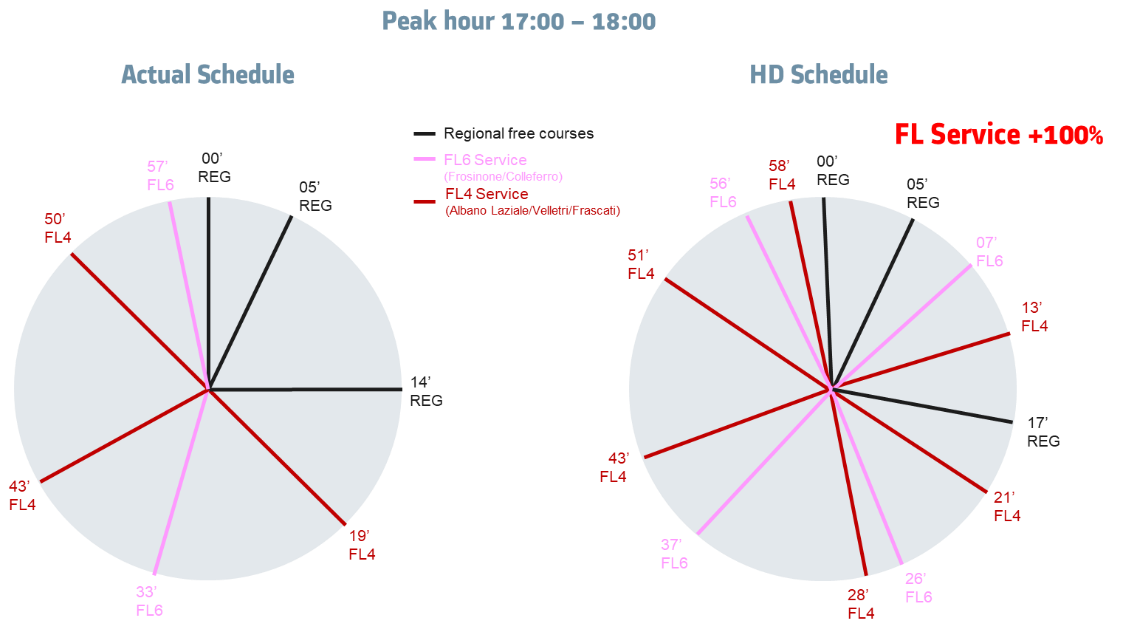


Figure 369 – Ciampino (departure to Casilina): existing and HD service from 17:00 to 18:00

5.6.6.2 Roma Tiburtina – Roma Tuscolana – Roma Ostiense Corridor

For the Rome Tiburtina - Tuscolana – Ostinese corridor the analysis of the flows has evidenced that the higher flow is found in correspondence of 12:00 to 15:00. However, it was decided to take as reference time the peak hour 17:00 - 18:00 to ensure continuity with the route Roma Ostiense - Cesano di Roma.

The services that affect the corridor are the only urban services FL1 (Fiumicino line) and FL3 (Viterbo line). The enhanced operational program in this section is characterized by:

- frequency of the FL1 service at 7/8 minutes, compared to the current 15 minutes, to/from Fiumicino;
- frequency of the FL3 service to 15 minutes, compared to the current 30 minutes, from/to Cesano;
- frequency of the FL3 service to 30 minutes, compared to the current 60 minutes from/to Bracciano.

The analysis conducted for each station is described below, with the results.

Roma Tiburtina

Below in Figure 370, the departure times from Roma Tiburtina (direction Roma Ostiense) are reported on the left from 17:00 to 18:00 of the existing services (FL1 and FL3), while on the right are defined the departure times made available by strengthening the program of exercise, with ERTMS HD system.

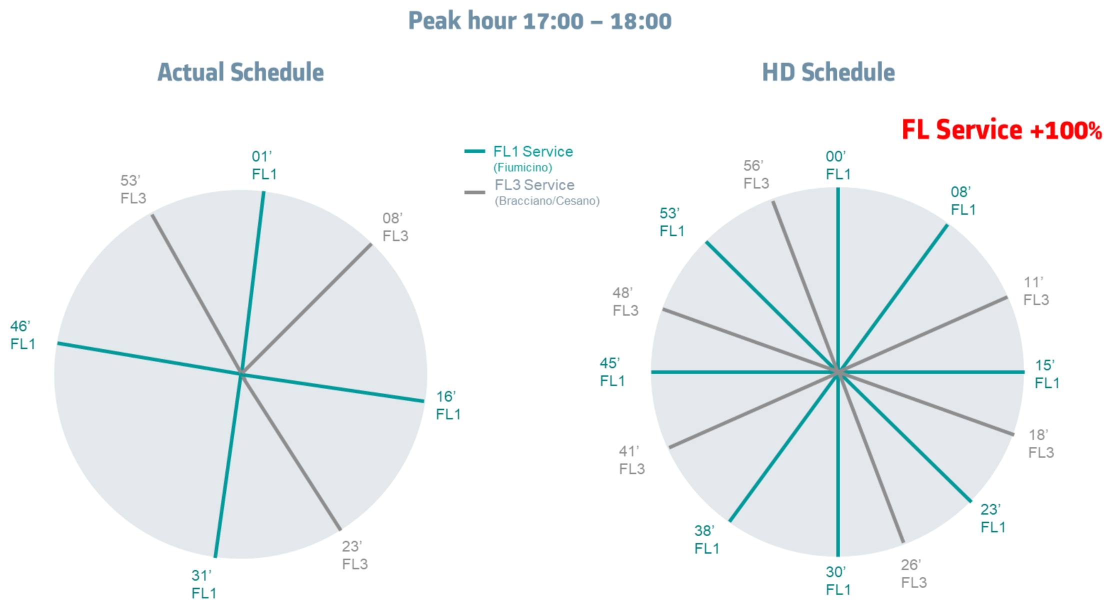


Figure 370 – Roma Tiburtina (departure to Ostiense): existing and HD service from 17:00 to 18:00

Below in Figure 371 is reported on the left the arrival times to Roma Tiburtina from 17:00 to 18:00 of the existing services (FL1 and FL3), while on the right the times made available by strengthening the program of operation, with ERTMS HD system.

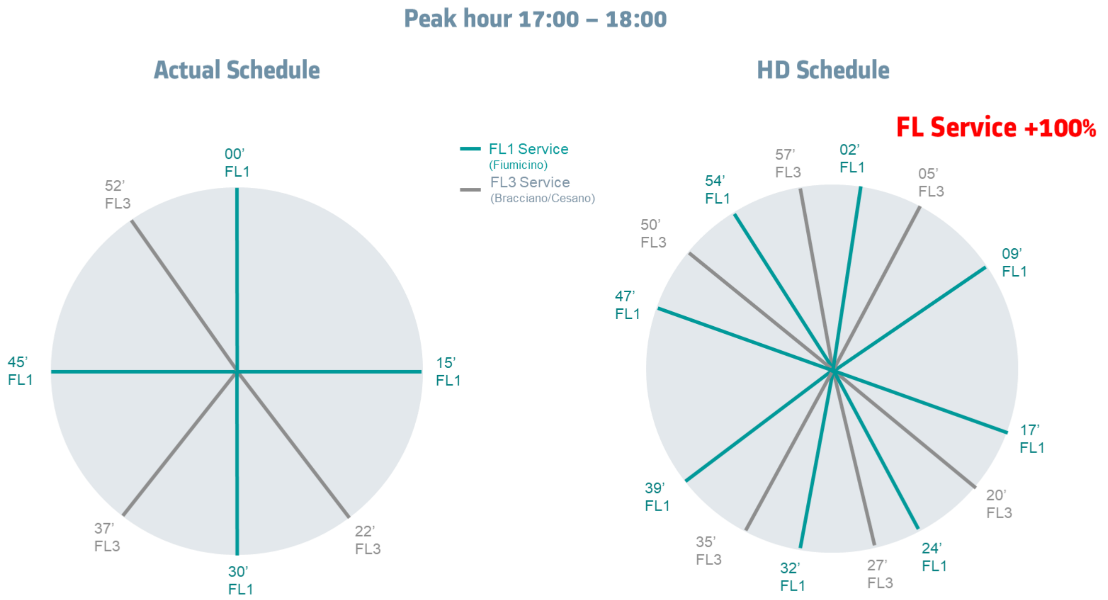


Figure 371 – Roma Tiburtina (arrival from Ostiense): existing and HD service from 17:00 to 18:00

Roma Ostiense

Below in Figure 372, the departure times from Roma Ostiense (direction Roma Tiburtina) are reported on the left from 17:00 to 18:00 of the existing services (FL1 and FL3), while on the right are defined the departure times made available by strengthening the program of exercise, with ERTMS HD system.

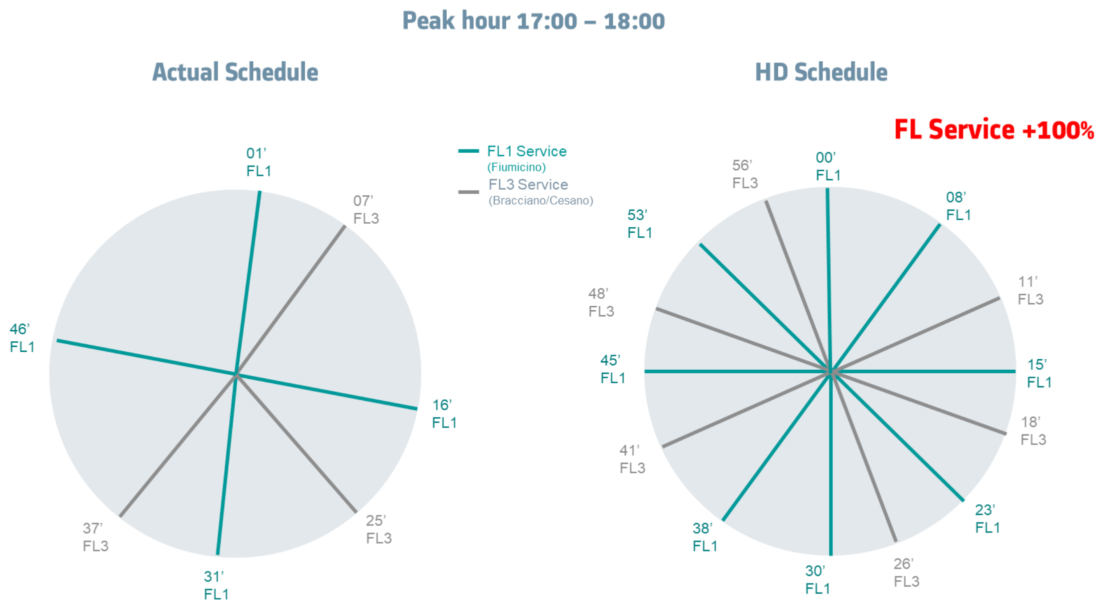


Figure 372 – Roma Ostience (departure to Tiburtina): existing and HD service from 17:00 to 18:00

Below in Figure 373, we report on the left the times of arrival to Roma Ostiense from Roma Tiburtina from 17:00 to 18:00 of the existing services (FL1 and FL3), while on the right are defined the arrival times made available by enhancing the program of operation, with ERTMS HD system.

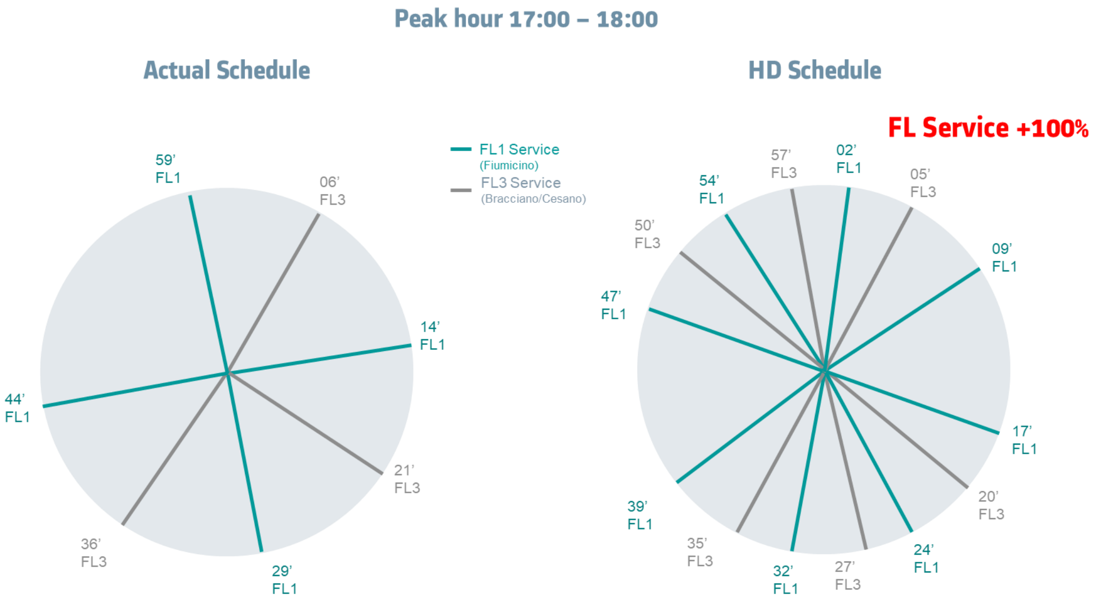


Figure 373 – Roma Ostience (arrival from Tiburtina): existing and HD service from 17:00 to 18:00

5.6.6.3 Simulation Results

In the Train Graph of the Roma Tiburtina - Ciampino corridor (Figure 374, Figure 375), from 17:00 to 18:00, are represented:

- traces of suburban services stopping in Rome Capannelle and Ciampino;
- the traces of regional trains, which pass through both Rome Capannelle and Ciampino.

The Ciampino tracks used for arrivals/departures are affected by three different flows and therefore represent the bottleneck; with the enhanced exercise program, the Ciampino station is saturated.

Regarding the Train Graph of the Roma Tiburtina - Roma Tuscolana - Roma Ostiense corridor reported in Figure 376 and Figure 377, from 17:00 to 18:00, are represented:

- the tracks of the suburban FL1 service, which run along the Fiumicino line and exit the study perimeter at the Roma Ostiense station;
- the tracks of the suburban service FL3, which run along the line Viterbo, tracks undergoing redevelopment up to the station of Cesano in Rome.

With the enhanced operating program, the Tiburtina - Tuscolana - Ostiense corridor is saturated, as it is crossed by two flows with high frequencies.

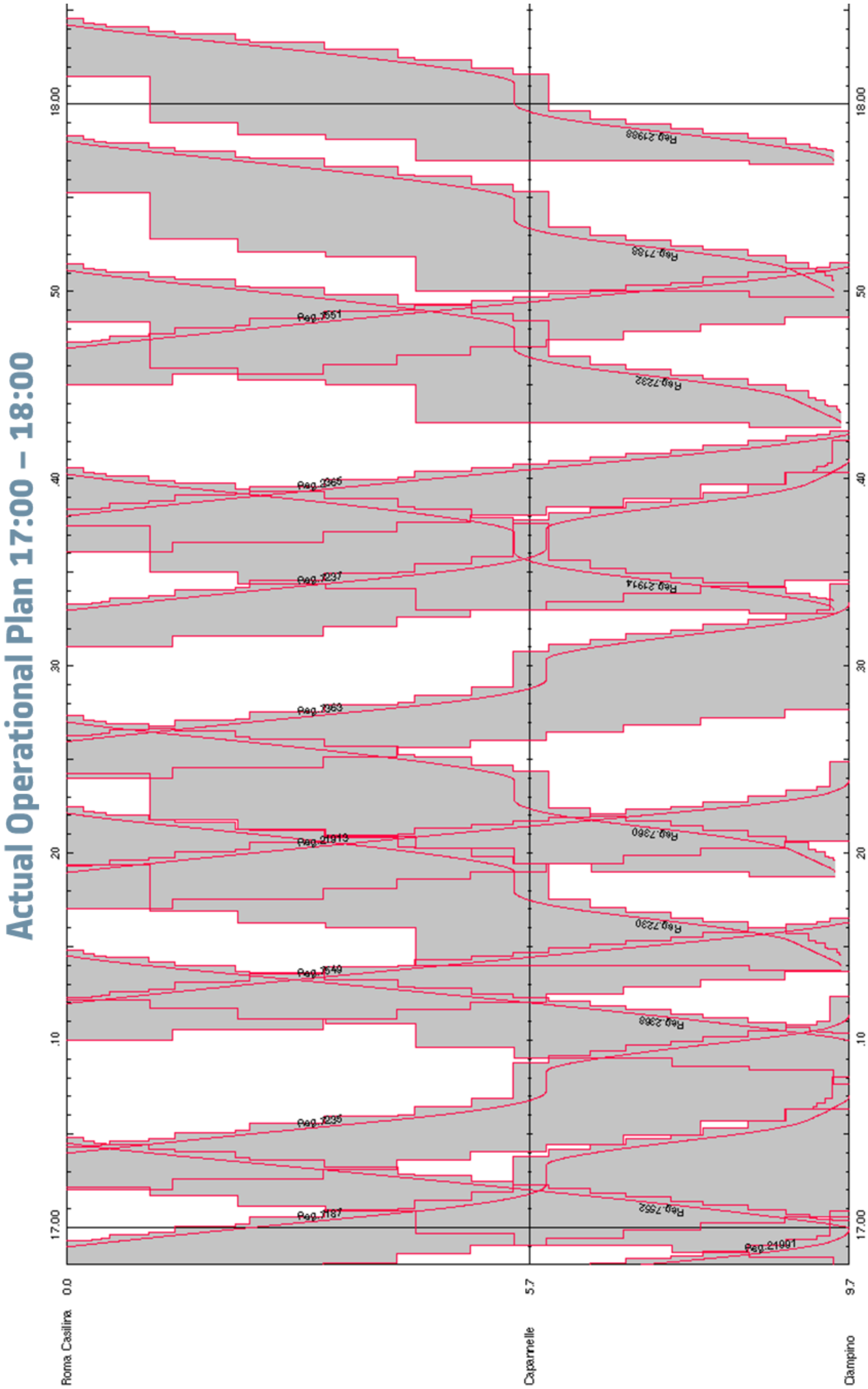


Figure 374 – Roma Casilina – Ciampino: Existing Operational Plan from 17:00 to 18:00

