

Blocking signals

The impact of block section designs for ERTMS/ETCS Level 2 under non-disruptive and disruptive conditions

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**UNIVERSITY
OF TWENTE.**



Haskoning
Enhancing Society Together

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The impact of block section designs for ERTMS/ETCS Level 2 under non- disruptive and disruptive conditions

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Preface

This master thesis marks the end of my time as student Civil Engineering at the University of Twente. Over the past seven months, I have been working on this thesis, titled '*The impact of block section designs for ERTMS/ETCS Level 2 under non-disruptive and disruptive conditions*'. Delving into the world of trains, and especially ERTMS/ETCS Level 2, has given me insights into the complexity of railway system, to always remain critical of results, but also useful skills regarding academic writing, OpenTrack simulations, and data analysis.

This thesis gave me the opportunity to get in contact with many train enthusiasts who were willing to help me better understand ERTMS/ETCS Level 2, its limitations, and its possibilities. Therefore, I would like to thank all the people who made time for me for an interview.

Furthermore, I want to thank Haskoning for giving me the opportunity to complete my graduation project. From day one, people were curious about my research, willing to help, and (repeatedly) explain subjects that I did (or maybe still do) not fully understand. A special thanks to my external supervisors: Lucas van der Hoeven, Arnoud de Jong, and Max van Dokkum. The weekly meetings were both fun (!) and very useful; you ensured that I remained critical of the results. I am also very grateful for the day that I got to ride along with a train driver to experience ERTMS/ETCS Level 2 in practice on the high speed line. I learned a lot from this, especially when we encountered a disruption ourselves. Lucas, thank you very much for making this possible!

Secondly, I want to thank my daily supervisor Oskar Eikenbroek and UT supervisor Eric van Berkum from the University of Twente for their continuous support. You kept me on track when I wandered a bit off and provided highly detailed, constructive feedback that helped me to stay critical throughout the research process.

Lastly, I would like to thank my family, friends, (former) roommates from 'T HOI, and O.D. MSCS for their support, making my time at Enschede amazing, and always listening to my train fun facts. Also thanks to the people in Utrecht who let me stay with them, you made sure that I didn't always have to get up incredibly early. At last, a special shout-out to all people in 'UT Hok' and offering a listening ear whenever I started my sentence with 'I have a question' and while I was explaining my (way too complicated) question, I already answered it myself.

I hope you enjoy reading this thesis as much as I did researching it!

Welmoed Spanjer
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Summary

The Dutch rail infrastructure is approaching its capacity limit, while demand for both freight and passenger transport by rail is increasing (Programma ERTMS, n.d.). To address this challenge, the Dutch government made the decision to implement the European Rail Traffic Management System (ERTMS), specifically Level 2. This system replaces the current NS'54/ATB-EG system and enables an increase in capacity.

The aim of this study was to evaluate different block section design strategies under ERTMS/ETCS Level 2, assessing their performance under both non-disruptive and disruptive conditions. Performance was measured using Key Performance Indicators, which were identified through a literature review and validated through interviews with stakeholders such as ProRail, Haskoning, and Dutch passenger transport operators. Under normal conditions, capacity, travel time, travel time deviation, and infrastructure costs were evaluated. In disruptive situations, resilience (both recovery and disruption periods) and the Weighted Travel Time Extension, which reflects the impact on passengers, were examined.

Five ERTMS/ETCS Level 2 block section design strategies were investigated, ranging from a minimum distance layout to cost-efficient design. The current NS'54/ATB-EG situation was also included as a reference. These strategies were evaluated using OpenTrack simulations on three corridors with varying traffic intensities: Zwolle – Deventer (low), Amersfoort Centraal – Apeldoorn (medium), and Arnhem Centraal – Nijmegen (high).

The results show that ERTMS/ETCS Level 2 offers clear advantages over NS'54/ATB-EG on corridors with high traffic volumes, particularly in terms of capacity and travel time. On low volume routes, the benefits are more limited, and travel time may even increase due to the more conservative braking curve of ERTMS/ETCS Level 2. Strategies with short blocks, such as the minimum distance strategy and design manual strategies, achieve the best performance under normal conditions but also involve higher infrastructure costs.

During disruptions (specifically, a defective train and communication failure were simulated), block section designs with shorter blocks showed better recovery performance for train failures, as they allow trains to run closer together. However, in the event of communication failures, a high number of Stop Marker Boards (SMBs) led to longer recovery and disruption periods. This is because trains have to stop at each SMB and request a European Instruction. This problem is greatly reduced when Location Marker Boards (LMBs) are used: these make it possible to continue driving without the intervention of a traffic controller, which improves resilience.

The trade-off analysis shows that there is no universal 'best' strategy. The choice depends on the desired balance between costs, capacity, travel time and resilience. For example, the minimum distance strategy offers maximum performance, but at high costs. The cost-efficient strategy offers low costs, but can limit performance in the event of disruptions. The implementation of LMBs appears to be an effective way to counteract the disadvantages of short blocks during communication failures.