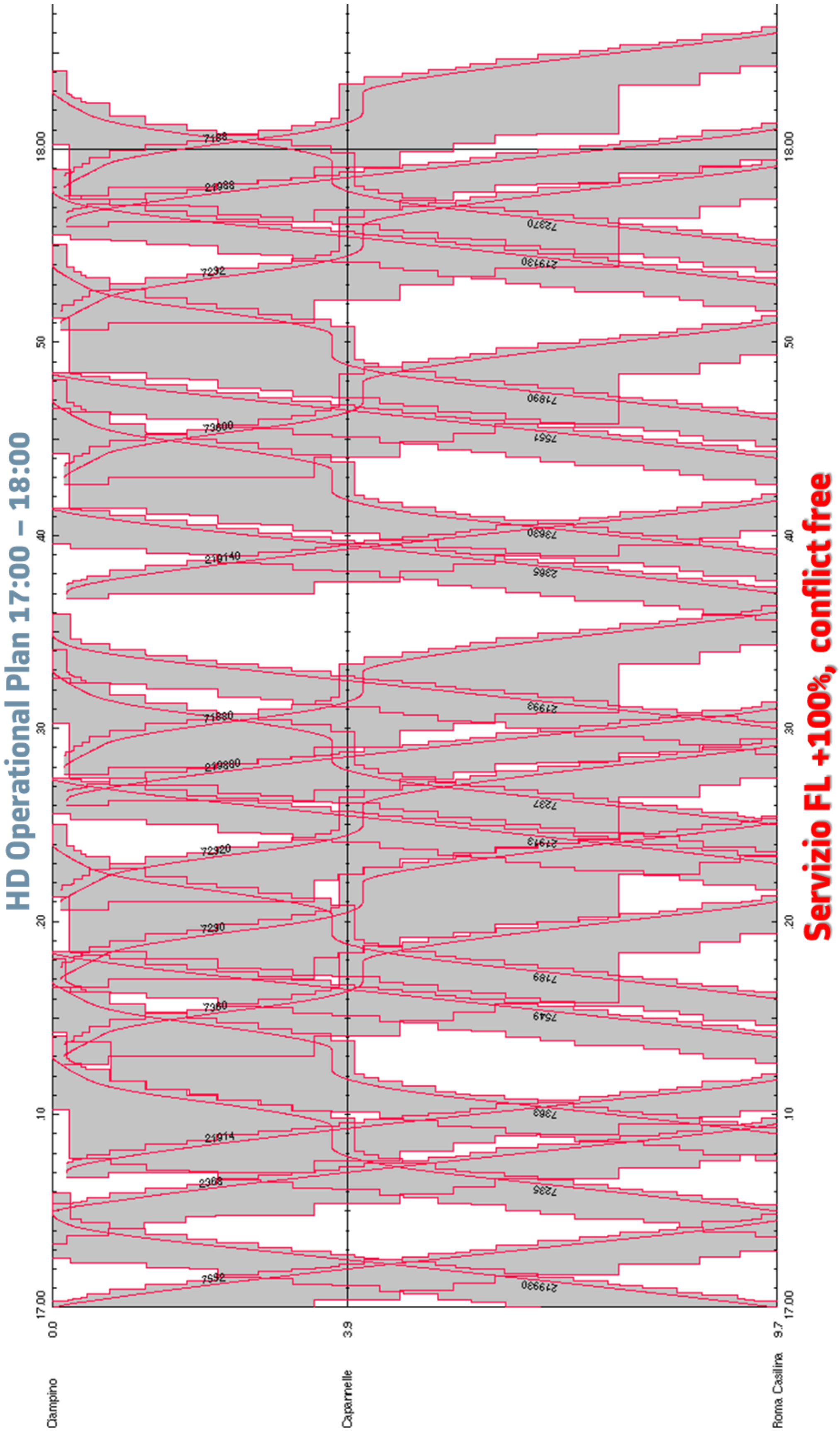


Figure 375 – Roma Casilina – Ciampino: HD Operational Plan from 17:00 to 18:00

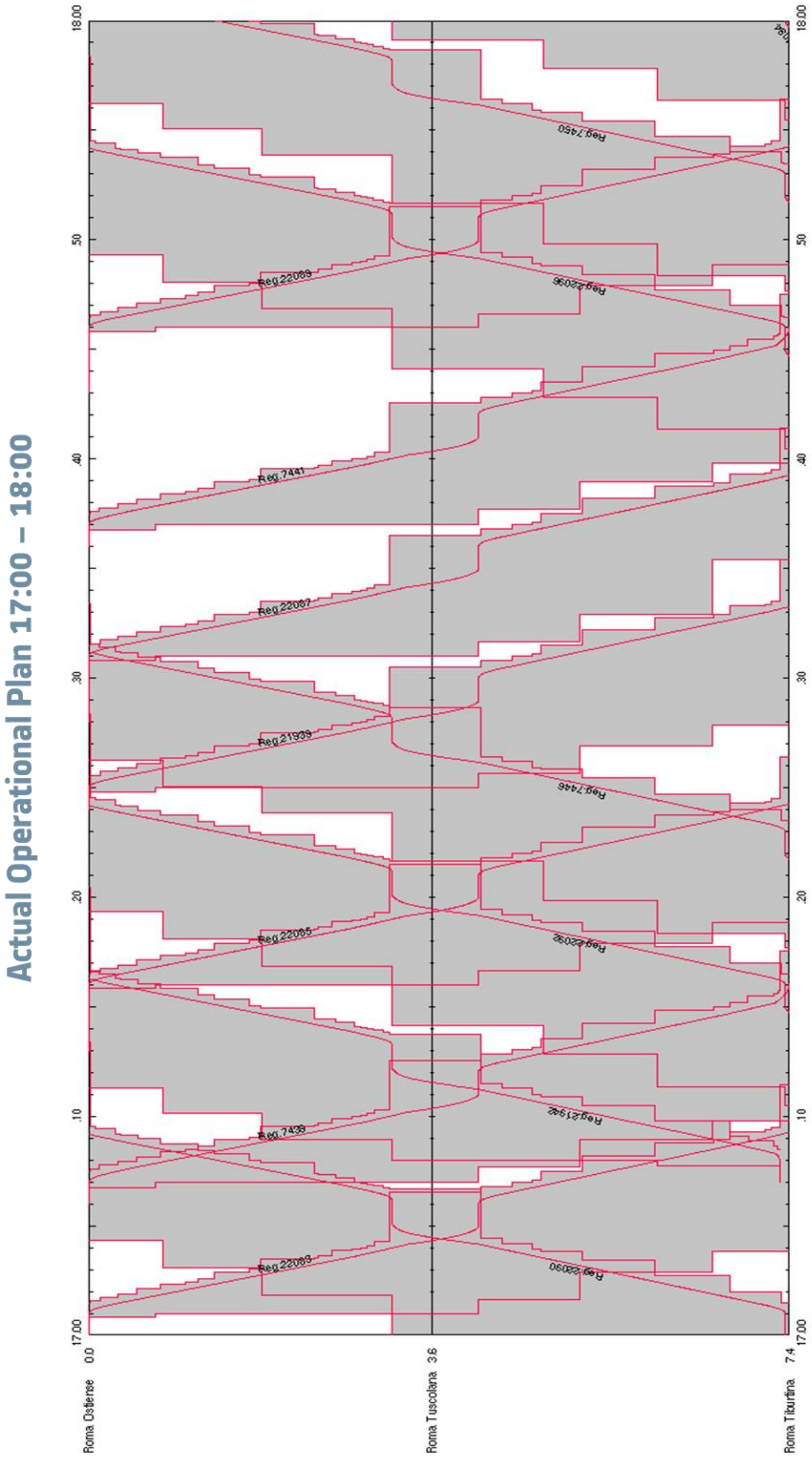


Figure 376 – Roma Tiburtina – Roma Tuscolana – Roma Ostiense: Existing Operational Plan from 17:00 to 18:00

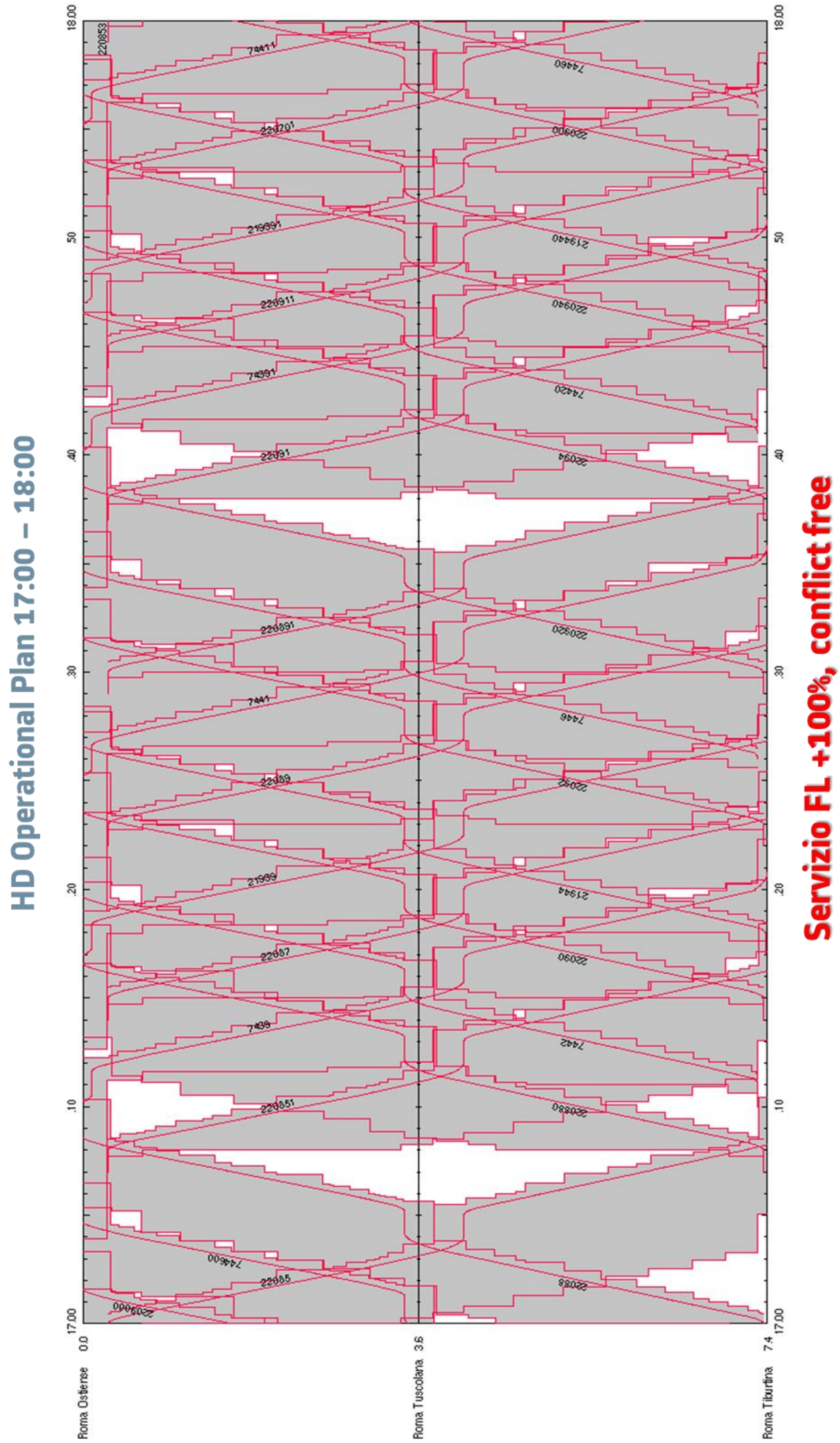


Figure 377 – Roma Tiburtina – Roma Tuscolana – Roma Ostiense: HD Operational Plan from 17:00 to 18:00

Focusing on the peak hour of the day approximately from 17:00 to 18:00, it possible to obtain the results reported in Table 62.

Stations	Arrival From	Departure From	Transit for	Actual frequency [Train/h]	Future frequency [Train/h]	Increment [%]
Casilina	\	\	Ciampino	9	14	56 %
Casilina	\	\	Termini	8	13	63 %
Ciampino	Casilina	\	\	9	14	56 %
Ciampino	\	Casilina	\	8	13	63 %
Tiburtina	\	Ostiense	\	7	14	100 %
Tiburtina	Ostiense	\	\	7	14	100 %
Ostiense	\	Tiburtina	\	7	14	100 %
Ostiense	Tiburtina	\	\	7	14	100 %

Table 63 – Actual and future train frequency comparison.

The results show how system optimization, reducing the headway, positively affects line capacity. The capacity is increased by about 56 % minimum for each station and sometimes reaching twice of the capacity in some stations.

The enhanced operational program also includes the occupancy diagrams of the tracks of each station.

The M53 Module has been designed by assigning to each train a station based on the constraints of the tracks in the station as from the current schedule of operation.

Below the M53 is reported for each station from 17:00 to 18:00; on the right is the specialization based on the flows of each track (as per current program) (Figure 378, Figure 379, Figure 380, Figure 381, Figure 382).

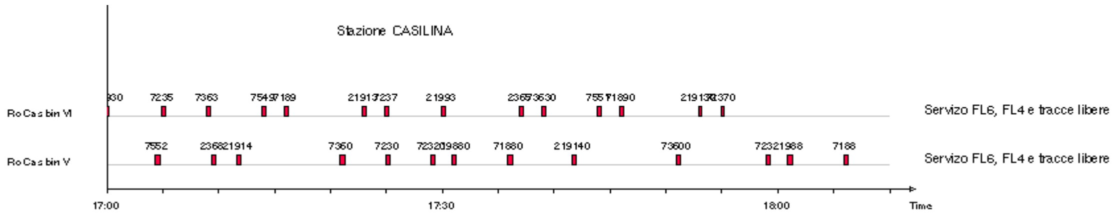


Figure 378 – Casilina Station occupation chart

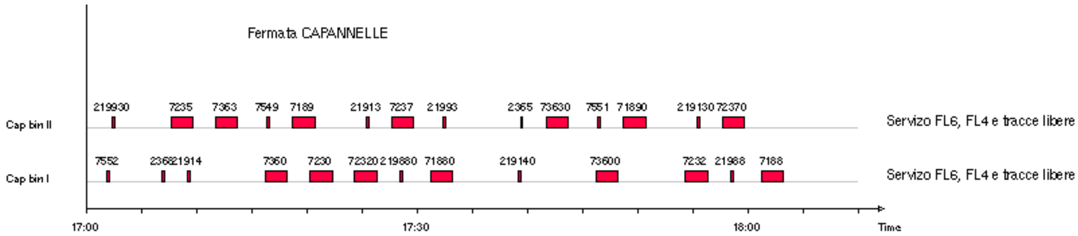


Figure 379 – Capannelle Station occupation chart

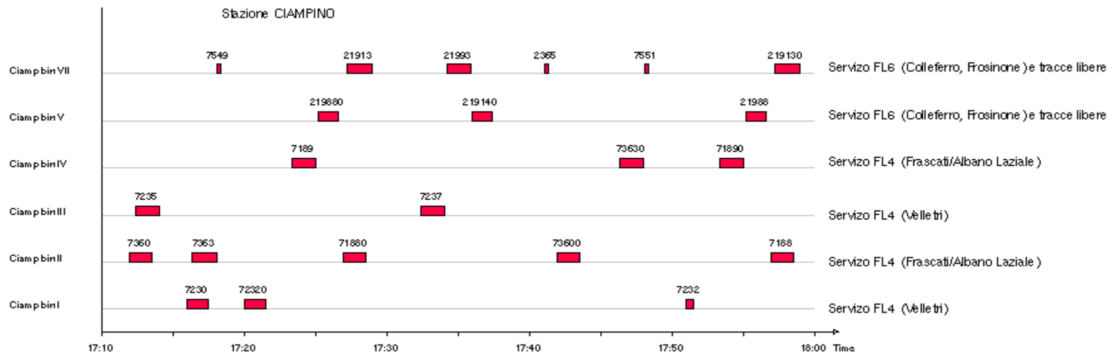


Figure 380 – Ciampino Station occupation chart

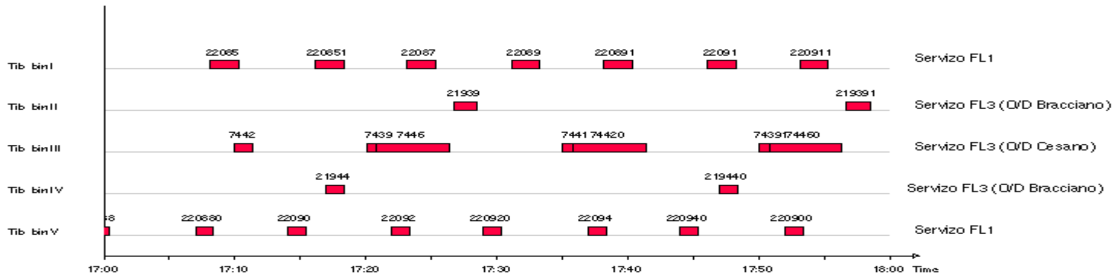


Figure 381 – Roma Tiburtina Station occupation chart

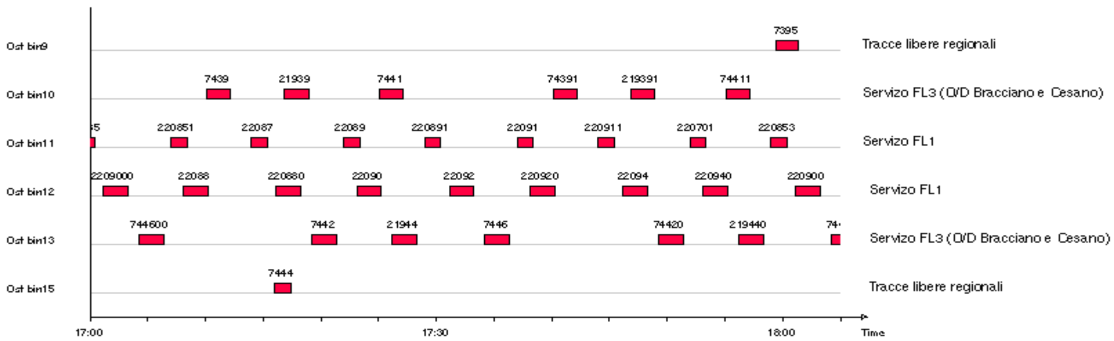


Figure 382 – Roma Ostiense Station occupation chart

5.6.7. Project Conclusion

The purpose of this project is to analyze the High Density ERTMS system from the point of view of increasing capacity of the railway nodes. It was designed to overlap the Italian national signalling system, through a virtual subsectioning of the block sections. The use of a radio block center for the exchange of information between trains, has allowed to reduce the installation material costs. In this paper, the railway node of Rome has been analyzed and several proposals for virtual sectioning of block sections have been investigated and compared. Starting from a tabular solution proposed by RFI, the optimization involved variation of the number and length of virtual subsections related to block sections between 900 and 1150 m and over 1350 m long. Results show that HD Solution #3 is the most effective in terms of performance and cheapest in term of installation cost, but in general the values indicate how, using the HD System with virtual sectioning, it's possible to reduce the headway and reach good performance passing from 5 min to 3 min headway between trains. Reducing the headway positively affects also line capacity. The capacity is increased by about 56% minimum for each station and sometimes reaching twice of the capacity in some stations. Probably the first implementations will take place in the nodes of Rome, Florence and Milan from which will be possible to see the system real potential and benefits. Subsequently, the system will be extended to other urban nodes such as Turin, Venice, Bologna, Naples, Genoa by 2022 and Bari by 2029. Future developments may be focused on further optimization of the signalling system through the complete implementation of the mobile block (L3) with the aim of further increasing capacity by reducing service disruption and maintenance costs. Potential future research should be based on the evaluation of capacity benefits under delayed operation as a relevant contribution to literature to understand overall performances of hybrid signalling systems.

5.7 Tvärbanan line: Solna – Sickla (Sweden)

Tvärbanan is a tram/light rail line in Stockholm, Sweden. Its name literally translated into English is Crossways line. It links together many bus and rail lines crossways through its connections with the southern, western and northern subway branches of the Stockholm Metro (Tunnelbana) and the Stockholm commuter rail (Pendeltåg). The possibility to travel between southern, western and northern greater Stockholm without having to enter the city centre significantly reduces the number of transit passengers, also reducing the number of trains having to pass through the Old Town bottleneck during peak hours. Near Liljeholmen the track is shared with freight traffic in a short section, this being the only place in Sweden where freight traffic and trams share the same track (Figure 383).

Figure 383 – Tvärbanan line geographical map

The tramway is separated from roads in most parts, but there are sections in Gröndal, Sundbyberg and Solna where the tracks run on roads among regular road traffic. In Hammarby sjöstad the trams run in a reservation in the centre of the road rather than in mixed traffic, but there are several level crossings.

Construction on a branch line to Kista and Helenelund started in February 2018 (Claesson, 2018), while traffic started in 2000, first between Gullmarsplan and Liljeholmen, then later between Liljeholmen and Alvik, in 2002 between Gullmarsplan and Sickla Udde, and in 2013 between Alvik and Solna centrum. It has later been extended to Solna Station (2014), Sickla (2017) and most recently, Bromma Airport (2021), the last of which being the first part of the new Kista branch. The first part of the new branch opened on 17th May 2021, with trams running on Line 31 between Alviks strand and Bromma flygplats (Claesson, 2021).

Tvärbanan was used by around 108,000 passengers per weekday in 2019 (Storstockholms Lokaltrafik, 2019).

5.7.1. Scope of the Simulation

The aim of the project is to evaluate the performance of the designed architecture through the simulation of train traffic on the Tvärbanan line.

The simulation activity was divided into several phases: starting from the evaluation of the minimum headway along the line moving to a complete operational simulation applying a deep analysis on the startup phase, the peak hour, and on the management of level crossing.

5.7.2. Lines Overview

Tvärbanan has two lines (30 and 31). Line 30 with 26 stops, going from Sickla south of the Stockholm city centre through Gullmarsplan, Årsta, Liljeholmen, Gröndal, Stora Essingen, Alvik west of the city centre, and Sundbyberg to Solna (Figure 384). A single-stop extension from Sickla udde to Sickla opened on October 2017 (Barrow, 2017). The Friends Arena can be reached within 15 minutes' walk from there. Bromma Airport is a 600 metre walk from Karlsbodavägen stop.

The infrastructure analysed by the simulations is the light rail system between Solna and Sickla Station. The lines involved in the analyses are the following:

- Solna line;
- Sickla line.

Solna line runs between the stations of Solna and Alvik while Sickla line runs between the stations of Alvik and Sickla Station.

Three mixed zones are part of the infrastructure data (Figure 384):

- The first one is called in this document “Mixed Zone 1”, or “MZ 1”, and it is located inside the Solna line;
- The second one is called in this document “Mixed Zone 3”, or “MZ 3”, and it is located inside the Sickla line;
- The third one is called in this document “Mixed Zone 4”, or “MZ 4”, and it is located inside the Sickla line.

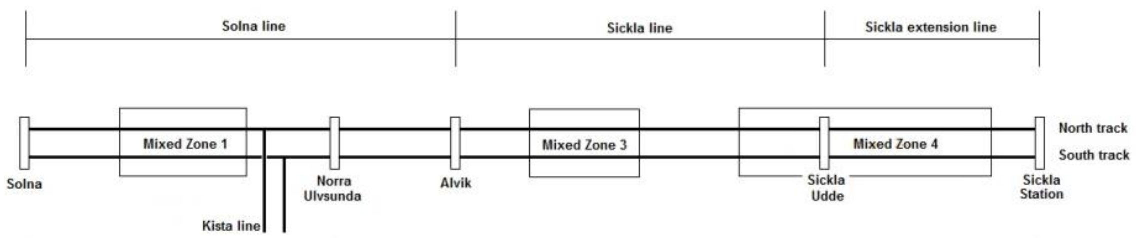


Figure 384 – Tvärbanan line

5.7.3. Simulation Model Assumption

Here below the modelling assumptions related to the input used for the simulation are described.

5.7.3.1 Line Topology

The network layout is modelled in OpenTrack tool with a sequence of nodes and links. Each node is identified with a kilometric reference, where a singular point is located (signal, point, axle counter, stopping point, speed profile or gradient profile changing).

Each edge is characterized by the following features:

- length (difference between the progressive kilometres of two consecutive vertices);
- gradient (based on ATC Diagram gradient profile);
- no tunnel if is an outside edge;
- tunnel double smooth if is an inside tunnel edge;
- none information about curve radius;
- loop/ Radio ETCS (flagged for all edges, to allow a continue communication between track and tram);
- overlap (flagged only for overlap edges);
- speed for tram speed type and both directions, according to track speed profile.

Signals types used in OpenTrack, are:

- Main Signal (home, block or exit signal for Signal);
- Stopping position (stop head signal at platform for passenger tram);
- Level crossing (start/end of the level crossing section).

Each Signal, in OpenTrack, is set as track speed only (based on track speed profile).

5.7.3.2 Overlap

The overlap distances are calculated in accordance with the safety overlap braking model described in the ATP stopping distance and overlap calculation document and based on that document, a separate calculation of the overlap distance will be provided for each main signal.

5.7.3.3 Speed Profile

The simulations will be carried out using the ATP speed profile reported on drawings.

5.7.3.1 Interlocking Routes

In addition to the infrastructure elements, interlocking routes are needed to model tram runs. An interlocking route is defined from one main signal to a following main signal. Each route is characterized by a setting time (reserve time) and a release time.

Route Setting time

Route Setting time has been estimated at nominal conditions considering the following contributions:

- IXL to set the route;
- AIRGAP microwave to transmit the MA to the on-board.

considering the architectural principles and the behaviour of Alstom subsystems, IXL unit cycle and the related response times.

We assumed the following values:

- 1.5 s for routes without need for point movement (e.g. routes sections without points or without need for point movement);
- 6.5 s for routes with need for point movement (i.e. the route including the splitting point).

Route Release Time

The section clearing (based on release groups and overlap, according to signalling characteristics) is assumed in 0.3 seconds.

If a main route is locked for signal 1 to signal 2 and signal 1 is displaying a proceed aspect, under normal tram working conditions signal 1 will be set to stop as soon as the incoming tram has occupied the $T_{F1(1)}$ track section.

The 'Approach Lock' will be released as soon as the tram occupies the second track section $T_{F2(1)}$ and proving the sequential occupancy of the first $T_{F1(1)}$ and second $T_{F2(1)}$ track sections.

After releasing the signal 1 approach lock, the interlocking will initiate the passage release (TORR) as soon as $T_{F1(1)}$ track becomes clear.

When the tram clears the $T_{F1(1)}$ track section, the $T_{F1(1)}$ track section becomes not locked. When the tram clears the $T_{F2(1)}$ track section, then the track section $T_{F2(1)}$ will become not locked.

As soon as track sections $T_{F1(1)}$ and $T_{F2(1)}$ are not locked, then another route can be set from the signal 1 to signal 3, if all the other required conditions for setting a route are satisfied.

When the tram clears the $T_{F3(1)}$ track section, then the $T_{F3(1)}$ track section will become not locked.

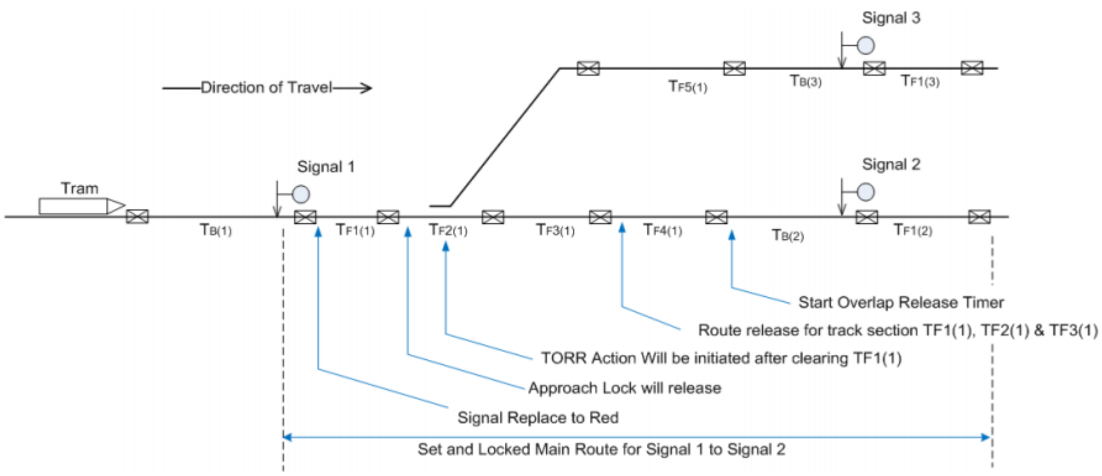


Figure 385 – Typical Route Passage Release

The last track section $T_{B(2)}$ of the route and the overlap track section $T_{F1(2)}$ will be released at the same time, when the last track section $T_{B(2)}$ has become occupied and the Overlap Release Timer has timed out and no forward route has been set.

The individual Overlap Release Timer values is assumed 0.3 s.

5.7.3.1 Level Crossing

The presence of the Level Crossings (KSIs) has been considered along the whole line; here below related assumptions are shown:

- if two trams are crossing a LC in the opposite direction, the first tram requests and gets the priority and it passes through its P point, starting the timeout of 150 sec, and a second tram reaches its strike out point up to 150 seconds from the timeout initialized by the first tram, the second tram crosses the LC area in the same priority of the first;
- if two trams are crossing a LC in the opposite direction, and the first tram requests and gets the priority, and it pass through its P point, starting the timeout of 150 sec, and a second tram reaches its strike out point after 150 seconds from the timeout initialized by the first tram, the second tram crosses the LC area in different priority of the first one with the following different possible behaviors:
    - if T car passage > 25 sec the second tram pass through the level crossing without stopping at the main signal before the level crossing;
    - if T car passage ≤ 25 sec the second tram have to stop at the main signal before the level crossing in order to allow a minimum T car passage equal to 25 sec.

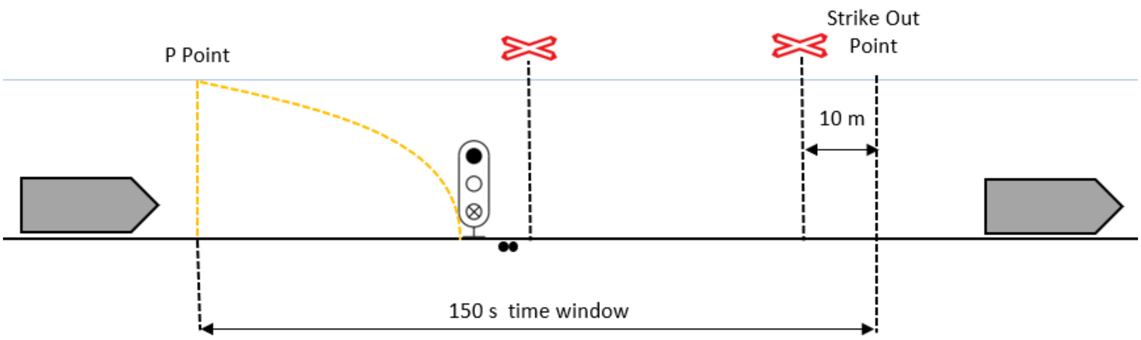


Figure 386 – Level Crossing time window

where:

- P is the point where the tram should start to brake if the signal before the LC is red;
- Strike out point is fixed 10 meters after the LC.

5.7.3.2 Rolling Stock

On the basis of information available, it has been assumed that trams are Bombardier Flexity Swift composed of two A32 vehicle types for a total length of 60 m (30 m for each car).

The Figure 387 shows the single tram set composition.

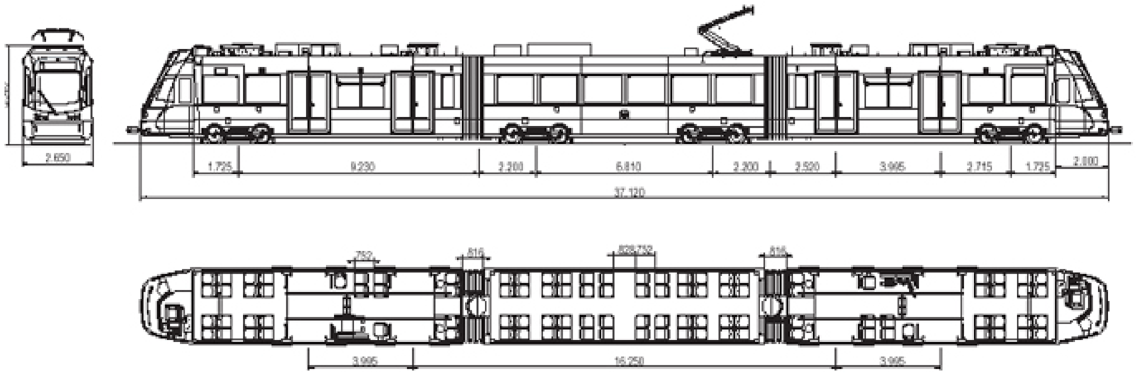


Figure 387 – A32 Single Tram Set

In Table 64 the technical data is shown of A32 tram single set.

Parameter	Value
Load	55 t
Adherence load (Not influence, covered by tractive effort / speed diagram)	51 t
Length	30 m
Max. Tractive Effort	60 KN
Max. Acceleration	0,8 m/s^2
Resistance Factor (OT default value)	3,2999
Rotating Mass Factor (OT default value)	1,073
Engine	Electric Engine

Table 64 – A32 single set technical data.

In Figure 388 the IR4 traction force diagram is shown.

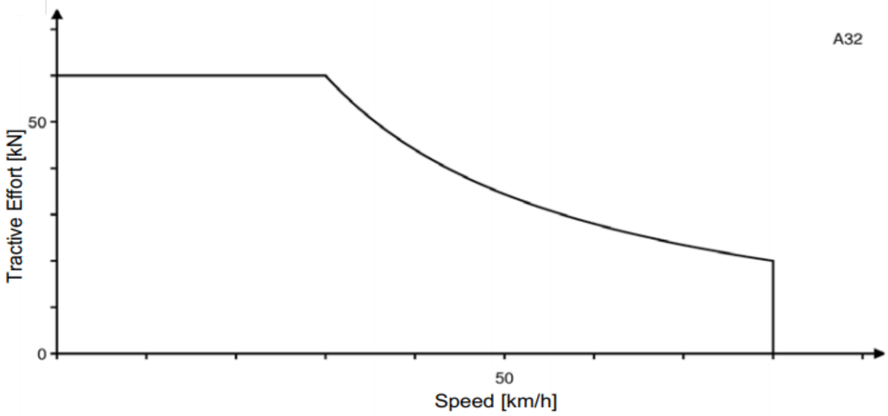


Figure 388 – A32 Traction Force.

Considering the final composition of 2 train sets, Table 65 reports the A32 train technical data.

Parameter	Value
Load	110 t
Length	60 m
Air Resistance	Strahl / Sauthoff Formula
Curve Resistance (Roeckl Formula)	Not Applied
Braked Weight Percentage (BWP)	Not Relevant for Deceleration function
Deceleration function	Default (ETCS)
Comfort Braking Deceleration Profile (C Curve)	**Speed interval / km/h**: 0 – 80; **Deceleration / m/s²**: 0,8
Service Braking Deceleration Profile (S Curve)	**Speed interval / km/h**: 0 – 80; **Deceleration / m/s²**: 1,3

Table 65 – A32 tram technical data.

5.7.3.3 ATP Braking Curve

In accordance to the Storstockholms Lokaltrafik requirements all the capacity simulations are carried out using:

- the Comfort Braking Curve (C);
- the Service Braking Curve (S).

Figure 389 shown an example of C, S curves provided for each tram.

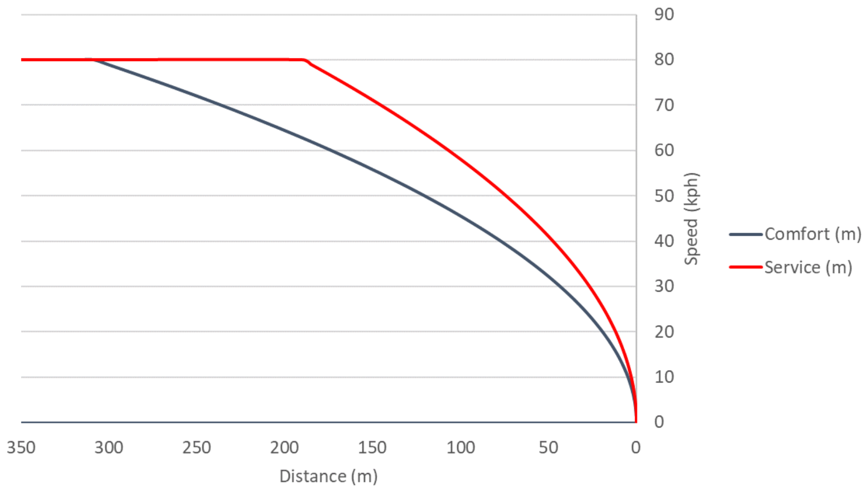


Figure 389 – ATP Braking Curves

The braking curves and the braking distances provided by Storstockholms Lokaltrafik are based on normal adhesion condition and at level track (0% gradient), the simulations are carried out using also in a sloping track (gradient profile different from 0) the same braking curves and braking distances used in a level track.

Here below, in Table 66 and Figure 390, the Flexity Swift (A32) tram new braking curves depending by the length.

Speed (km/h)	Comfort Braking Distance (m)	Service Braking Distance (m)
80	309	190
70	236	145
60	174	107
50	121	74
40	77	47
30	43	27
20	19	12
10	5	3
0	0	0

Table 66 – A32 braking curves.

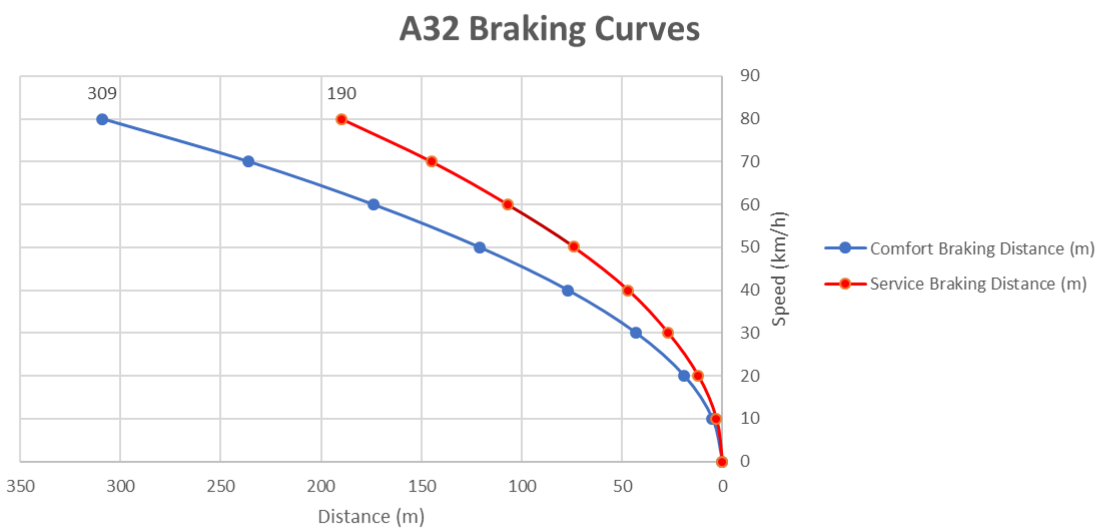


Figure 390 – A32 braking curves

5.7.3.4 Dwell Time

The dwell time at stations has been defined as the time required for loading and unloading passengers (Table 67).

Acronyms	Station	Dwell Time [s]	Line
SOA	Solna Station	180	Solna Line
SOC	Solna Centrum	60	Solna Line
SBP	Solna Business Park	35	Solna Line
SBG	Sundbyberg centrum	60	Solna Line
BAB	Bällsta Bro	25	Solna Line
KOV	Karlsbodavägen	25	Solna Line
NUS	Norra Ulvsunda	45	Solna Line
JOF	Johannesfred	25	Solna Line
ALV	Alvik	60	Solna Line / Sickla Line
AVS	Alviks Strand	25	Sickla Line
SES	Stora Essingen	25	Sickla Line
GRD	Gröndal	25	Sickla Line
TRK	Trekanten	25	Sickla Line
LIH	Liljeholmen	60	Sickla Line

Acronyms	Station	Dwell Time [s]	Line
ÅRD	Årstadal	25	Sickla Line
ÅRB	Årstaberg	40	Sickla Line
ÅRF	Årstafältet	25	Sickla Line
VTO	Valla Torg	25	Sickla Line
LDE	Linde	25	Sickla Line
GLB	Globen	25	Sickla Line
GUP	Gullmarsplan	60	Sickla Line
MÅD	Mårtensdal	25	Sickla Line
LUM	Luma	25	Sickla Line
SIA	Sickla Kaj	25	Sickla Line
SIU	Sickla Udde	25	Sickla Line
SIK	Sickla Station	180	Sickla Line

Table 67 – Stations Dwell Time.

5.7.4. Capacity Headway Requirements

According to Figure 391 the headway requirements are:

- 120 sec for the part of line between Solna and Norra Ulvsunda;
- 110 sec for the part of line between Norra Ulvsunda and Sickla station.

The headway cases must be fulfilled for each scenario and for each track in nominal direction. The achievement of the requested headway cannot be calculated in the mixed zones, because in the mixed zones there is no signalling system and trams respect traffic light system.

The operational headway to be achieved is the following (Figure 391):

- 5 min for the part of line between Solna and Norra Ulvsunda;
- 2.5 min for the part of line between Norra Ulvsunda and Sickla station;
- 5 min for the insertion/deletion of Kista line tram service.

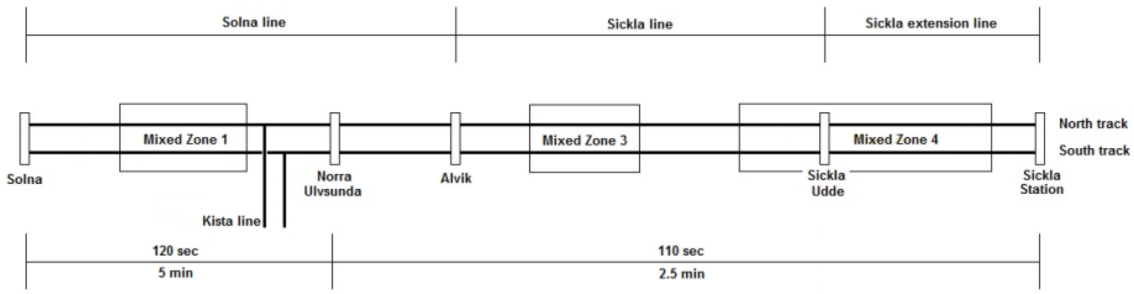


Figure 391 – Headway Requirements

As the minimum headway has not to be evaluated in the mixed zones, the line has been divided in four sections (Figure 392):

- Section 1: Solna Station – Mixed zone 1 (headway 120 sec);
- Section 2: Mixed zone 1 – Norra Ulvsunda (headway 120 sec);
- Section 3: Norra Ulvsunda Station – Mixed Zone 3 (headway 110 sec);
- Section 4: Mixed Zone 3 – Mixed Zone 4 (headway 110 sec);
- Section 5: Mixed Zone 4 – Sickla Station (headway 110 sec).

The mixed zones are considered as a "black box":

- Each tram takes the same amount of time to cross a mixed zone;
- The second tram does not gain or lose time compared to the first tram.

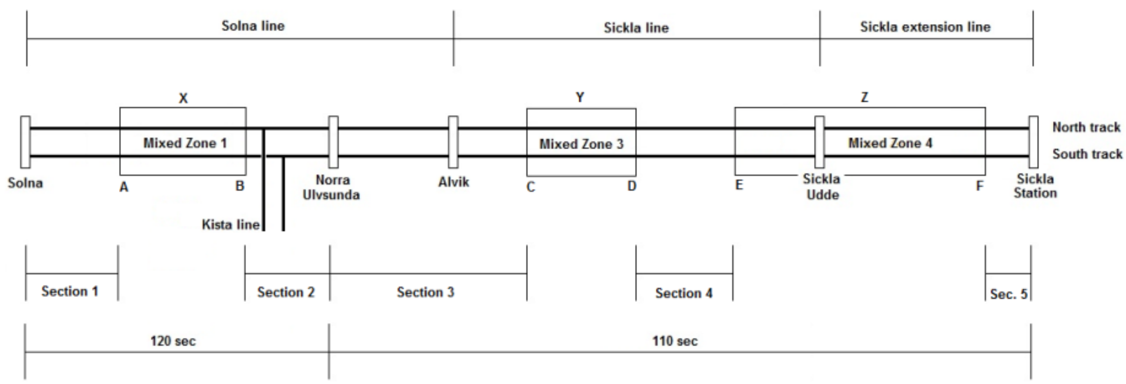


Figure 392 – Mixed Traffic Zone assumptions

For example, regarding trams running on South track:

- X is the amount of time a tram takes to cross the mixed zone 1;
- Y is the amount of time a tram takes to cross the mixed zone 3;
- Z is the amount of time a tram takes to cross the mixed zone 4;
- Each tram reaches point A, point C and point E with a speed greater than zero;
- Each tram leaves point B, point D and point F with a speed greater than zero;
- X amount of time has to be added to the timetable of the trams leaving the point B;

- Y amount of time has to be added to the timetable of the trams leaving the point D;
- Z amount of time has to be added to the timetable of the trams leaving the point F.

To achieve the minimum headway, simulations are performed running two trams, one after the other, starting with the required headway, i.e. 110 sec or 120 sec, depending on the section and the line, as in the following tables, both for south and north track (Table 68, Table 69):

Section	Route	Requested Headway [s]
1	Solna Station – Mixed Zone 1	120
2	Mixed Zone 1 – Norra Ulvsunda	120
3	Norra Ulvsunda – Mixed Zone 3	110
4	Mixed Zone 3 – Mixed Zone 4	110
5	Mixed Zone 4 – Sickla Station	110

Table 68 – South track: requested headway.

Section	Route	Requested Headway [s]
5	Sickla Station – Mixed Zone 4	110
4	Mixed Zone 4 – Mixed Zone 3	110
3	Mixed Zone 3 - Norra Ulvsunda	110
2	Norra Ulvsunda - Mixed Zone 1	120
1	Mixed Zone 1 – Solna Station	120

Table 69 – North track: requested headway.

After the first simulation, two probable results are possible:

- The second tram, following the first one, has no perturbation. It means that the minimum headway is lower than or equal to the required headway. Simulations are iterated, headway is lowered until the second tram has a delay: that is the minimum achievable headway;
- The second tram, following the first one, has delay. This means that for that section the required headway cannot be achieved. Simulations are then iterated, headway is raised until the second tram has no perturbation: that is the minimum achievable headway.