Overall, the implementation of ERTMS/ETCS Level 2 leads to improvements in capacity and operational reliability, especially on heavily used corridors. The choice of a block section strategy should be context-specific, depending on traffic volume, investment scope and performance requirements.

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List of abbreviations and definitions

Abbreviation	Meaning
ATB-EG	Automatische Trein Beveiliging – Eerste Generatie (English: <i>'Automatic Train Protection – First Generation'</i>)
EoA	End of Authority
ERTMS	European Rail Traffic Management System
ETCS	European Train Control System
European Instruction 1	Procedure that must be carried out in order to pass a SMB during disruptive conditions
HSL	High speed line
LMB	Location Marker Board
MA	Movement Authority
NS'54	Signalling system 1954 (Dutch: <i>'Seinstelsel 1954'</i>)
OVS	Design regulation (Dutch: <i>'OntwerpVoorSchrift'</i>)
Railway yard (Dutch: <i>'emplacement'</i>)	Area consisting of switches and operated signals, station area
RBC	Radio Block Centre
SMB	Stop Marker Board
Open line (Dutch: <i>'vrije baan'</i>)	Tracks in between stations

1. Introduction

The first chapter introduces the problem context, along with background information on NS'54/ATB-EG and ERTMS/ETCS Level 2, and the rationale behind the study. Subsequently, an outline of the report is provided.

1.1. Problem context

The use of rail for both freight and passenger trains in the Netherlands is expected to increase in the coming years (Programma ERTMS, n.d.). However, the rail infrastructure in the Netherlands is quite close to its capacity limit, unless additional infrastructure is constructed. Currently, most of the Dutch railway consists of a combination of the NS'54 block signalling system and automatic train protection. This combination is called *NS'54/Automatische TreinBeïnvloeding Eerste Generatie*, also known as ATB-EG (de Pundert et al., 2010). This system enforces early braking to 40 km/h before a yellow light, leading to slow station approaches and long headways. Moreover, the placement of signals is constrained by strict visibility requirements and long generic braking distances (Landex, Jensen, et al., 2019), which do not sufficiently account for the different braking characteristics of freight and passenger trains. These factors make efficient block section design particularly difficult, especially in curved or urban areas.

The proposed solution to address this capacity problem is the implementation of the European Rail Traffic Management System (ERTMS), which is intended to become the new standard for train safety systems across Europe. With this new system, the limitations of NS'54/ATB-EG related to braking and signal visibility no longer apply. ERTMS has different levels and in 2014, the Dutch government decided to replace the whole network with Level 2 (Programma ERTMS, 2016). ERTMS increases rail capacity by allowing trains to run closer together, as the system enables more precise braking compared to NS'54/ATB-EG (ERTMS, n.d.). Furthermore, the interoperability across countries is improved since the same system is used everywhere, and it improves safety by enabling continuous supervision of the train (Goverde et al., 2012). Level 2 consists of two components: European Train Control System (ETCS), providing train control and safety, and Global System for Mobile Communications – Railways (GSM-R), enabling real-time data exchange between trains and track equipment through a dedicated communication network (Cansu et al., 2023).

The transition from NS'54/ATB-EG to ERTMS/ETCS Level 2 is a major undertaking with numerous complex puzzles that require careful considerations. As part of this transition, all current NS'54/ATB-EG signals are removed and replaced by marker boards, providing an opportunity to redesign block sections. Although ERTMS/ETCS Level 2 allows for continuous communication between train and the control centre, fixed block sections remain necessary due to uncertainty in train integrity since the system cannot always verify whether a train is still complete or if any wagons have been left behind.

Besides enabling a new infrastructure layout, the shift to ERTMS-ETCS Level 2 also has potential benefits in terms of operational reliability. On average, the Dutch railways have experienced an average of 5,200 disruptions per year over the past five years (Rijden de Treinen, n.d.). These incidents can range from train failures and collisions to signalling system malfunctions. With the new system, some improvements are expected. For instance, the failure probability of axle counters is lower than that of track circuits, which are commonly used under NS'54/ATB-EG, and the new system eliminates traditional signal failures as we know them today. However, disruptions may occur, such as failures in Eurobalises or GSM-R communication (ProRail et al., 2014). While ERTMS/ETCS Level 2 may reduce the occurrence of certain failures, it cannot prevent all disruptions.

Rather than focussing on reducing the number of disruptions, this study aims to investigate how different block section design strategies can improve the system's ability to recover from them. It is expected that the placement of block sections influences how quickly and efficiently train traffic can be restored after a disruption. This is because ERTMS/ETCS Level 2 allows trains to brake later and run with shorter headways, thanks to the removal of the enforced 40 km/h braking step present in NS'54/ATB-EG. Additionally, the location of a SMB no longer determines the exact point where braking must begin, allowing for more flexibility. These strategies are evaluated based on their impact on punctuality, capacity, and resilience, both during normal and disruptive conditions. Since railway networks must function reliably not only during regular operations but also during disruptions, understanding how block layouts affect recovery is a crucial aspect. In this context, a strategy refers to the approach used to place and define block sections.