Simulations have been performed outside the mixed zones, as these sections are controlled by signalling, while in mixed zones trams follows traffic light signals.

5.7.5. Minimum Headway Simulation Results

The following chapters show the results of the simulations related to the minimum achievable headway. Simulation are performed with both values of deceleration.

5.7.5.1 Simulation with Comfort Braking

The following paragraphs show the results of the simulations performed searching the minimum headway, for south and north track with comfort braking applied.

It must be noted that the concepts of “delay” and “minimum headway” are not related in a linear way.

The delay is concerning the first simulation trying to reach the requested headway: if the requested headway is not reached, the second tram takes a delay. Then, simulations are performed to understand the achievable headway value where the second tram has no delay.

In the following tables the column showing the delay is referred to the delay concerning the first simulation trying to reach the requested headway, while the minimum headway is referred to the simulations performed after the information that the first simulation provokes delay of the second tram.

South Track

Table 70 show the results of the simulations for each section of the South track.

Section	Route	Requested Headway	Minimum Headway	Delay [s]
1	Solna Station – Mixed Zone 1	120	**109**	-
2	Mixed Zone 1 – Norra Ulvsunda	120	**90**	-
3	Norra Ulvsunda – Mixed Zone 3	110	**122**	**4**
4	Mixed Zone 3 – Mixed Zone 4	110	**111**	**1**
5	Mixed Zone 4 – Sickla Station	110	**37**	-

Table 70 – Headway: Comfort Braking – Normal Flow – South Track.

For the “Solna station – Mixed zone 1” section the requested headway of 120 s is achieved. The minimum headway is lower than the requested headway. Figure 393 show the running profile of the tram in this section while Figure 394 show the tram graph.

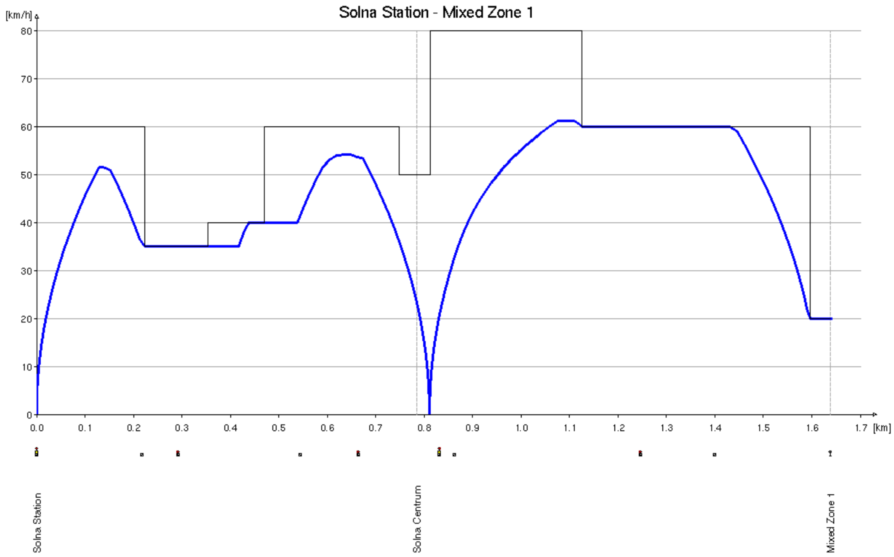


Figure 393 – Comfort Braking: Solna Station – MZ1: Speed–Distance diagram

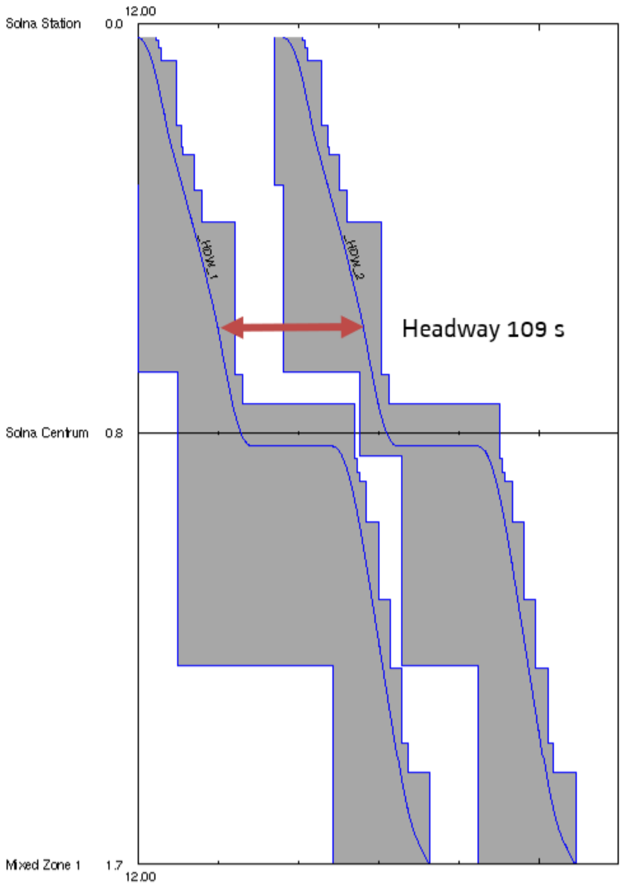


Figure 394 – Comfort Braking: Solna Station – MZ1: Tram graph diagram HW 109 s

For the “Mixed zone 1 – Norra Ulvsunda” section the requested headway of 120 s is achieved. The minimum headway is lower than the requested headway. Figure 395 show the running profile of the tram in this section while Figure 396 show the tram graph.

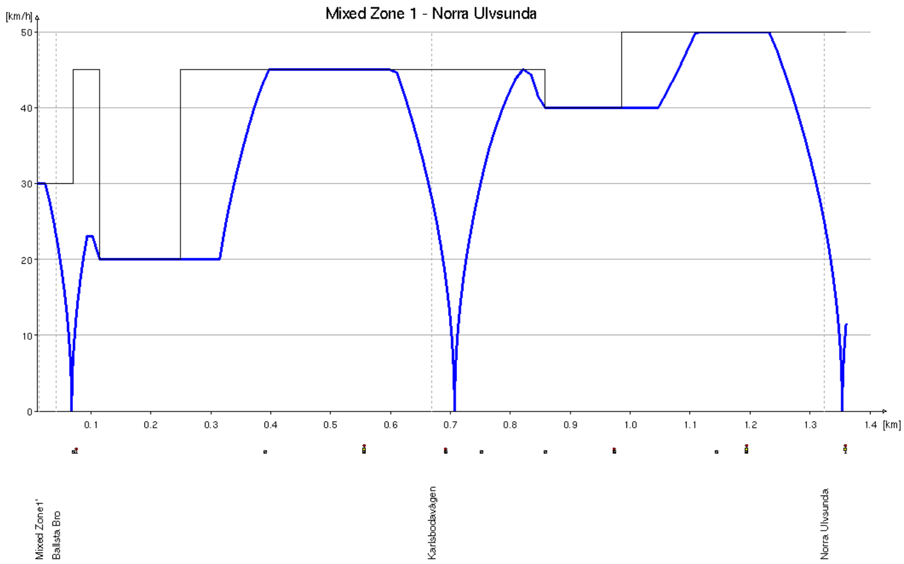


Figure 395 – Comfort Braking: MZ1 – Norra Ulvsunda: Speed–Distance diagram

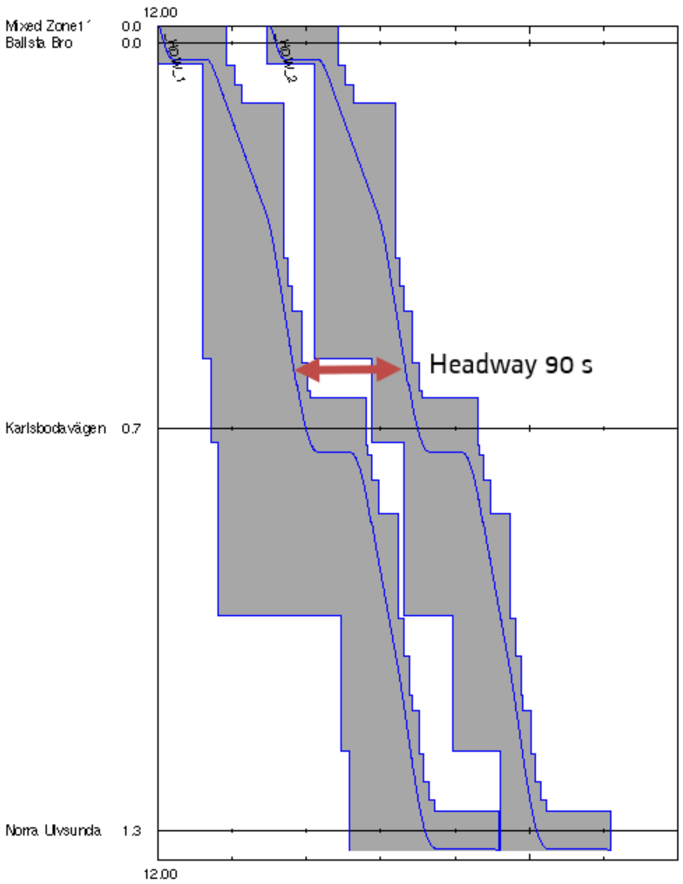


Figure 396 – Comfort Braking: MZ1 – Norra Ulvsunda: Tram Graph with HW 90 s

For the "Norra Ulvsunda – Mixed zone 3" section the requested headway is not achieved:

- The minimum achievable headway without perturbation between trams is 122 s;
- The simulation for the achievement of the requested headway of 110 sec shows a conflict.

The conflict is due to the breaking action of the second tram before the signal 0023.The presence of the first tram in the station of Alvik (dwell time 60 sec) inhibits the release of the section after the signal 0023. The position of signal 0023 is not possible to move to a location where headway is achieved as this would reduce the signal visibility to be non-compliant to SL standards.

Figure 397 shows the Speed-Distance diagram of the trams while Figure 398 shows the tram graph with the minimum achievable headway and the conflict point with 110 s headway.

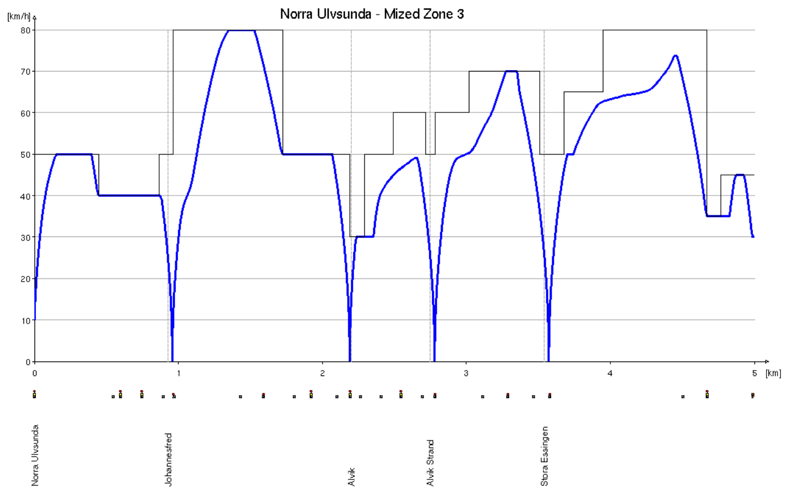


Figure 397 – Comfort Braking: Norra Ulvsunda – MZ3: Speed–Distance diagram

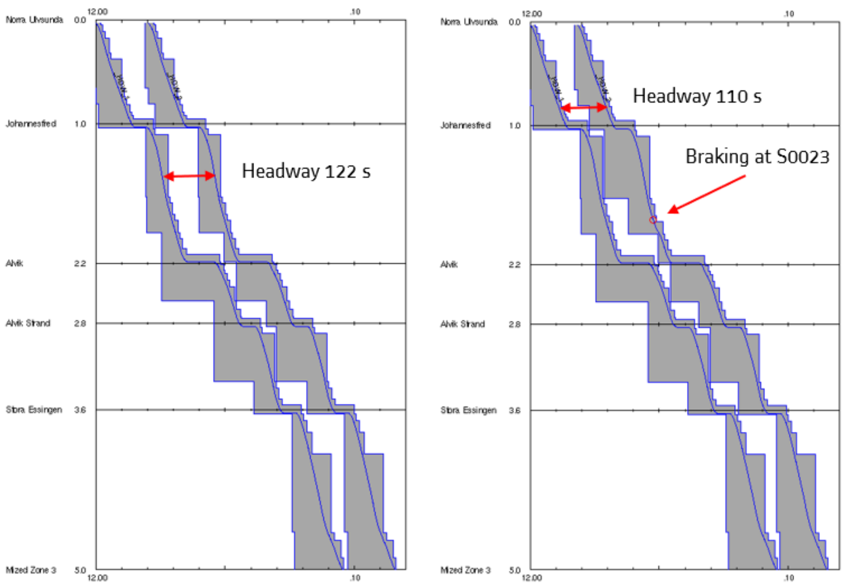


Figure 398 – Comfort Braking: Norra Ulvsunda – MZ3: Tram Graph with HW 122s (left) and with HW 110s (right)

For the “Mixed Zone 3 – Mixed Zone 4” section the requested headway is not achieved:

- The minimum achievable headway without perturbation between trams is 111 s;
- The simulation for the achievement of the requested headway of 110 sec shows a conflict.

The conflict is due to the breaking action of the second tram before the signal 1063.The presence of the first tram in the station of Gullmarsplan (dwell time 60 sec) inhibits the release of the section after the signal 1063.

Figure 399 shows the Speed-Distance diagram of the trams while Figure 400 shows the tram graph with the minimum achievable headway and the conflict point with 110 s headway.

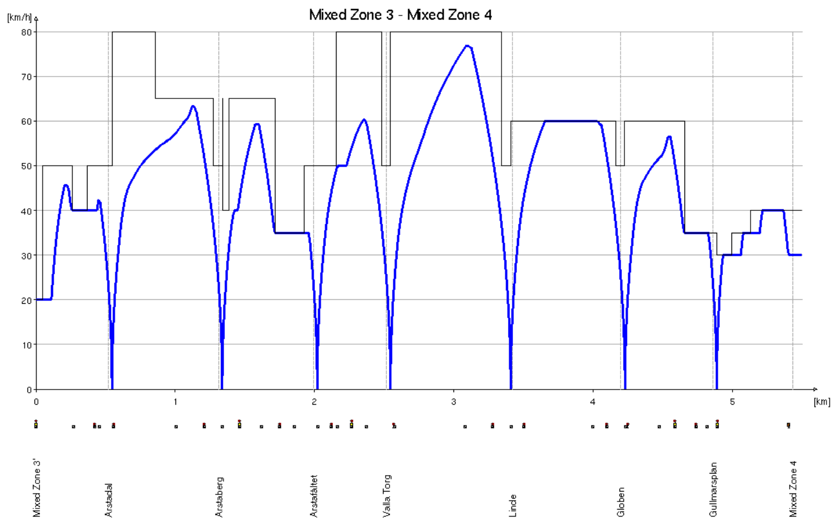


Figure 399 – Comfort Braking: Mz3 – MZ4: Speed–Distance diagram

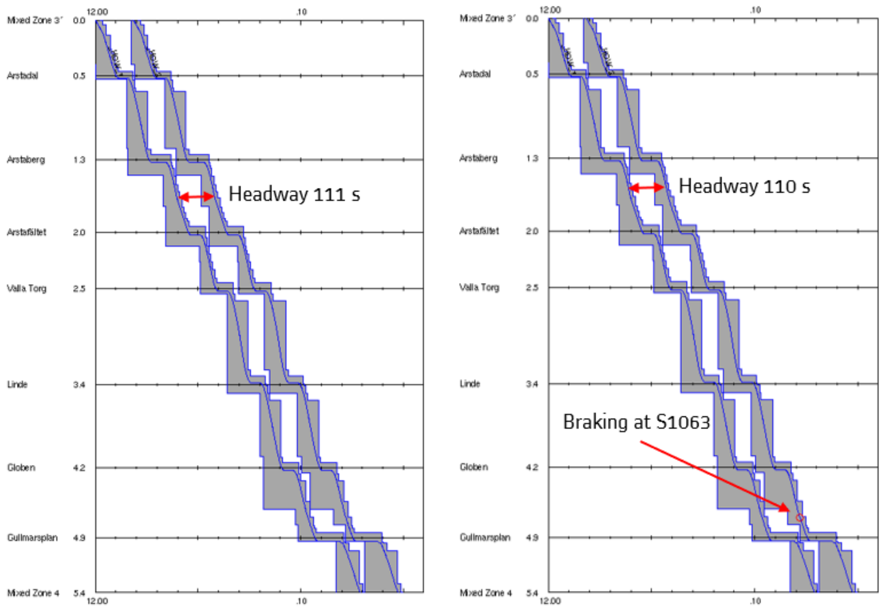


Figure 400 – Comfort Braking: Mz3 – MZ4: Tram Graph with HW 111s (left) and with HW 110s (right)

For the "Mixed Zone 4 – Sickla Station" section the requested headway of 110 s is achieved. The minimum headway is lower than the requested headway. Figure 401 show the running profile of the tram in this section while Figure 402 show the tram graph.

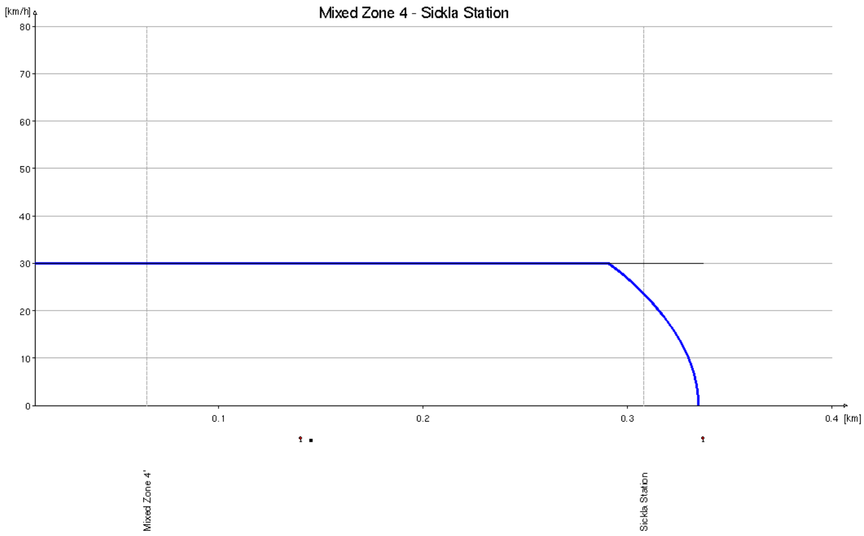


Figure 401 – Comfort Braking: Mz4 – Sickla Station: Speed–Distance diagram

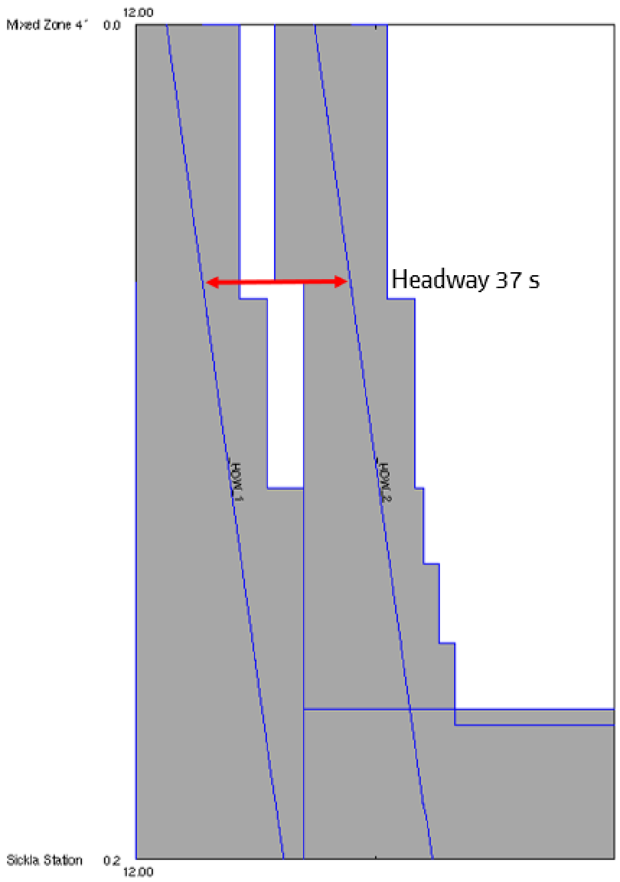


Figure 402 – Comfort Braking: Mz4 – Sickla Station: Tram Graph with HW 37s

North Track

Table 71 show the results of the simulations for each section of the North track for normal flow.

Section	Route	Requested Headway	Achievable Headway	Delay [s]
5	Sickla Station – Mixed Zone 4	110	**18**	-
4	Mixed Zone 4 – Mixed Zone 3	110	**116**	**2**
3	Mixed Zone 3 – Norra Ulvsunda	110	**121**	**5**
2	Norra Ulvsunda – Mixed Zone 1	120	**82**	-
1	Mixed Zone 1 – Solna Station	120	**112**	-

Table 71 – Headway: Comfort Braking – Normal Flow – North Track

For the “Sickla Station – Mixed Zone 4” section the requested headway of 110 s is achieved. The minimum headway is lower than the requested headway. Figure 403 show the running profile of the tram in this section while Figure 404 show the tram graph.