The effectiveness of these strategies is assessed in the simulation environment OpenTrack by considering different performance indicators. By comparing different block section design strategies in combination with different disruptions, the study aims to determine which strategy performs best according to an trade-off analysis with the defined performance indicators.

1.2. Background

This sub-chapter provides background information on the signalling and train protection systems. It begins with an explanation of the current system, NS'54/ATB-EG, followed by a description of the proposed system, ERTMS/ETCS Level 2.

1.2.1. Current system: NS'54/ATB-EG

Currently, most railways in the Netherlands are equipped with the NS'54 block signalling system and the ATB-EG automatic train protection system. The NS'54 system relies on light signals to communicate speed commands to drivers, ensuring that trains can always stop safely before reaching a signal indicating a stopping command. With the use of signals, fixed block sections have to be used. These blocks are designed to be at least as long as the maximum braking distance required for the worst-case braking scenario, plus an additional margin to account for the ATB system (Pachl, 2009).

NS'54 is a 2-block 3-aspect signalling system, which means that information is provided for the upcoming 2 blocks while using three types of light signals: green (clear), yellow (approach) and red (stop). A green light allows a train to proceed without speed adjustments, while a yellow light indicates that the train should reduce speed and prepare for a possible stop at the next signal, and a red light mandates an immediate stop. An example of such a situation can be seen in Figure 1. In this example, both trains are approaching a green light, meaning they do not need to brake. The second train has just passed a green light, which caused the signal to become red (Goverde et al., 2013).

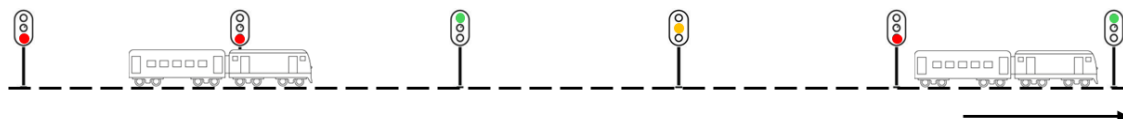


Figure 1: NS'54, a 2-block and 3-aspect signalling system

In the current signalling system, the entire railway network is divided into smaller block sections. Trains are detected at fixed points using, for example, axle counters or track circuits, which happens only when they enter or leave a block. This means that it is possible to know whether a block is occupied, but the exact location of the train between these two points remains unknown (Maschek, 2018).

On railway lines where train separation by block sections is used, the length of the block sections may not be smaller than the maximum distance a train would need to come to a complete stop in a worst-case braking scenario. This ensures that the block is long enough to guarantee safe operations. Although the block length represents the minimum safe distance, it is based on the maximum required braking distance, which depends on the type of signalling and ATB system used (Quaglietta, 2014). These blocks may be exclusively occupied by only one train.

1.2.2. Proposed system: ERTMS/ETCS Level 2

The European Rail Traffic Management System (ERTMS) Level 2 is a standardised signalling system designed to improve the safety and efficiency of rail traffic across Europe. It consists of two main components: the European Train Control System (ETCS), responsible for train control and safety, and the Global System for Mobile Communications – Railways (GSM-R), a communication network that enables real-time data exchange between trains and track-side equipment (Cansu et al., 2023).

ERTMS/ETCS can be implemented at three different levels, each differing in how they interact with trackside infrastructure and in the way traffic authorities are communicated to train. Level 2 is characterised by continuous, real-time communication between trains and track infrastructure via GSM-R. Position updates are supported by Eurobalises, which are fixed devices installed between the rails. These provide reference points for the train's on-board odometry system, helping correct and refine its calculated position (Bloomfield et al., 2012; Ministerie van Infrastructuur en Milieu et al., n.d.)

In Level 2, the continuous exchange of position and control data is managed by the Radio Block Centre (RBC). The RBC continuously receives updates about the train's speed, direction, and position via GSM-R. Based on this information, it issues movement authorities (MAs), which are digitally defined track segments that the train is permitted to occupy. These come with additional data such as speed limits and possible braking instructions (Bloomfield et al., 2012). This information is transmitted directly back to the train via the GSM-R network. The movement authority, along with other operational instructions such as speed limits and braking points, are then displayed to the driver on the train's ETCS train system, ensuring that the train travels within safe parameters.

One of the key advantages of ERTMS/ETCS Level 2 is that it enables trains to run closer together, thanks to the communication between the train and the RBC. The RBC receives the train's position and sends back track data such as the distance that the train can run until the MA ends. Based on this information, the train calculates the braking curve based on the train's current speed, braking characteristics, and infrastructure details such as gradients and (local) speed restrictions (Goverde et al., 2013). When a train needs to stop, the RBC determines the precise stopping point, allowing the braking distance of the following train to be optimised. This effectively reduces the gap between trains and increases overall capacity (de Pundert et al., 2010).

Figure 2 shows the general setup of ERTMS/ETCS Level 2, including the position of onboard and trackside components such as Eurocab, Eurobalises, GSM-R communication link and Radio Block Centre (RBC).

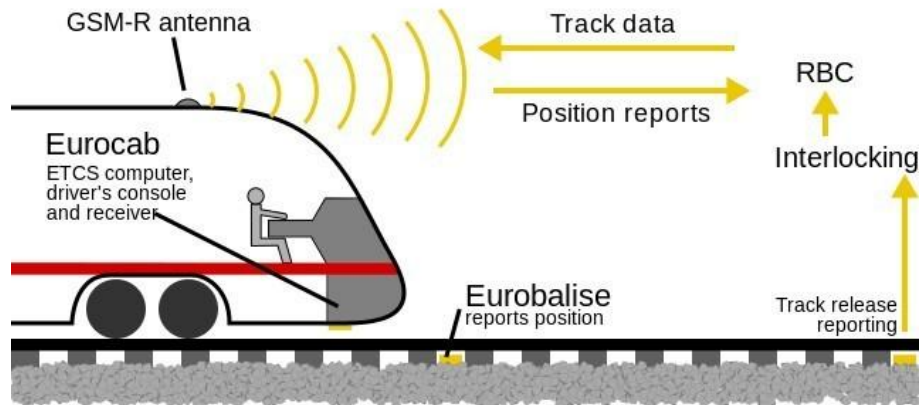


Figure 2: Setup of ERTMS/ETCS Level 2 (European Commission, n.d.)

1.2.2.1. Interlocking

Interlocking in train infrastructure is a crucial safety system designed to prevent conflicting train movements and ensure safe operation across the railway network. It coordinates the control of signals, track switches and other infrastructure elements to prevent dangerous situations, such as collisions or derailments. When a signal is released to allow a train to pass, the interlocking system ensures that all other signals and track switches that could lead to a collision are locked in a safe position (Pachl, 2009). In ERTMS/ETCS Level 2, the same safety procedure is maintained but then digitally.

The RBC receives continuous updates from the train, including its speed, direction, and position, via the GSM-R network. Based on the combined location data of all trains, the RBC issues movement authorities, defining how far and how fast the train is allowed to travel. These MAs, along with speed limits and braking instructions, are shown on the Driver Machine Interface (DMI) in the train's Eurocab.

To ensure safety, traditional detection of track occupancy remains crucial. The train is equipped with Eurocabs at both ends of the train (see Figure 2), but only the Eurocab at the front, in the direction of travel, is active. This front Eurocab scans the Eurobalises along the track and transmits the train's location data to the RBC, which acts as the interlocking system. However, since only the front of the train is monitored in real time, the system inherently does not check whether the entire train, including all carriages or wagons, is intact (Goverde, 2012). Therefore, traditional track occupancy detection systems, such as axle counters or track circuits, remain essential. These systems provide a second layer of safety by ensuring that a track section is completely clear and not occupied by any part of the train, improving overall operational safety.

1.2.2.2. Marker boards

With ERTMS/ETCS Level 2 block boundaries (with physical marker boards) is still necessary. These boundaries ensure that trains maintain safe distances from each other, similar to the current system. These physical boundaries, created by Stop Marker Boards (SMBs) and Location Marker Boards (LMBs), provide clear points for the train driver where the train could stop.

During non-disruptive situations, there is no difference between the two marker boards. During a disruption, for example, a communication failure between the RBC and the train, the difference becomes critical. When approaching an SMB, the train must come to a full stop and the dispatcher must be contacted in order to get an European Instruction 1 (hereafter referred to as 'European Instruction'). This European Instruction is a procedure that gives the train driver permission to the next SMB. If LMBs are located between two SMBs, they may be passed without

further dispatcher contact. Both with LMBs and SMBs, the train may continue with a maximum speed of 40 km/h. If the communication with the RBC is still not restored upon reaching the next SMB, the train driver must contact the dispatcher again to receive a new European Instruction (European Union Agency for Railways, n.d.; ProRail, 2021a).

ProRail regulates the implementation of the ERTMS/ETCS system and sets specific design requirements, including placement criteria for SMBs. These requirements state for example that they must be spaced at least 200 metres apart (reducible to 100 metres in consultation) and no more than 5,000 metres. These constraints support accurate odometry.

LMBs, on the other hand, are not part of ProRail's implementation strategy and are therefore not formally regulated ProRail (2021a). ProRail has chosen not to introduce LMBs, as it is concerned that their use could cause confusion among train drivers (Leune, 2022). Instead, ProRail plans to introduce virtual blocks, which is a concept that works in the same way as LMBs, but without placing a physical board along the track.

For this study, the exact technical implementation is less relevant. What matters is distinguishing between different procedures during disturbed conditions, which may or may not require a European Instruction. Whether this is achieved by LMBs or virtual blocks, the critical point is that the dispatcher does not have to be contacted at every new block section. Nevertheless, this study will refer to LMBs rather than virtual blocks.

1.2.2.3. *Braking curves*

A defining feature of ERTMS/ETCS Level 2 is the use of dynamic braking curves. These curves are calculated in real time by the train based on the information received by the RBC. The RBC sends information such as train characteristics (e.g. braking performance), infrastructure details (e.g. gradients), and speed limits. The braking curve ensures that trains can always stop safely before reaching the end of their movement authority (European Railway Agency, 2020; Landex, Wittrup, et al., 2019).