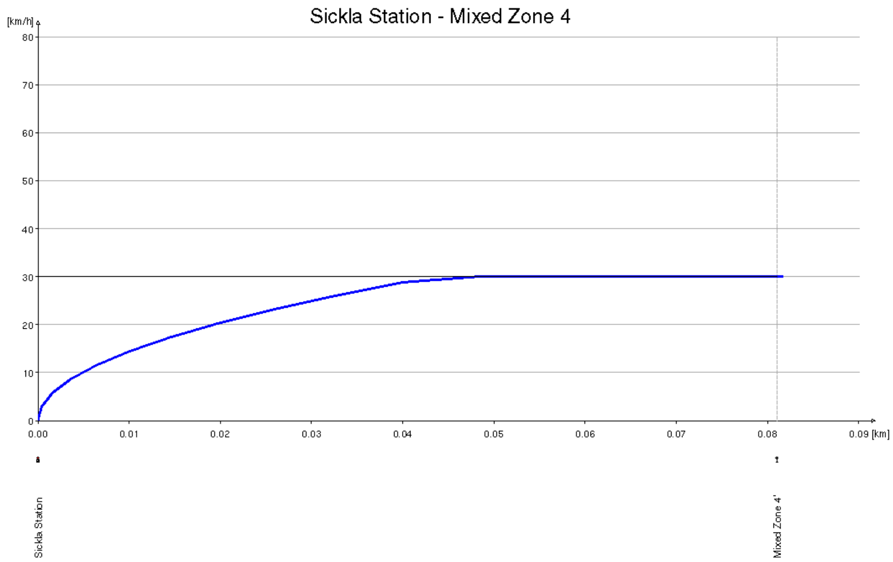


Figure 403 – Normal Flow 0.8 m/s2: Sickla Station – MZ4: Speed–Distance diagram

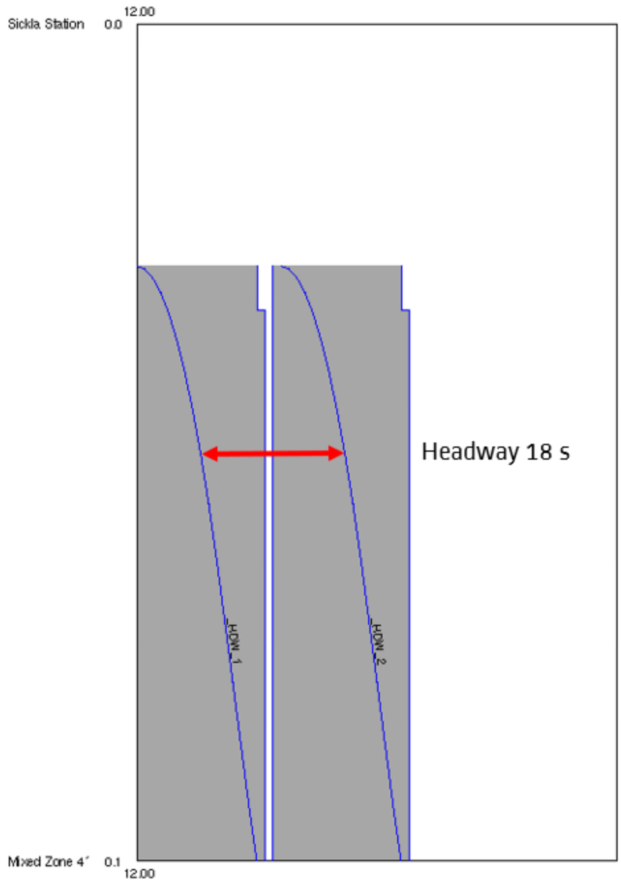


Figure 404 – Normal Flow 0.8 m/s2: Sickla Station – MZ4: Tram Graph with HDW 18s

For the "Mixed Zone 4 – Mixed Zone 3" section the requested headway is not achieved:

- The minimum achievable headway without perturbation between trams is 116 s;
- The simulation for the achievement of the requested headway of 110 sec shows a conflict.

The conflict is due to the breaking action of the second tram before the signal 1092.The presence of the first tram in the station of Gullmarsplan (dwell time 60 sec) inhibits the release of the section after the signal 1092.

Figure 405 shows the Speed-Distance diagram of the trams while Figure 406 shows the tram graph with the minimum achievable headway and the conflict point with 110 s headway.

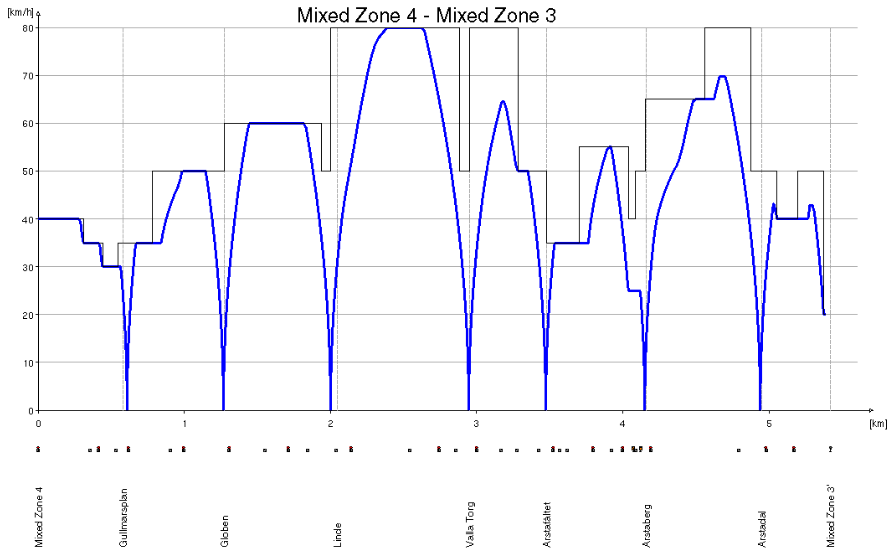


Figure 405 – Comfort Braking: MZ4 – MZ3: Speed–Distance diagram

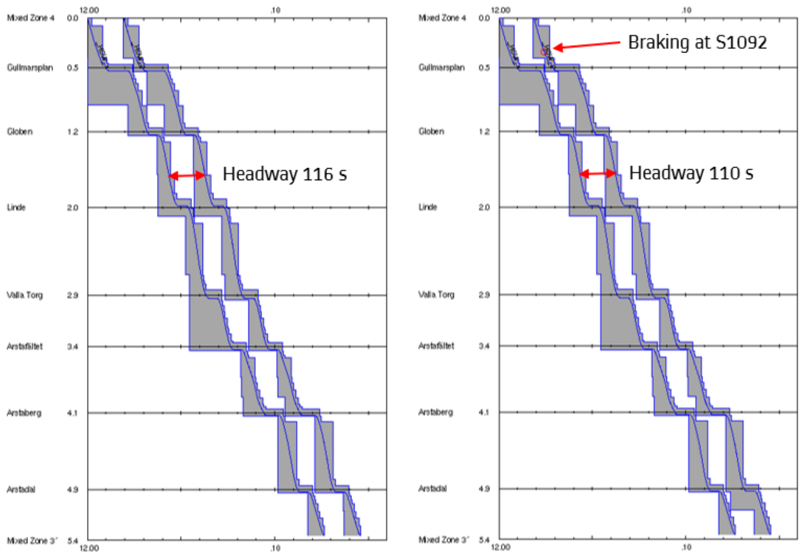


Figure 406 – Comfort Braking: MZ4 – MZ3: Tram Graph with HW 116s (left) and with HW 110s (right)

For the "Mixed Zone 3 – Norra Ulvsunda" section the requested headway is not achieved:

- The minimum achievable headway without perturbation between trams is 121 s;
- The simulation for the achievement of the requested headway of 110 sec shows a conflict.

The conflict is due to the breaking action of the second tram before the signal 0178.The presence of the first tram in the station of Alvik (dwell time 60 sec) inhibits the release of the section after the signal 0178. The position of signal 0178 is not possible to move to a location where headway is achieved as this would reduce the signal visibility to be non-compliant to SL standards.

Figure 407 shows the Speed-Distance diagram of the trams while Figure 408 shows the tram graph with the minimum achievable headway and the conflict point with 110 s headway.

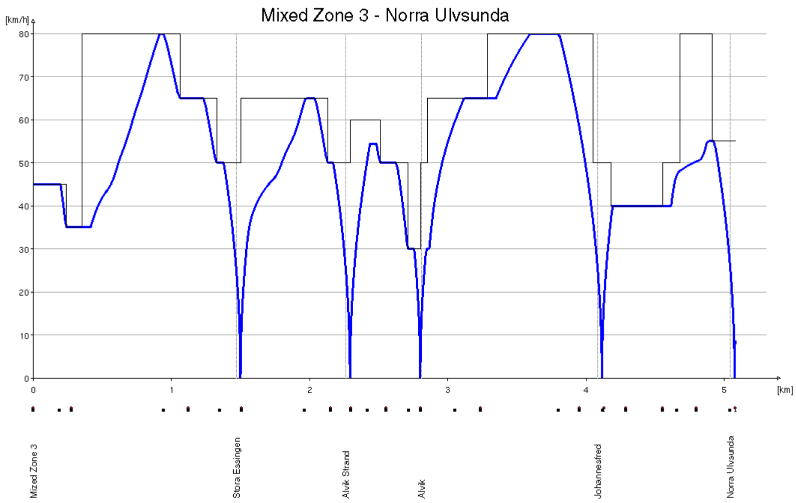


Figure 407 – Comfort Braking: MZ3 – NUS: Speed–Distance diagram

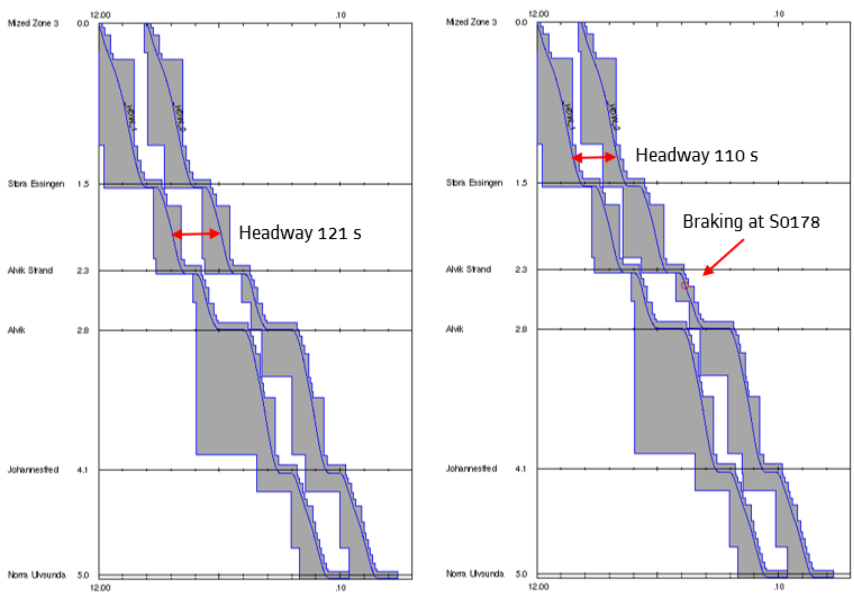


Figure 408 – Comfort Braking: MZ3 – NUS: Tram Graph with HW 121s (left) and with HW 110s (right)

For the "Norra Ulvsunda – Mixed Zone 1" section the requested headway of 120 s is achieved. The minimum headway is lower than the requested headway. Figure 409 show the running profile of the tram in this section while Figure 410 show the tram graph.

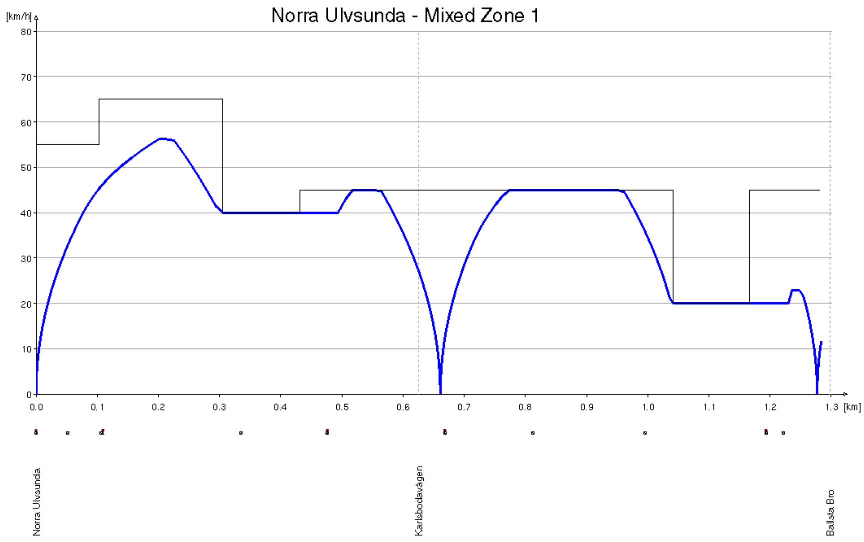


Figure 409 – Comfort Braking: NUS – MZ1: Speed–Distance diagram

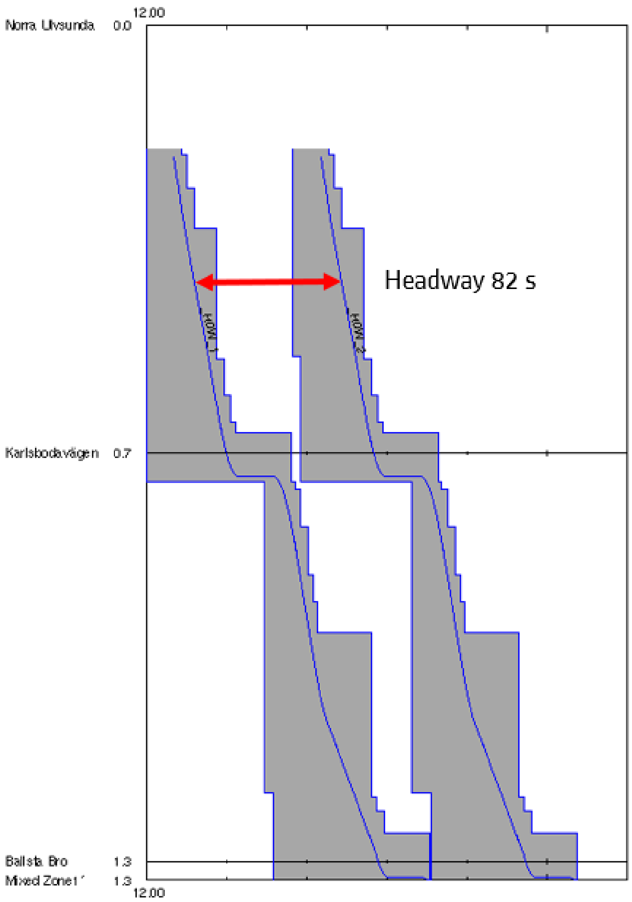


Figure 410 – Comfort Braking: NUS – MZ1: Tram Graph with HW 82s

For the "Mixed Zone 1 – Solna Station" section the requested headway of 120 s is achieved. The minimum headway is lower than the requested headway. Figure 411 show the running profile of the tram in this section while Figure 412 show the tram graph.

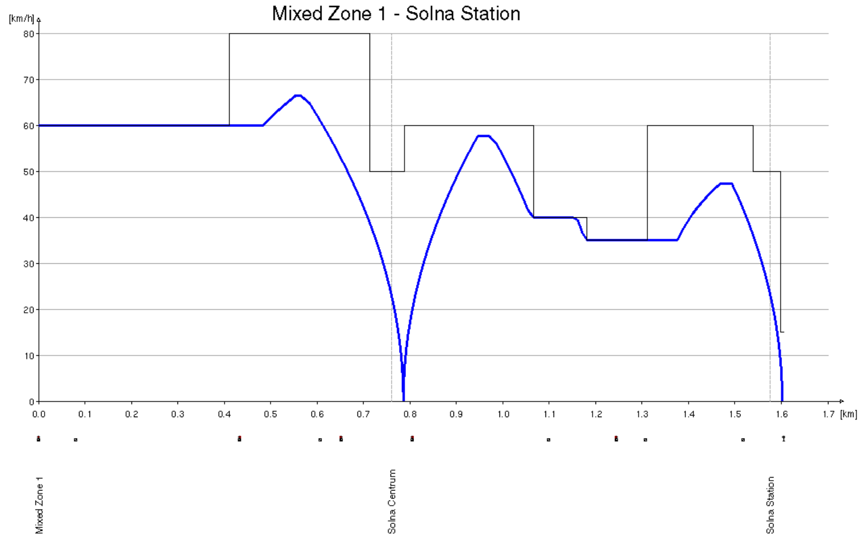


Figure 411 – Comfort Braking: MZ1 – Solna Station: Speed–Distance diagram

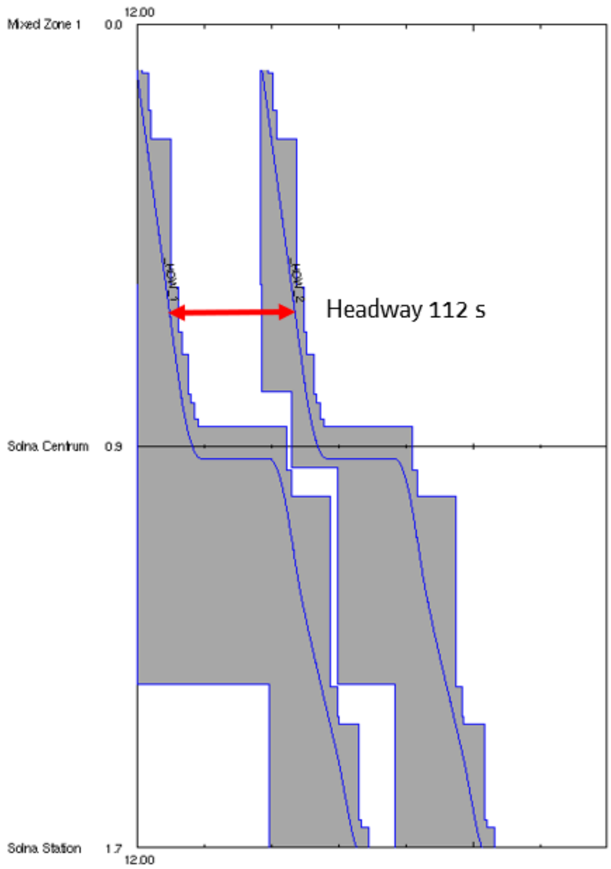


Figure 412 – Comfort Braking: MZ1 – Solna Station: Tram Graph with HW 112s

5.7.5.1 Simulation with Service Braking

This set of simulations aim to understand if there is impact on the achievement of the required headway increasing the braking action of trams.

The braking characteristics of trams are changed from 0.8 m/s^2 to 1.3 m/s^2, which is the service brake value of a tram with an operational ATP system.

The following paragraphs show the result of this new set of simulations searching the minimum headway for south and north track.

It must be noted that the concepts of "delay" and "minimum headway" are not related in a linear way.

The delay is concerning the first simulation trying to reach the requested headway: if the requested headway is not reached, the second tram takes a delay. Then, simulations are performed to understand the achievable headway value where the second tram has no delay.

In the following tables the column showing the delay is referred to the delay concerning the first simulation trying to reach the requested headway, while the minimum headway is referred to the simulations performed after the information that the first simulation provokes delay of the second tram

South Track

Table 72 show the results of the simulations for each section of the South track.

Section	Route	Requested Headway	Achievable Headway	Delay [s]
1	Solna Station – Mixed Zone 1	120	**104**	-
2	Mixed Zone 1 – Norra Ulvsunda	120	**84**	-
3	Norra Ulvsunda – Mixed Zone 3	110	**117**	**4**
4	Mixed Zone 3 – Mixed Zone 4	110	**107**	-
5	Mixed Zone 4 – Sickla Station	110	**34**	-

Table 72 – Headway: Service Brake – Normal Flow – South Track

In sections with required headway of 120 sec the minimum headway is lower than the required headway.

In sections with required headway of 110 sec:

- The simulation for the achievement of the required headway of 110 sec shows a delay due to a conflict between trams;
- The minimum headway is higher than the required headway.

For the “Solna station – Mixed zone 1” section the requested headway of 120 s is achieved. The minimum headway is lower than the requested headway. Figure 413 show the running profile of the tram in this section while Figure 414 show the tram graph.