As the train approaches a speed restriction or stop indication, the driver will receive information through appropriate graphics, colours, and sounds on the Driver Machine Interface (DMI). Initially, the system gives an Indication (I), advising the driver to brake to stay within the Permitted speed (P). If the driver fails to respond, the system provides an additional audible Warning (W) before intervening with automatic braking. If the driver still takes no action, the system activates Service Brake Intervention (SBI), causing a smooth deceleration. If this deceleration is insufficient to reduce the speed of the train, the system activates Emergency Brake Intervention (EBI), applying the emergency brakes which follows the Emergency Brake Deceleration (EBD) curve (European Railway Agency, 2020; Landex, Wittrup, et al., 2019). These different supervised locations of the brake curve can also be seen in Figure 3.

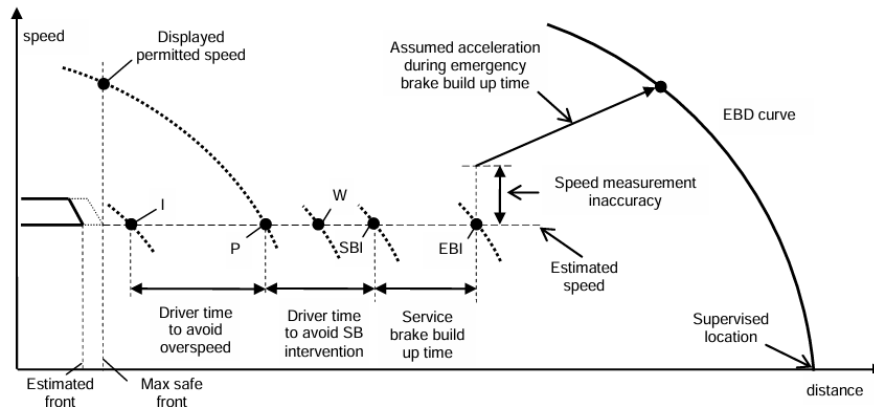


Figure 3: Overview of different supervision locations of ETCS braking curve (European Railway Agency, 2020)

These different braking curves are necessary to be determined when the train approaches the next marker board for which it has received movement authority. Figure 4 illustrates with an example how these braking curves ‘jump’ to the next SMB every time the movement authority is extended. Every SMB (blue with yellow arrow board) is a supervised location, which is a defined point along the railway where a movement authority may (not) be granted. In case of the second train in Figure 4, the movement authority is granted to the last SMB for which the entire block is free.

The figure illustrates three predicted braking curves: green (service brake by train driver), blue (Service or Emergency Brake Intervention, combined for simplicity), and red (Emergency Brake Deceleration). As there can be seen, when the first train passes a SMB, the braking curves of the second train shift to that specific SMB (European Railway Agency, 2020). This means that the movement authority of the second train is only extended after the first train has cleared a section. While this logic is similar to that of NS’54/ATB-EG, where signal aspects also depend on block clearance, ERTMS/ETCS Level 2 introduces dynamically shifting braking curves. This allows trains to brake later and closer to the consecutive train.

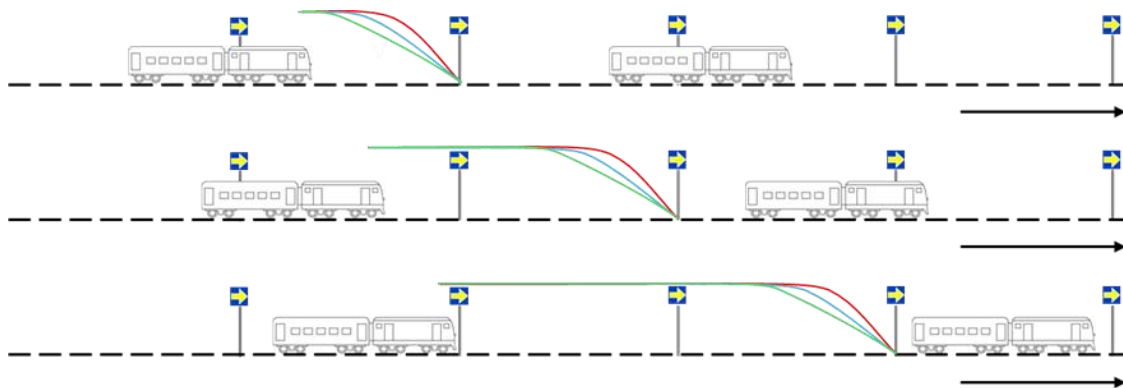


Figure 4: Overview of braking curves towards different SMBs

Because braking curves under ERTMS/ETCS Level 2 are calculated dynamically, trains are no longer required to first brake to 40 km/h before coming to a stop, as is the case under NS’54/ATB-EG. This more flexible braking behaviour is expected to increase capacity by allowing trains to operate closer together. Therefore, this study makes an explicit distinction between braking under NS’54/ATB-EG and ERTMS/ETCS Level 2 to accurately assess the impact on capacity.

1.3. Report outline

In this document, firstly the theoretical framework is presented in Chapter 2. Chapter 3 outlines the research aim, research questions, scope and provides an overview of the steps of the methodology. The selected study areas are described in Chapter 4. Chapter 5 addresses the first research question by presenting the assessment of the Key Performance Indicators. Chapter 6 covers the second research question, comparing the impact of various ERTMS/ETCS Level 2 block section design strategies to the NS'54/ATB-EG situation under both normal and disruptive conditions. Chapter 7 presents the third research question, focussing on the effect of using LMBs instead of SMBs during a communication failure. The fourth and final research question, in which a trade-off analysis is conducted, is discussed in Chapter 8. Chapter 9 is the discussion in which the limitations of the model and design choices are reflected. This study concludes with the conclusions per research question and an overarching conclusion in Chapter 10, followed by the recommendations in Chapter 11.

2. Theoretical framework

This chapter presents the theoretical framework used to explore how ERTMS/ETCS Level 2 influences both railway capacity and the performance during disruptions based on information of previous studies. This consists of the capacity definitions, definitions of resilience related to railway transport and disruptions of trains and their effects. The chapter ends with the research gap in this literature.

2.1. Capacity

Capacity is an important measure to evaluate performance of a railway network (Ranjbar et al., 2022). There are different definitions of capacity. The definitions presented in this subchapter are based on the line capacity, instead of the railway network. To provide clarity, this subchapter discusses the different definitions of capacity, the method used to assess capacity and how these approaches are applied in the context of this study.

2.1.1. Capacity definitions

Line capacity refers to the maximum traffic flow (measured in trains per time unit) that the infrastructure can handle under specific operating conditions (Pachl, 2009). According to Abril et al. (2008), there are different types of capacity definitions within the railway industry, which are explained in this section. Per capacity definition, an example is presented in italic.

Theoretical capacity

The theoretical capacity is the number of trains that could operate on a line within a specific time interval under ideal conditions. Since assumptions, such as homogeneous traffic, no disruptions, and identical trains, are made, it causes that theoretically it would be possible to let the trains run with the minimum headway between two consecutive trains. However, such conditions cannot occur in reality, so this capacity is only used as upper bound.

Under ideal conditions, assume that it is possible for a train to run between A and B every 5 minutes with the minimum headway. In a 1-hour period, the theoretical capacity would be:

$$\frac{60 \text{ minutes}}{5 \text{ minutes headway}} = 12 \text{ trains per hour.}$$

Practical capacity

Practical capacity is a more realistic estimate of line capacity and is usually between 60-75% of the theoretical capacity. This capacity corresponds to the actual number of trains running with a defined level of service quality. It also takes into account factors such as disruptions, disturbances, traffic variability, and signalling system performances.

*In practice, trains do not operate under perfect conditions. There might be slight differences in train speeds, some delays due to signalling or station stops, and disturbances from time to time. Based on operational experience, the railway operator assumes that 75% of the theoretical capacity is realistic for maintaining a high-quality service. This gives a practical capacity of: 12 trains * 0.75 = 9 trains per hour.*

Used capacity

The used capacity is the actual capacity utilised in the network. The used capacity is usually lower than the practical capacity.

Currently, the operator runs 6 trains per hour on this line. This number accounts for the demand and the current service levels in normal conditions. So, the used capacity is 6 trains per hour.

Available capacity

The available capacity is the difference between the practical capacity and the used capacity. This capacity indicates if there is a loss in capacity, and thus if trains could be added to the network.

The available capacity is the difference between the practical capacity and the used capacity, representing the room left for additional trains if needed. This means that the available capacity is: 9 trains per hour - 6 trains per hour = 3 trains per hour. Thus, the operator could theoretically add 3 more trains per hour to the line without compromising service quality.

2.1.2. Capacity assessment – UIC Leaflet 406: Train compression method

The blocking time compression method is used to improve the efficiency of train traffic by reducing the intervals or gaps between consecutive trains, allowing better use of rail infrastructure (Pachl & White, 2004). While this method allows for detailed analysis of track usage and helps in timetable assessment, it can be used to determine both theoretical and practical capacity.

The blocking time is the time interval in which a section of a track (block section) is exclusively allocated to a train and therefore blocked for other trains. This period starts when the latest possible movement authority must be provided (e.g. by clearing a signal) for the train to enter the section without causing delays. It ends once movement authority can be granted to another train to enter the same section. Typically, the blocking time is much longer than the actual time the train occupies the track element (Pachl, 2009).

The first step of the train compression method involves determining the various occupancy times for a train on a specific block. Figure 5 below shows the components that make up the occupancy time. As shown, occupancy time includes not only the period when the block is physically occupied, but also factors in safety margins ('time for route information', 'time for visual distance', and 'time for approach section'), clearing of the block, and the time needed for signal switching for the next train ('time for route release').