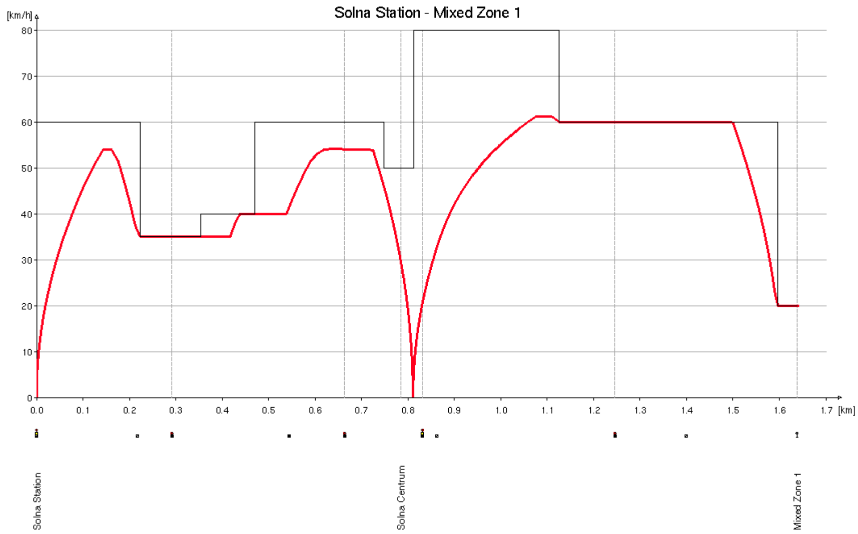


Figure 413 – Service Brake: Solna Station – MZ1: Speed–Distance diagram

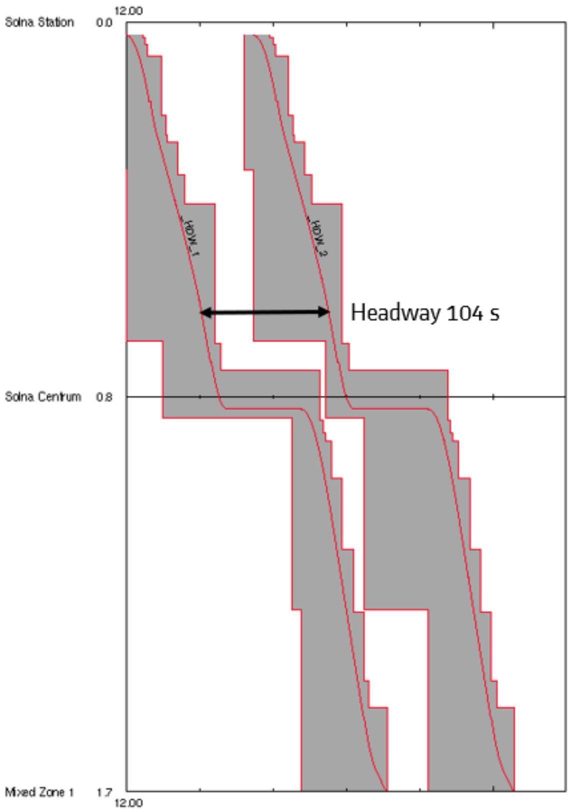


Figure 414 – Service Brake: Solna Station – MZ1: Tram Graph with HW 104s

For the “Mixed zone 1 – Norra Ulvsunda” section the requested headway of 120 s is achieved. The minimum headway is lower than the requested headway. Figure 415 show the running profile of the tram in this section while Figure 416 show the tram graph.

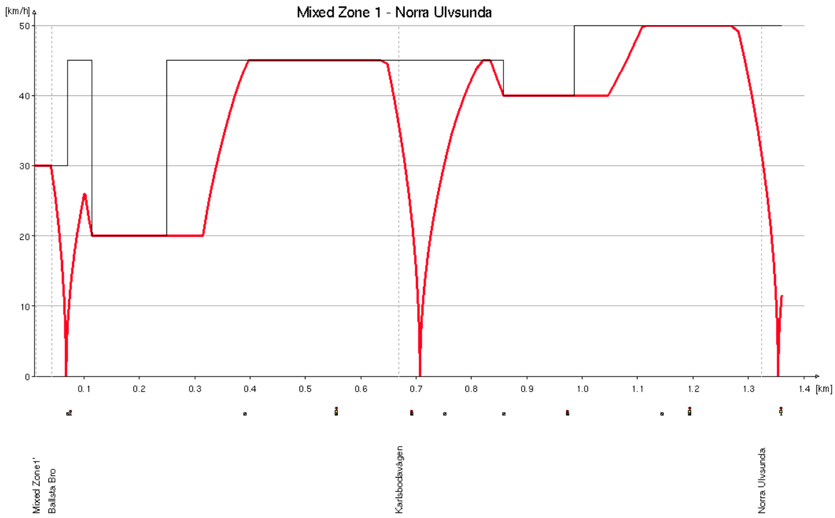


Figure 415 – Service Brake: MZ1 – Norra Ulvsunda: Speed–Distance diagram

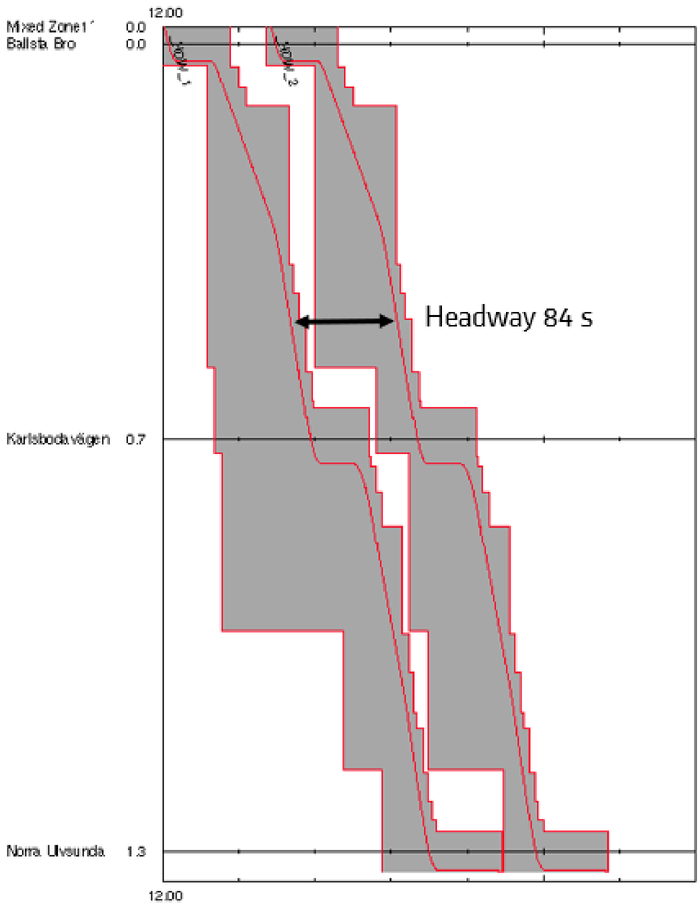


Figure 416 – Service Brake: MZ1 – Norra Ulvsunda: Tram Graph with HW 84s

For the “Norra Ulvsunda – Mixed zone 3” section the requested headway is not achieved:

- The minimum achievable headway without perturbation between trams is 117 s;
- The simulation for the achievement of the requested headway of 110 sec shows a conflict.

The conflict is due to the breaking action of the second tram before the signal 0023.The presence of the first tram in the station of Alvik (dwell time 60 sec) inhibits the release of the section after the signal 0023. The position of signal 0023 is not possible to move to a location where headway is achieved as this would reduce the signal visibility to be non-compliant to SL standards.

Figure 417 shows the Speed-Distance diagram of the trams while Figure 418 shows the tram graph with the minimum achievable headway and the conflict point with 110 s headway.

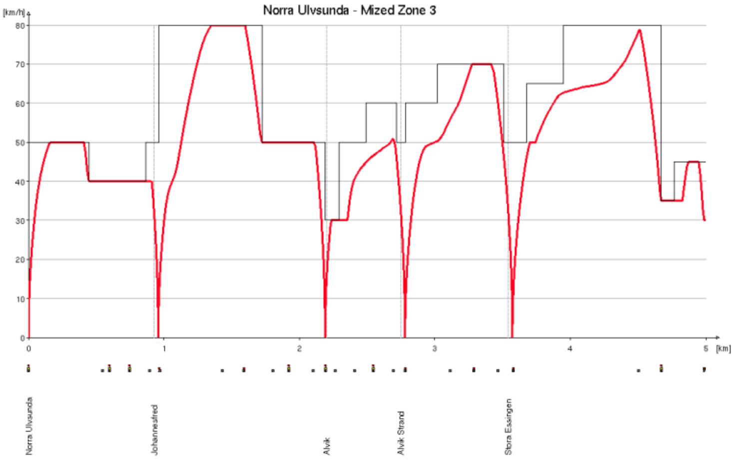


Figure 417 – Service Brake: Norra Ulvsunda – MZ3: Speed–Distance diagram

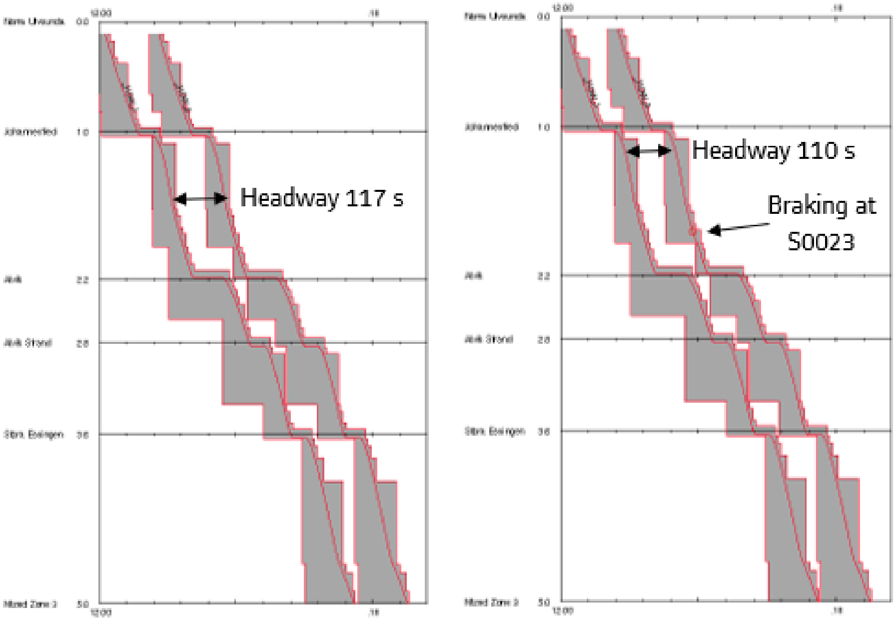


Figure 418 – Service Brake: Norra Ulvsunda – MZ3: Tram Graph with HW 117s (left) and with HW 110s (right)

For the “Mixed Zone 3 – Mixed Zone 4” section the requested headway of 110 s is achieved. The minimum headway is lower than the requested headway Figure 419 shows the Speed-Distance diagram of the trams while Figure 420 shows the tram graph.

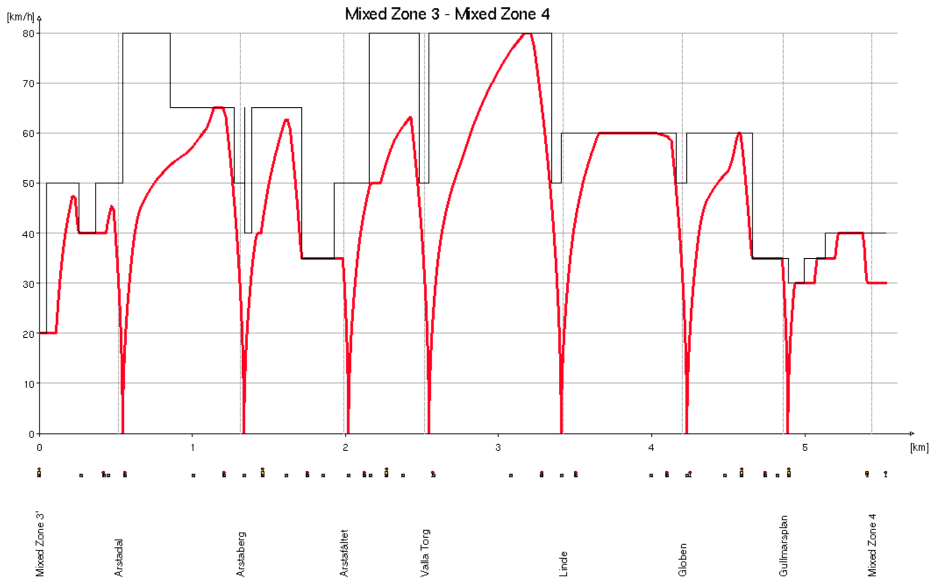


Figure 419 – Service Brake: Mz3 – MZ4: Speed–Distance diagram

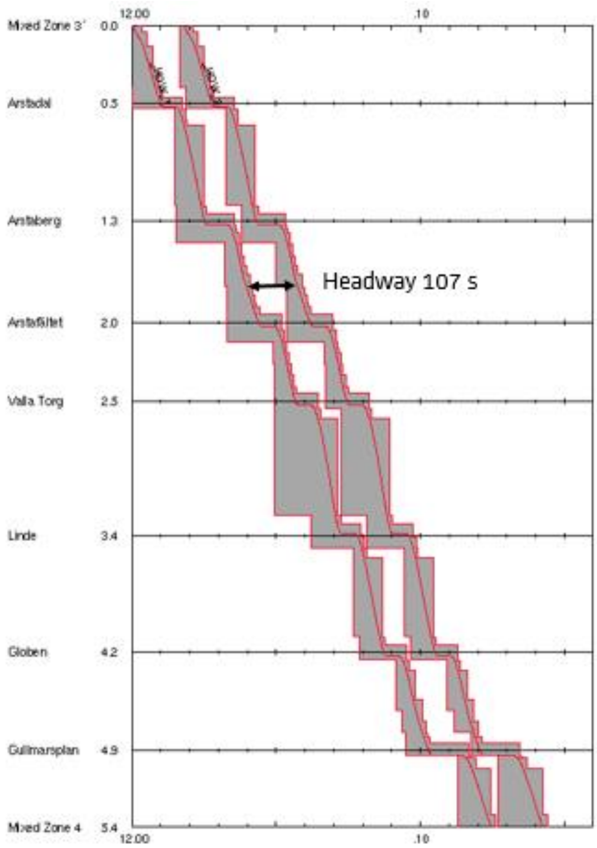


Figure 420 – Service Brake: Mz3 – MZ4: Tram Graph with HW 107s

For the “Mixed Zone 4 – Sickla Station” section the requested headway of 110 s is achieved. The minimum headway is lower than the requested headway. Figure 421 show the running profile of the tram in this section while Figure 422 show the tram graph.

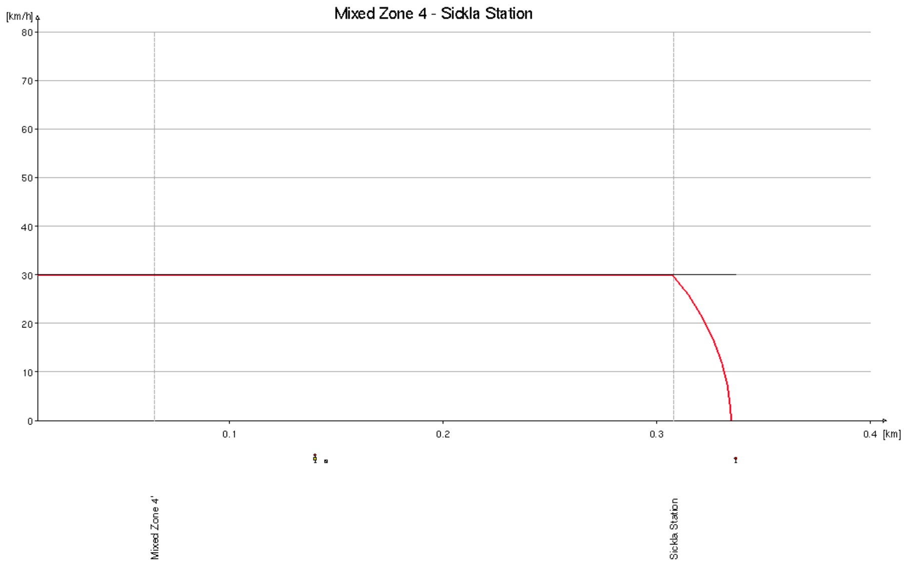


Figure 421 – Service Brake: Mz4 – Sickla Station: Speed–Distance diagram

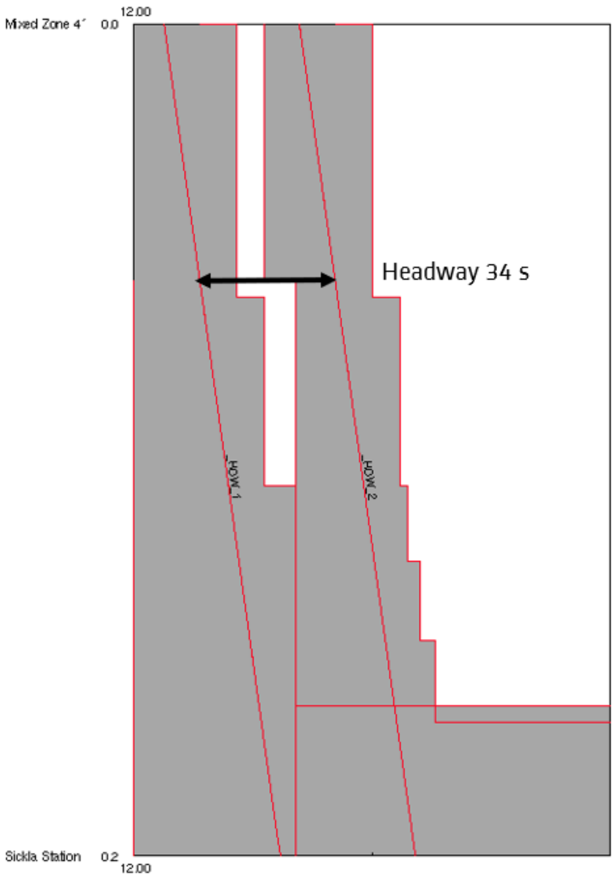


Figure 422 – Service Brake: Mz4 – Sickla Station: Tram Graph with HW 34s

North Track

Table 73 show the results of the simulations for each section of the North track.

Section	Route	Requested Headway	Achievable Headway	Delay [s]
5	Sickla Station – Mixed Zone 4	110	**18**	-
4	Mixed Zone 4 – Mixed Zone 3	110	**112**	**2**
3	Mixed Zone 3 – Norra Ulvsunda	110	**116**	**4**
2	Norra Ulvsunda – Mixed Zone 1	120	**81**	-
1	Mixed Zone 1 – Solna Station	120	**105**	-

Table 73 – Headway: Service Brake – Normal Flow – North Track

In sections with required headway of 120 sec the minimum headway is lower than the required headway.

In sections with required headway of 110 sec:

- The simulation for the achievement of the required headway of 110 sec shows a delay due to a conflict between trams;
- The minimum headway is higher than the required headway.

For each section details are provided.

For the "Sickla Station – Mixed Zone 4" section the requested headway of 110 s is achieved. The minimum headway is lower than the requested headway. Figure 423 show the running profile of the tram in this section while Figure 424 show the tram graph.

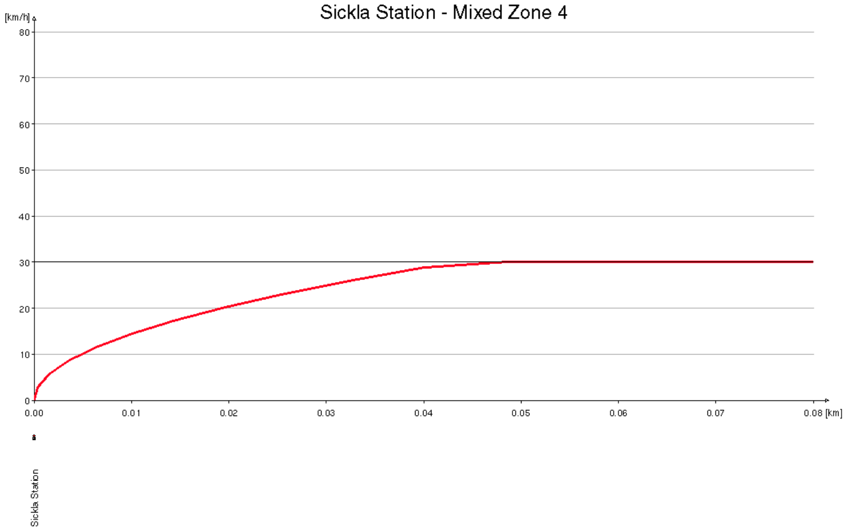


Figure 423 – Service Brake: Sickla Station – MZ4: Speed–Distance diagram

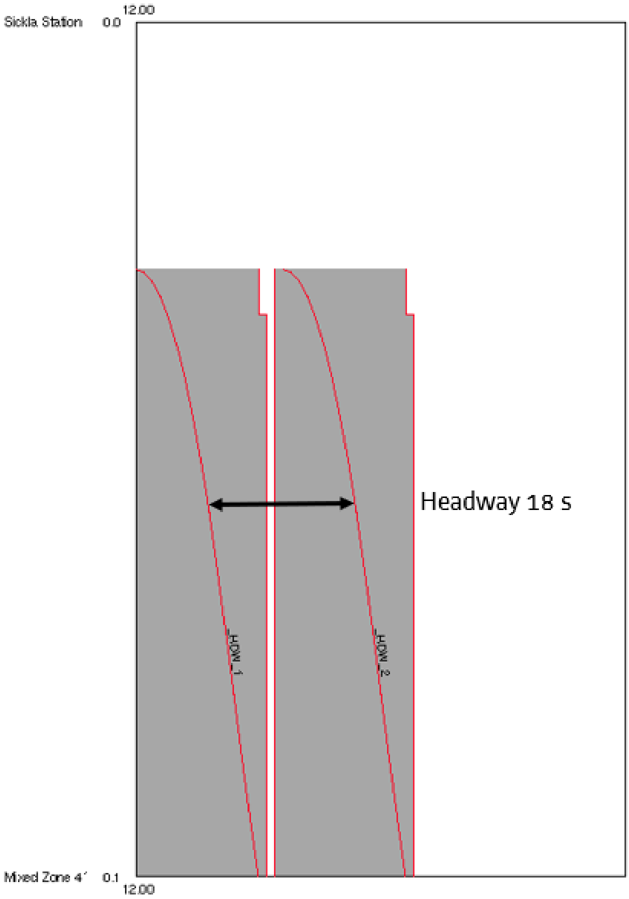


Figure 424 – Service Brake: Sickla Station – MZ4: Tram Graph with HW 24s

For the “Mixed Zone 4 – Mixed Zone 3” section the requested headway is not achieved:

- The minimum achievable headway without perturbation between trams is 112 s;
- The simulation for the achievement of the requested headway of 110 sec shows a conflict.