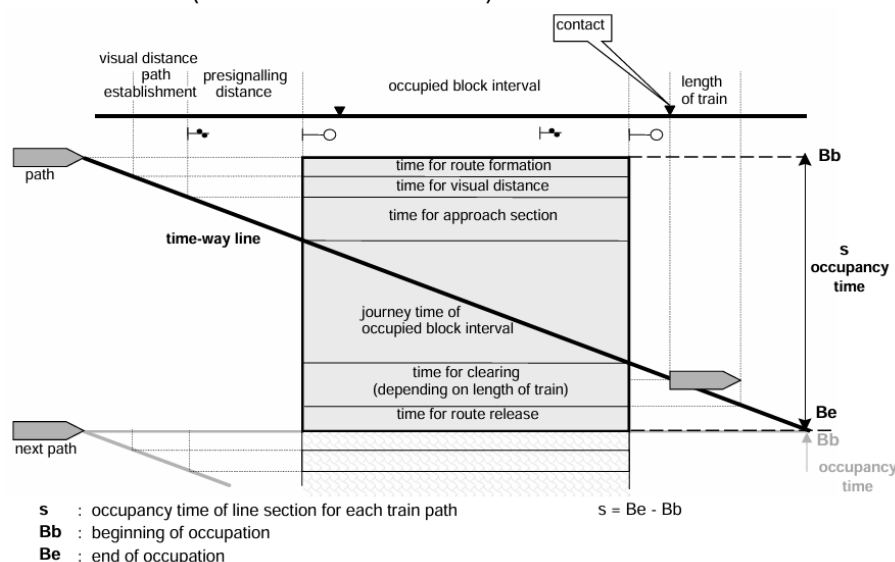


Figure 5: Overview of different aspects of blocking time of a block section (International Union of Railways, 2013)

When the occupancy times for each block are sequentially arranged for each train, a stairway pattern as in Figure 6 is created. This pattern makes it possible to determine the minimum headway. The minimum headway is the shortest time interval in which two successive trains,

traveling in the same direction, can enter a block section without overlapping their respective blocking time stairways.

This headway is calculated for each possible pair of consecutive trains. The minimum line headway for a specific train combination (where one train follows another into the same section) must be determined for each subsection between points where the trains could potentially pass each other. The largest of these values is considered to be the critical section for the whole track, as it represents the minimum distance at which that pair of trains can safely follow each other. This is also called the critical headway (Dicembre & Ricci, 2011).

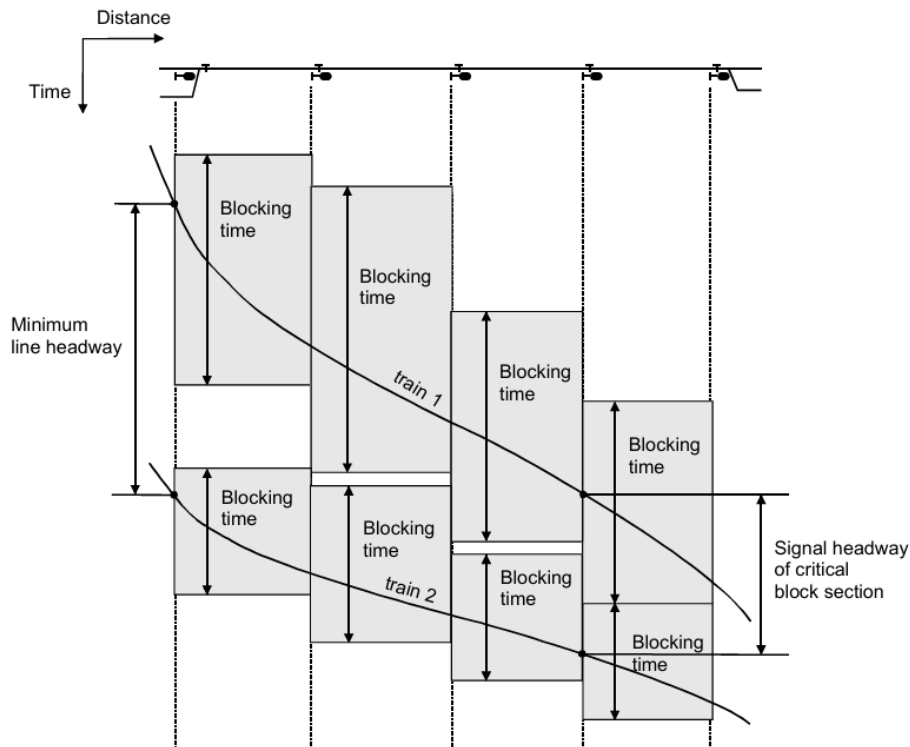


Figure 6: Blocking time stairway (Pachl & White, 2004)

The train compression method is usually applied to a specific section of the railway network rather than an entire line. This is done to reduce the number of influencing factors and to focus on the most critical part of the infrastructure. By examining a selected study area and its blocking times, buffer times between trains can be removed to create an ideal compressed timetable. In this situation, the blocking times follow each other directly, without gaps, meaning that trains are scheduled as close to each other as possible under optimal conditions. When applying this method, it is important to identify the critical part within the area. For example, if the study area contains a stretch of single track, compression is applied here. Figure 7 shows an example of a compressed time period where ideal conditions are assumed within the interlocking areas (from signal to signal).