The conflict is due to the breaking action of the second tram before the signal 1092.The presence of the first tram in the station of Gullmarsplan (dwell time 60 sec) inhibits the release of the section after the signal 1092.

Figure 425 shows the Speed-Distance diagram of the trams while Figure 426 shows the tram graph with the minimum achievable headway and the conflict point with 110 s headway.

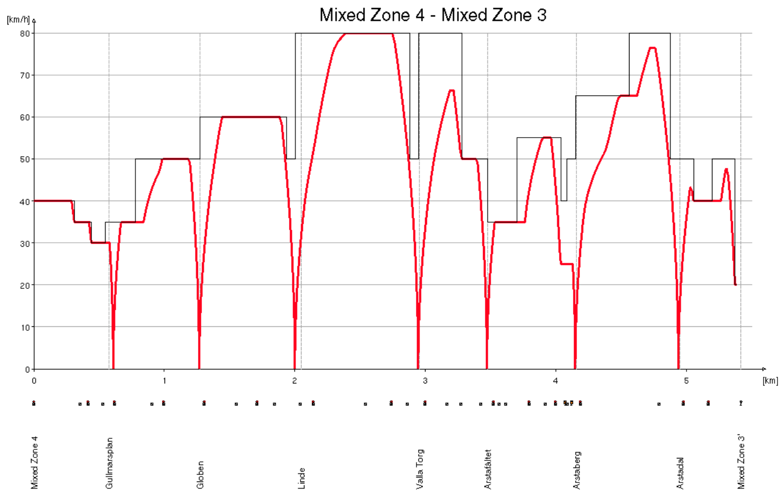


Figure 425 – Service Brake: MZ4 – MZ3: Speed–Distance diagram

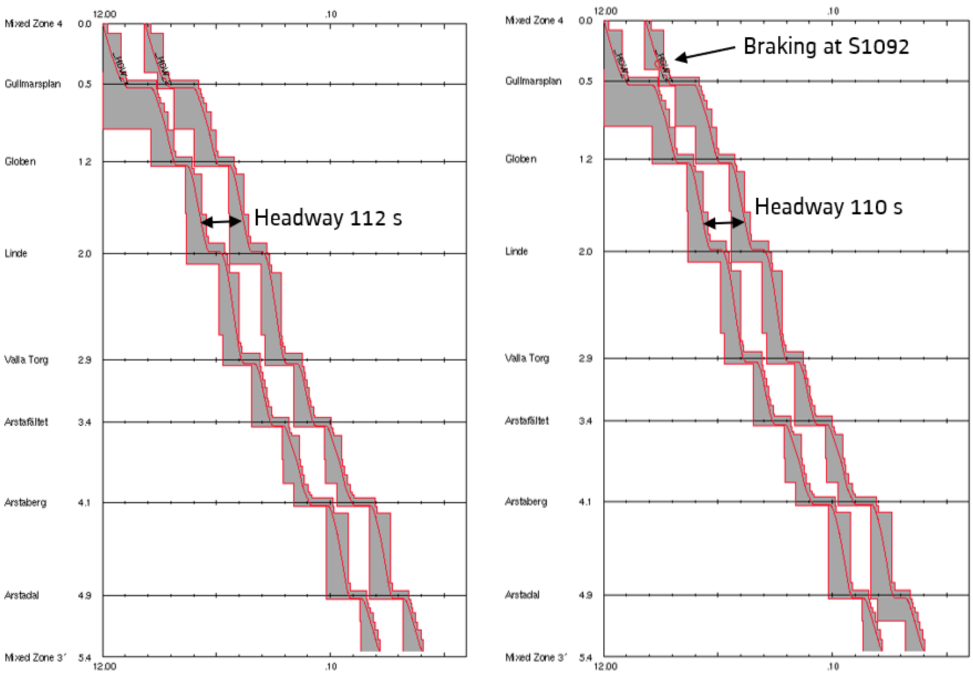


Figure 426 – Service Brake: MZ4 – MZ3: Tram Graph with HW 112s (left) and with HW 110s (right)

For the "Mixed Zone 3 – Norra Ulvsunda" section the requested headway is not achieved:

- The minimum achievable headway without perturbation between trams is 116 s;
- The simulation for the achievement of the requested headway of 110 sec shows a conflict.

The conflict is due to the breaking action of the second tram before the signal 0178.The presence of the first tram in the station of Alvik (dwell time 60 sec) inhibits the release of the section after the signal 0178. The position of signal 0178 is not possible to move to a location where headway is achieved as this would reduce the signal visibility to be non-compliant to SL standards.

Figure 427 shows the Speed-Distance diagram of the trams while Figure 428 shows the tram graph with the minimum achievable headway and the conflict point with 110 s headway.

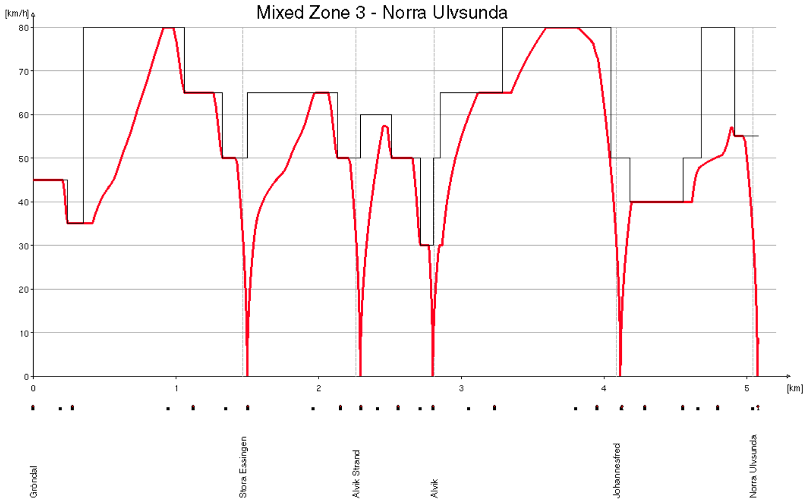


Figure 427 – Service Brake: MZ3 – NUS: Speed–Distance diagram

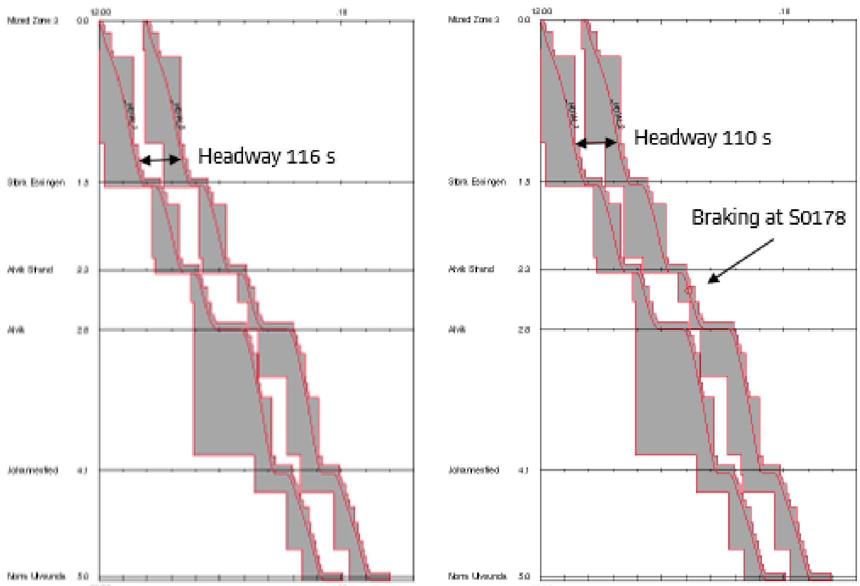


Figure 428 – Service Brake: MZ3 – NUS: Tram Graph with HW 116s (left) and with HW 110s (right)

For the “Norra Ulvsunda – Mixed Zone 1” section the requested headway of 120 s is achieved. The minimum headway is lower than the requested headway. Figure 429 show the running profile of the tram in this section while Figure 430 show the tram graph.

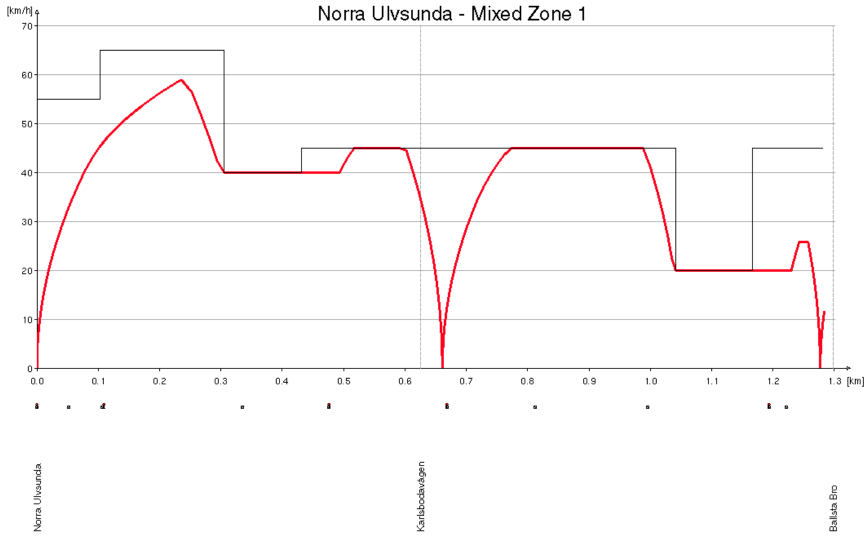


Figure 429 – Service Brake: NUS – MZ1: Speed–Distance diagram

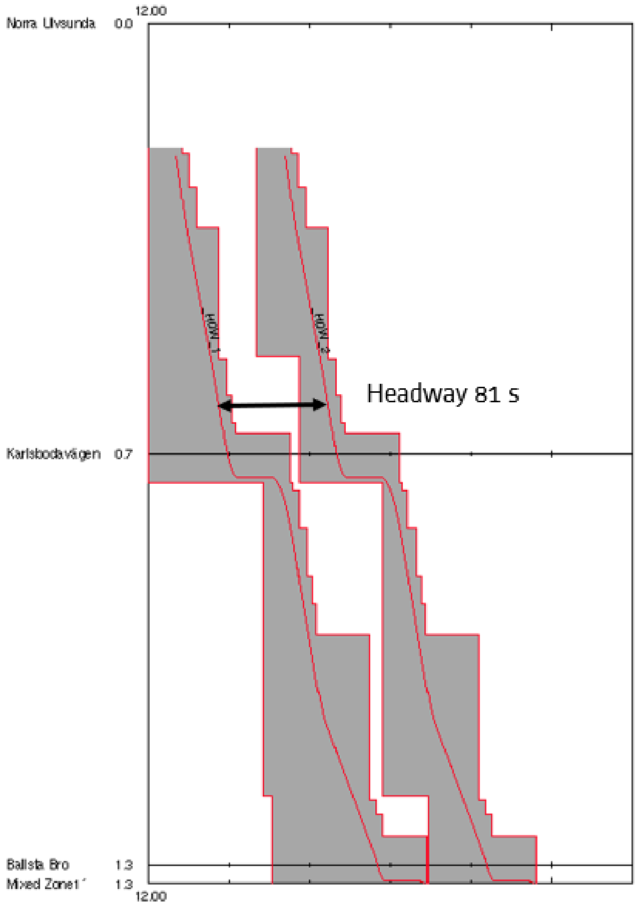


Figure 430 – Service Brake: NUS – MZ1: Tram Graph with HW 81s

For the "Mixed Zone 1 – Solna Station" section the requested headway of 120 s is achieved. The minimum headway is lower than the requested headway. Figure 431 show the running profile of the tram in this section while Figure 432 show the tram graph.

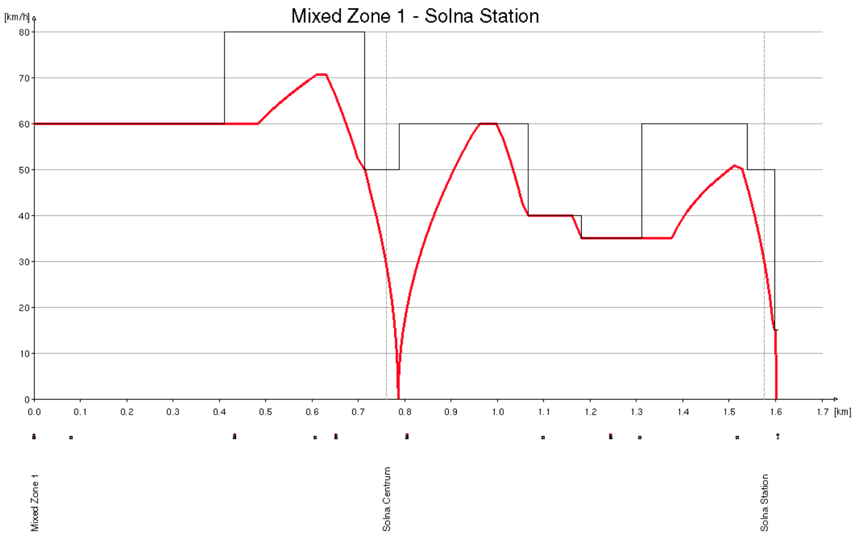


Figure 431 – Service Brake: MZ1 – Solna Station: Speed–Distance diagram

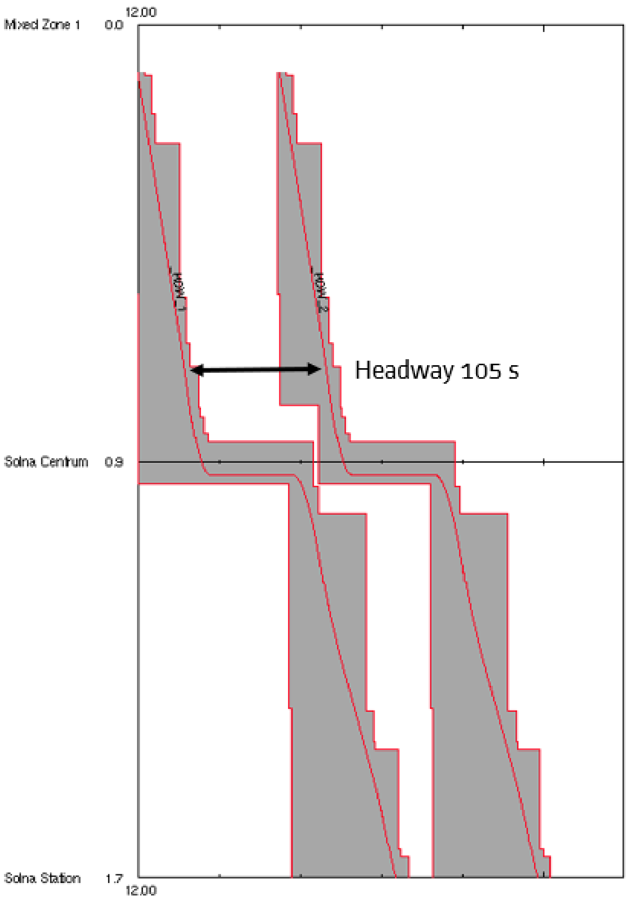


Figure 432 – Service Brake: MZ1 – Solna Station: Tram Graph with HW 105s

5.7.6. Operational Scenario Simulations

Minimum headway scenario simulations have demonstrated that it is possible to provide a service with the following operational headway:

- 5 min from Solna Station to Norra Ulvsunda, both tracks;
- 2.5 min from Norra Ulvsunda to Sickla Station, both tracks.

The simulation has been carried out with the following constraints:

- Service on the whole line composed by Solna line, Sickla line, Sickla Extension line, both south and north track;
- The Kista line will be considered helping the passage from a higher operational headway to a lower one, and vice versa. The operational headway in the Kista line will be considered as 5 min;
- Injection of trams from the two arms of the depot of Ulvsunda;
- The trams are in service right after they have left the depot.
- The headway of the line on North track will be changed in Norra Ulvsunda from 2.5 min to 5 min, moving trams accordingly from the line to the Kista line;
- The headway of the line on South track will be changed in Norra Ulvsunda from 5 min to 2.5 min, injecting trams accordingly from the Kista line;
- The level crossings are passed through by trams running in opposite directions in the same priority time, or, if not possible, in different priority time, without affecting the passage of cars and pedestrians, allowing them to cross the KSIs with a minimum time window.

Figure 433 shows the initial condition adopted for the simulation of the operational scenario:

- Trams leave the two arms of the depot of Ulvsunda;
- Trams leaving the right arm of the depot run to Solna Station;
- Trams leaving the left arm of the depot run to Sickla Station;
- The first tram will be in Sickla Station approximately at 5:00;
- The first tram will be in Solna Station approximately at 5:00.

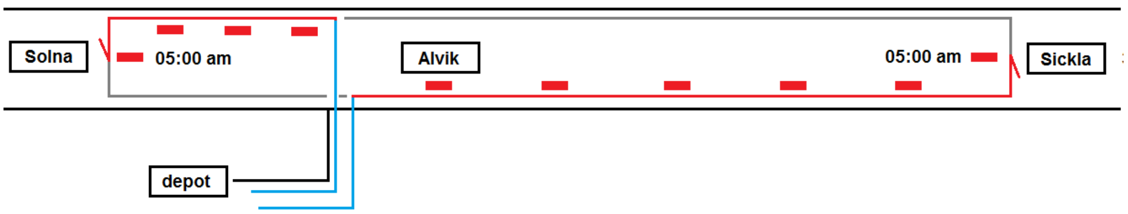


Figure 433 – Operational Scenario: Initial conditions

About 5 hours of service has been simulated.

Figure 434 and Figure 435 shown the overall service simulation. In those images:

- Trams leaving the depot of Ulvsunda to the terminus stations of Solna Station are highlighted in green;
- Trams leaving the depot of Ulvsunda to the terminus stations of Sickla Station are highlighted in blue;
- Trams leaving the depot of Ulvsunda to the Kista line are highlighted in red;
- Trams injected/retrieved to/from the Kista line are highlighted in purple;
- Mixed zones are highlighted in orange.

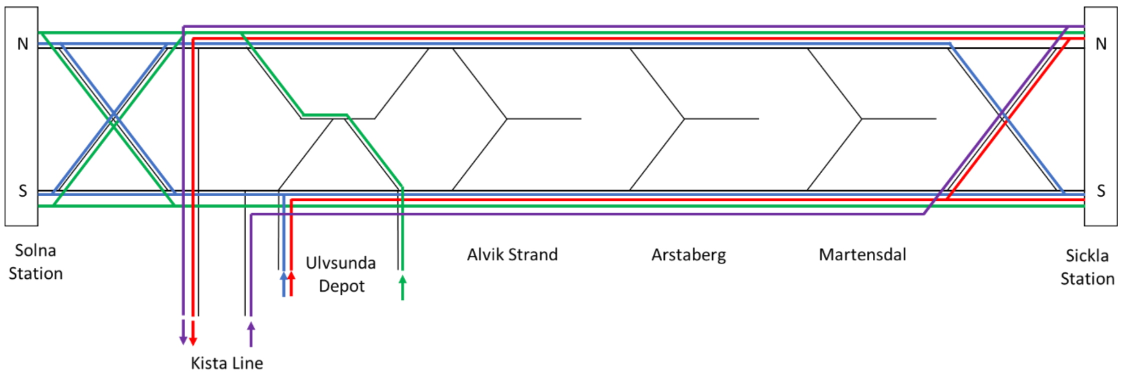


Figure 434 – Operational Scenario: Layout

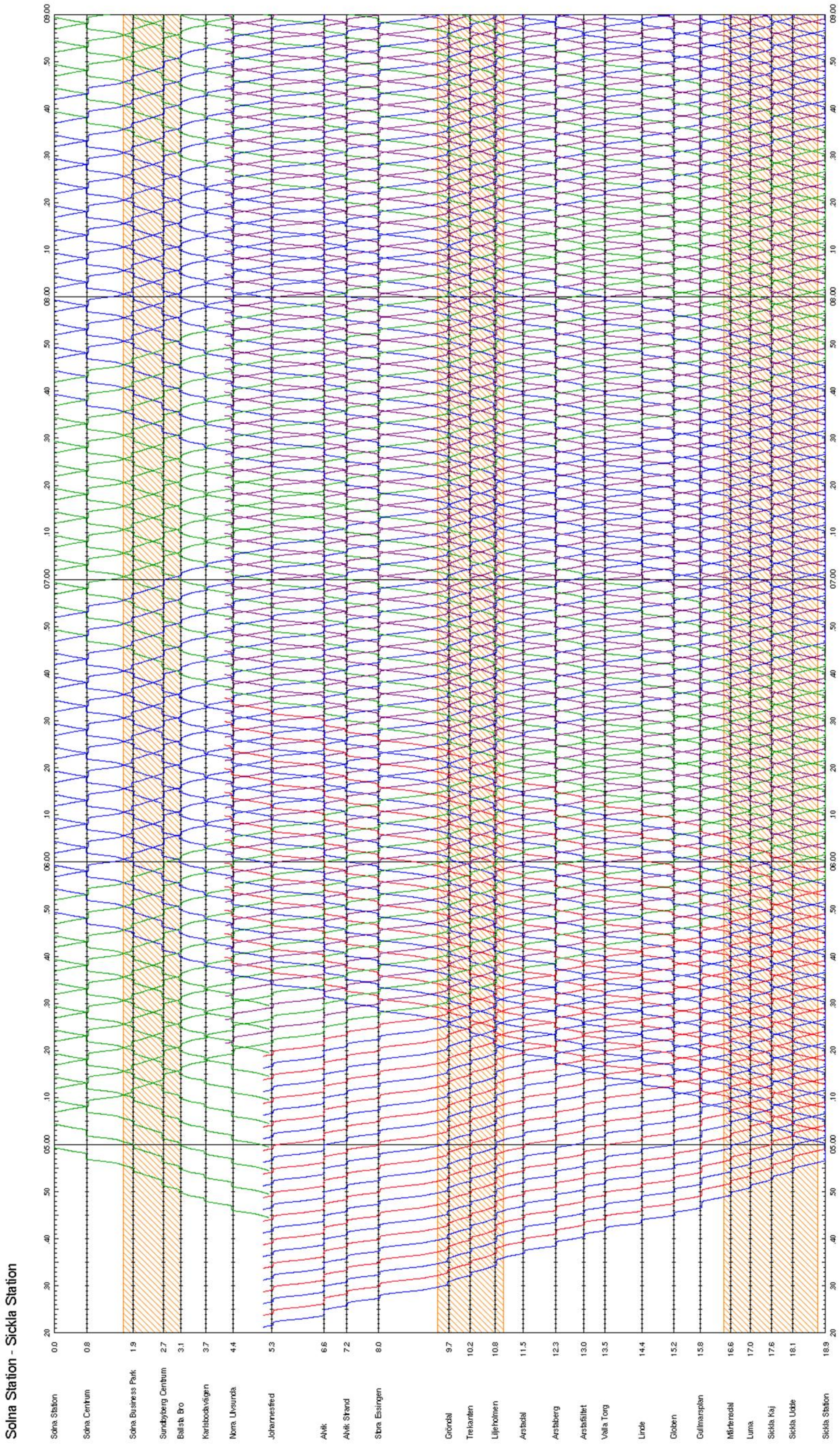


Figure 435 – Operational Scenarios: Overall Service

5.7.6.1 Startup Phase

Trams are in service after leaving the depot.

It is highlighted that trams arrive to Sickla Station alternatively to the South platform and to the North platform.

In order to start from Sickla station and Solna station approximately at 05:00, trams are injected from the depot of Ulvsunda, in service:

- Starting from 04:21 to Sickla Station;
- Starting from 04:44 to Solna Station.

Figure 436 shows the runs during the start-up phase, when trams are injected from the depot of Ulvsunda to the terminus stations.

In this image:

- Trams leaving the depot of Ulvsunda to the terminus stations of Solna Station are highlighted in green;
- Trams leaving the depot of Ulvsunda to the terminus stations of Sickla Station are highlighted in blue;
- Trams leaving the depot of Ulvsunda to the Kista line are highlighted in red;
- Trams injected/retrieved to/from the Kista line are highlighted in purple;
- Mixed zones are highlighted in orange.

Table 74 want to highlight the turnback in the terminal stations during the start-up phase and highlight that the minimum turnback time is respected for both terminal stations.

For the preparation of timetables, a buffer time has been added to the turnback time in order to improve the service synchronization and to create a feasible timetable.

The buffer time represents an operating margin that may be added to Terminal Stations during the preparation and validation of Timetable. The buffer time plays a key role regarding trams' synchronization when the loop is operated simultaneously with others loops.

Station	Turnback Time
Sickla	00:03:30
Solna	00:07:18

Table 74 – Operational Scenario: TB time in Solna and Sickla station during start-up phase

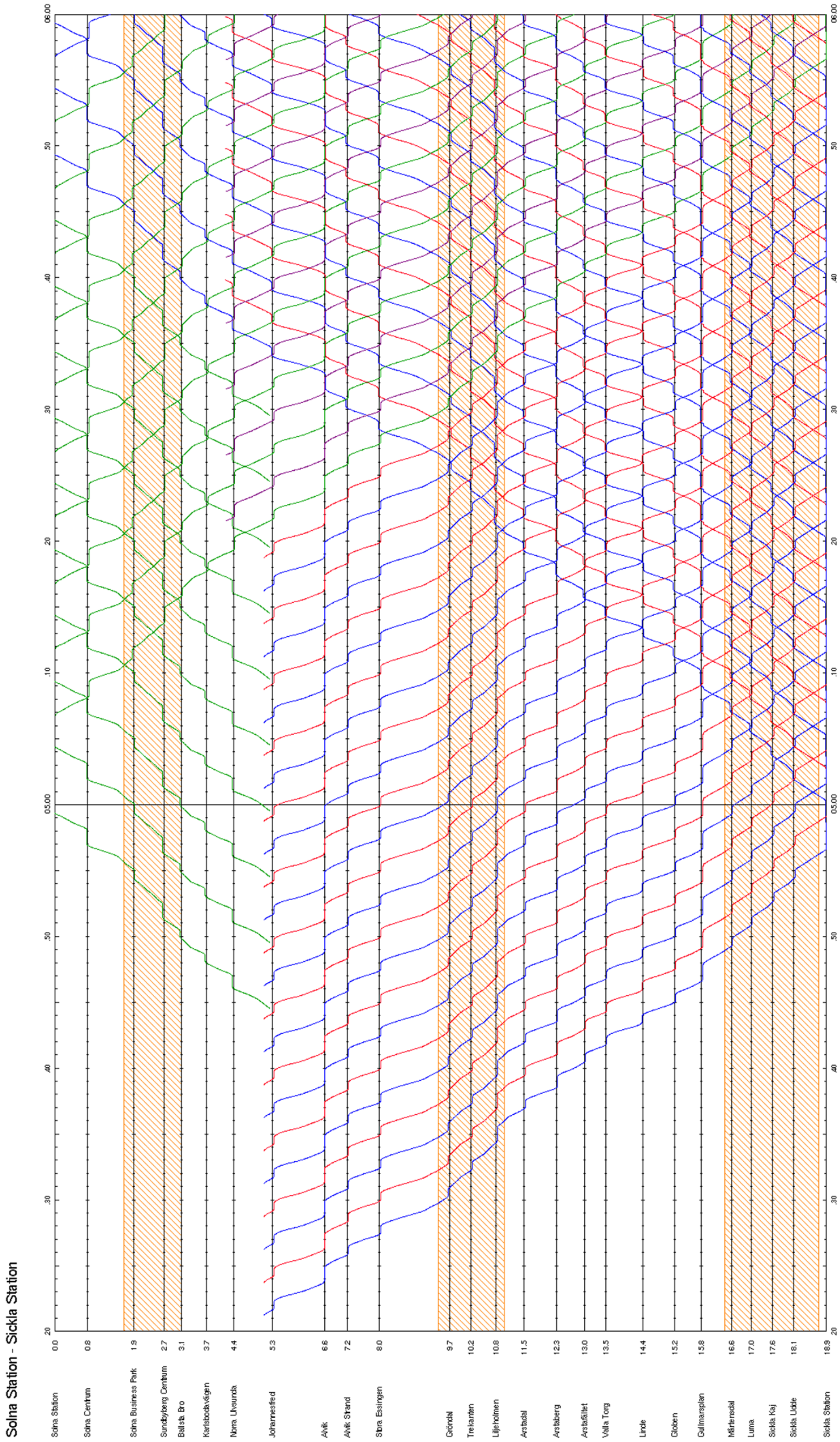


Figure 436 - Operational Scenario: Start-up

5.7.6.2 Peak Hours

The service on North track from Sickla Station is divided in two branches:

- Trams starting from the South platform of Sickla Station will run the entire line, up to Solna Station;
- Trams starting from the North platform of Sickla Station will leave the line, moving to the Kista line.

The service to Sickla Station is divided in two branches:

- Trams starting from both platforms of Solna Station will run the entire line up to Sickla Station, South platform.
- Trams injected from the Kista line will run on south track up to Sickla Station, North platform.

Timetables are built in order to guarantee that:

- Trams running in opposite direction will not brake or stop at the level crossings;
- Trams going to Kista line will not affect the service of the South track of the Solna line.

The following image shows the service of trams during the peak hours, approximately from 05:25, when the start-up phase ends.

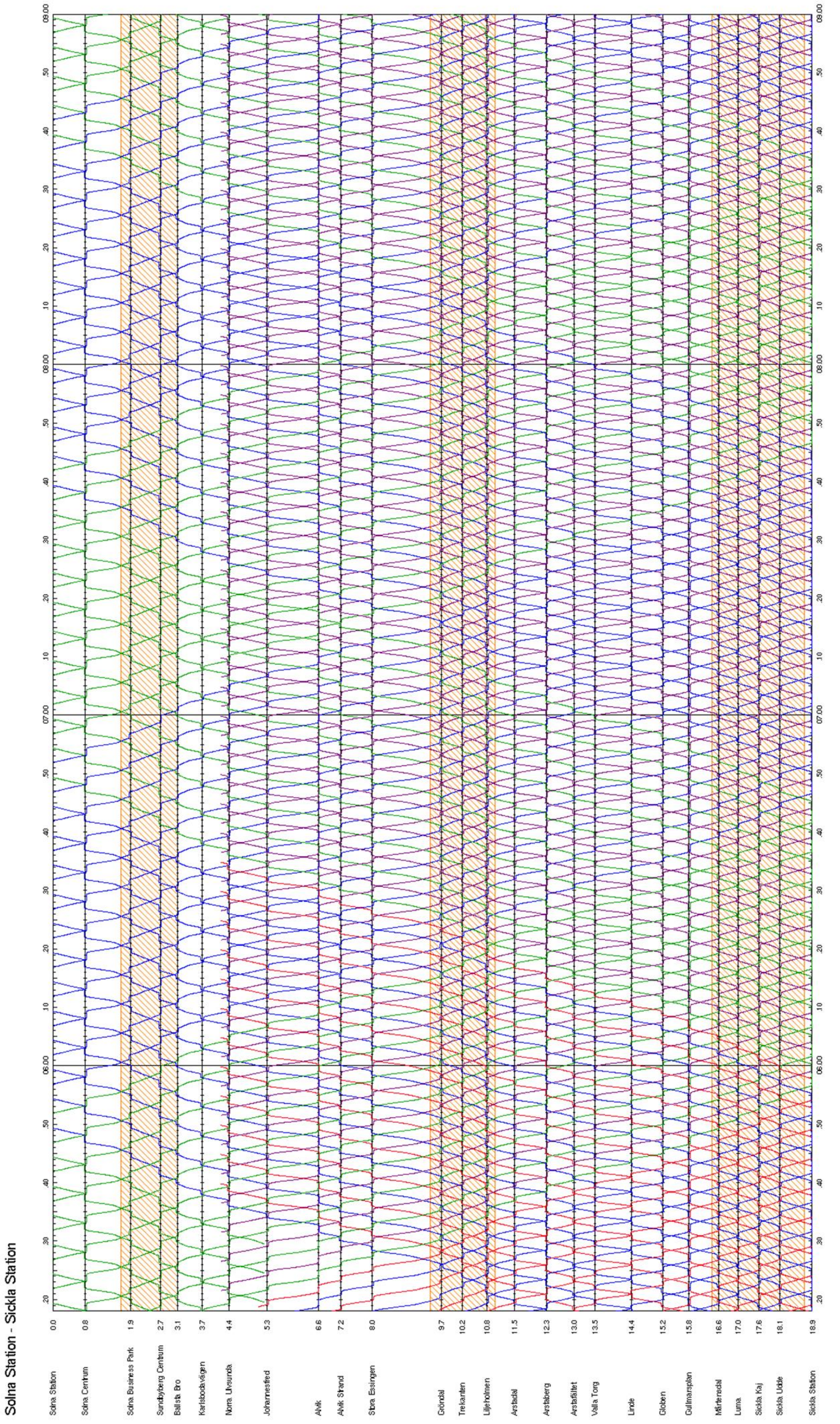


Figure 437 - Operational Scenario: Peak Hours

5.7.6.3 Level Crossing Management

Simulations of operational scenario have considered the behavior of level crossing as described in chapter 5.7.6.

Simulations aim is to optimize the crossing of a LC of two trams running in opposite direction on different tracks and the time available for cars and pedestrian to cross the LC area.

It's clear that if two trams running in opposite direction on different tracks are crossing a LC in the same time, the time available for cars and pedestrians tends to the best value.

Table 76 shows the behavior of two trams meeting the LC areas:

- The table has two columns (called "First Tram Passage") to show which of two trams, running in opposite direction on different tracks, arrives first in each LC area, the trams running from Solna Station or the tram running from Sickla Station;
- Each tram enters in a LC area crossing its P Point;
- The tram entering first in the LC area makes to start the timeout of 150 seconds;
- The tram exits from the LC area crossing its Strike Out Point.

The following table (Table 75) describes the meaning of each column of Table 76.

Acronym	Description
headway	Operational headway to be achieved
LC id	The identification for the KSI crossed by trams
run #	Number of the run (column both for Solna-Sickla Udde and Sickla Udde-Solna direction)
Is it the First Tram?	"X" if the tram passes as "First Tram" in the LC area (column both for Solna-Sickla Udde and Sickla Udde Solna direction)
P Point Passage	Timestamp of the passage of the tram in its P Point (column both for Solna-Sickla Udde and Sickla Udde Solna direction)
Strike Out Point Passage	Timestamp of the passage of the tram in its Strike Out Point (column both for Solna-Sickla Udde and Sickla Udde-Solna direction)
Amount of time spent to cross the LC	Time spent by the two trams to cross the LC. Interval of time between the timestamp when first tram crosses its P point and the timestamp when the second tram crosses its Strike Out point. This interval of time is compared with the time limit of 150 sec (timeout)
Trams cross in same priority	allowed values: "yes" / "no" "yes" if trams cross LC in same priority time "no" if trams do not cross LC in same priority time
Problems?	allowed values: "yes" / "no" problems could depend on "Amount of time spent to cross the LC" column

Table 75 – Description of the columns of the level crossing management table

In Table 76 the run of the tram n. 101.1, direction Solna Station – Sickla Station has been considered (Tram 101.1 is the first run that meet all the possible run in opposite direction), while for direction Sickla Station – Solna Station, all the runs that could be within/close to the time slot of the priority of the fixed one, for every LC of the line, have been considered.

In some cases, two LCs have been analyzed together, because there aren't main signals between them; for this reason, if a tram crosses the first one, it has to cross also the second one. The LCs analyzed together, in the two directions, can be staggered, in order to represent the reality. In other word:

- From Solna Station to Sickla Station:
    - KSI 4, KSI 5 have been analyzed together, because no main signal is present between them;
    - KSI 12 and KSI 13 have been analyzed together, because no main signal is present between them;
- From Sickla Station to Solna Station:
    - KSI 14 and KSI 13 have been analyzed together, because no main signal is present between them.

Also for trams that do not cross the LC in the same priority, the column "problems?" report "No" as result, because, following the assumptions earlier fixed, in case of passage of two trams in different priority, if the time T available for car passage is greater than 25 seconds, the second tram runs with no additional stop, following the normal operation (this behavior is represented inside the table in the column PROBLEM with the result "No").

		Direction Solna Sation – Sickla Station				Direction Sickla Sation – Solna Station				Results				
Headway [m]	KSI id	Tram	Is it the first tram?	Passage on P point	Passage on Strike Out point	Tram	Is it the first tram?	Passage on P point	Passage on Strike Out point	Amount of time spent to cross the KSI			Tram cross in the same priority	Problems?
5	KSI1	101.1		06:01:53	06:02:24	101.2	x	05:58:43	05:59:24	221	>	150	no	No
5	KSI2	101.1		06:03:12	06:04:35	101.3	x	06:01:38	06:01:51	177	>	150	no	No
5	KSI3	101.1	x	06:04:43	06:05:11	101.4		06:05:56	06:06:17	94	<	150	yes	No
5	KSI4	101.1		06:11:24	06:12:30	101.6	x	06:09:28	06:09:53	182	>	150	no	No
5	KSI5	101.1		06:11:24	06:12:30	101.6	x	06:08:34	06:09:04	236	>	150	no	No
5	KSI6	101.1		06:12:43	06:13:40	101.7	x	06:12:36	06:12:53	64	<	150	yes	No
2.5	KSI7	101.1		06:19:51	06:20:15	100.9	x	06:18:30	06:20:12	105	<	150	yes	No
2.5	KSI8	101.1	x	06:20:14	06:20:53	101.10		06:20:41	06:20:54	40	<	150	yes	No
2.5	KSI9	101.1		06:30:49	06:31:12	102.2	x	06:30:35	06:30:57	37	<	150	yes	No
2.5	KSI10	101.1	x	06:31:34	06:31:59	103.2		06:32:21	06:32:35	61	<	150	yes	No
2.5	KSI11	101.1	x	06:34:22	06:35:35	103.3		06:34:29	06:35:48	86	<	150	yes	No
2.5	KSI12	101.1	x	06:34:55	06:36:14	102.4		06:36:16	06:36:35	100	<	150	yes	No
2.5	KSI13	101.1	x	06:34:55	06:36:14	102.4		06:35:02	06:35:46	51	<	150	yes	No
2.5	KSI14	101.1		06:36:02	06:36:36	102.4	x	06:35:02	06:35:46	94	<	150	yes	No
2.5	KSI15	101.1		06:38:58	06:39:10	102.5	x	06:38:20	06:38:33	50	<	150	yes	No

Table 76 – Operational Scenario – Behaviour of trams at level crossings

Table 78 shows the interval of time available for cars/pedestrians to cross a LC when a tram running in one direction, or a couple of trams, running in opposite directions, cross a LC.

If two trams cross the LC in the same priority time, there is one only a time window available for cars and pedestrians, between the timestamp when the head of the second tram leaves its strike out point and the timestamp when the head of the first tram, belonging to the next run, reaches the LC area.

If two trams do not cross the LC in the same priority time, there are two time windows available for cars and pedestrians:

- between the timestamp when the tail of the first tram leaves its strike out point and the timestamp when the head of the second tram reaches its P point;
- between the timestamp when the tail of the second tram leaves its strike out point and the timestamp when the head of the first tram, belonging to the next run, reaches the LC area.

The following table (Table 77) describes the meaning of each column of the Table 78.

Acronym	Description
LC id	The identification for the LC crossed by trams
Opens (I)	Timestamp when the LC opens the first time for cars or pedestrians
Closes (I)	Timestamp when the LC closes the first time for cars or pedestrians
Time [s] (I)	Time available for cars or pedestrian, the first time
Opens (II)	Timestamp when the LC opens the second time for cars or pedestrians
Closes (II)	Timestamp when the LC closes the second time for cars or pedestrians
Time [s] (II)	Time available for cars or pedestrian, the second time

Table 77 – Operational Scenario: Behaviour of trams at level crossings

Time available for cars to cross the KSI							
Headway [m]	KSI id	Opens (I)	Closes (I)	Time [s] (I)	Opens (II)	Closes (II)	Time [s] (II)
5	KSI1	05:59:24	06:01:53	00:02:29	06:02:24	06:03:43	00:01:19
5	KSI2	06:01:51	06:03:12	00:01:21	06:04:35	06:06:38	00:02:03
5	KSI3	06:06:17	06:09:43	00:03:26			
5	KSI4	06:09:53	06:11:24	00:01:31	06:12:30	06:14:28	00:01:58
5	KSI5	06:09:04	06:11:24	00:02:20	06:12:30	06:13:34	00:01:04
5	KSI6	06:13:40	06:17:36	00:03:56			
2.5	KSI7	06:20:15	06:20:59	00:00:44			
2.5	KSI8	06:20:54	06:23:01	00:02:07			
2.5	KSI9	06:31:12	06:33:06	00:01:54			
2.5	KSI10	06:32:35	06:34:04	00:01:29			
2.5	KSI11	06:35:48	06:36:52	00:01:04			
2.5	KSI12	06:36:35	06:37:35	00:01:00			

Time available for cars to cross the KSI							
Headway [m]	KSI id	Opens (I)	Closes (I)	Time [s] (I)	Opens (II)	Closes (II)	Time [s] (II)
2.5	KSI13	06:36:14	06:37:35	00:01:21			
2.5	KSI14	06:36:36	06:37:33	00:00:57			
2.5	KSI15	06:39:10	06:40:51	00:01:41			

Table 78 – Operational Scenario: Time available for cars/pedestrians

Table 76 and Table 78 highlight that:

- For 3, 6÷15 level crossings, trams running in opposite direction cross LCs in the same priority time;
- For 1÷2, 4÷5 level crossings, trams running in opposite direction do not cross LCs in the same priority time, but the time window available for cars/pedestrian is greater than the minimum allowed.

5.7.7. Project Conclusion

The simulations carried out definitively stated that the line can manage the operational headway requested by the infrastructure owner. Moreover, through the simulation it has been possible to observe that also the minimums times for the transit of the vehicles on the level crossings are satisfied.

6. GENERAL CONCLUSION

The guiding principle for the elaboration of the thesis was that of the realization of a document that could serve as a possible guide to a user who finds the need to execute railway simulations. By reading the first chapters on the principles of signalling and railway capacity, the reader can learn the necessary bases to understand the railway system and transpose it inside any simulations software.

Once the basics have been learned, the reader can enter the heart of the document by analyzing in detail what simulations are and which methodology is appropriate to follow in order to achieve a result as close as possible to reality. In addition, a whole chapter is dedicated to the use of one of the many commercial software available on market: in this case we have dwelt in the detail of use of the Opentrack tool that allows micro-simulation of a railway network through modelling of infrastructure, signalling system, trains and timetables.

The final part of the thesis provides instead the application of the concepts described in the previous chapters through real case studies in which the simulations have been used with different purposes.

Through the reading of the chapter focused on the Danish project, it is possible to observe how simulations are used as a design aid for the purpose of dimensioning the block sections of a line. The chapter on the Rome node, in Italy, uses simulations for predictive purposes in order to understand what benefits could be obtained through a change of signalling system. This mode of use is very important for infrastructure managers as it helps them to assess possible investments in certain types of technology.

Finally, the chapters relating to the study and evaluation of an operational scenario demonstrate the versatility and the power of microsimulations in the study of real cases with many variable and requirements to be satisfied.

Potential future research should be based on the evaluation of capacity benefits under delayed operation as a relevant contribution to literature to understand overall performances of different signalling systems influenced by stochastic variables.

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