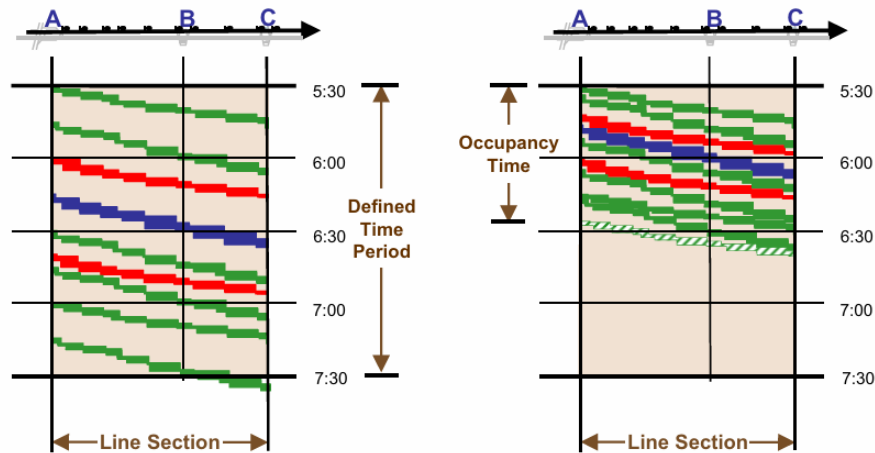


Figure 7: Example of train compression method (International Union of Railways, 2013)

The UIC has determined guidelines in order to get a recommended value for the ratio of consumed theoretical capacity of a line in order to create a stable and feasible timetable (International Union of Railways, 2004). The different values can be seen in Table 1. In the Netherlands, 80% consumed capacity for mixed traffic during peak hours is accepted (Goverde et al., 2012)

Table 1: Overview of recommended values for ratio of consumed theoretical capacity (International Union of Railways, 2013)

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

2.1.3. Impact of ERTMS/ETCS Level 2 on capacity

Several studies have investigated the impact of implementing ERTMS/ETCS Level 2 on railway capacity. In general, the shift from conventional signalling to ERTMS/ETCS Level 2 enables more flexible and short block sections, as signal visibility is not required (Landex, Jensen, et al., 2019). As a result, alternative block section designs have been explored in the literature to better understand their effect on capacity under ERTMS/ETCS Level 2.

According to Verkehrswissenschaftliches Institut (2008), the implementation of ERTMS/ETCS Level 2 with 400 m block sections and ERTMS/ETCS Level 3 would increase the capacity of the main line with 37.7% and 39.6%, respectively, in comparison with ERTMS/ETCS Level 1, as can be seen in Figure 8. In this comparison, it is assumed that ERTMS/ETCS Level 1 would use the same block section design as the current ATB situation.

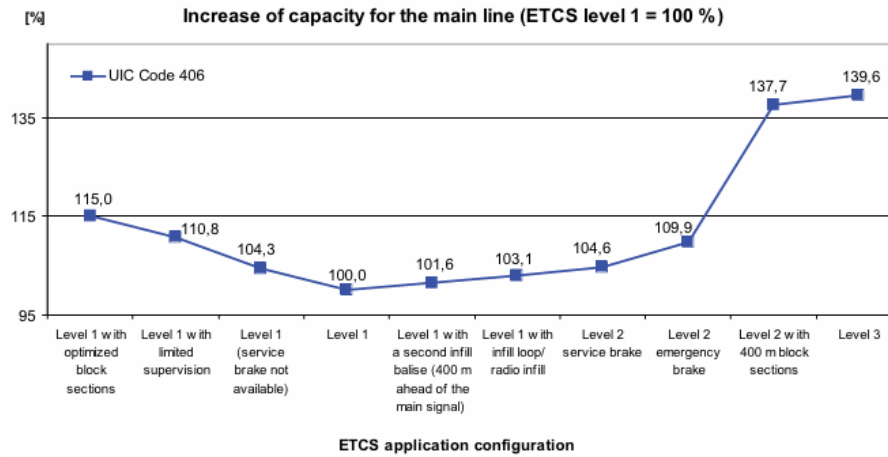


Figure 8: Comparison between ERTMS/ETCS levels regarding line capacity (Verkehrswissenschaftliches Institut, 2008)

Multiple case studies report capacity improvements when shifting from national systems to ERTMS/ETCS Level 2. In the study of Landex, Jensen, et al. (2019), a comparison between the current signalling system and ERTMS/ETCS Level 2 showed a 2% capacity consumption reduction with existing block sections, which increased to 9-17% with optimised block sections. In Sweden, the implementation of ERTMS/ETCS Level 2 on the Stockholm commuter line led to a 5% reduction in capacity consumption, and ERTMS/ETCS Hybrid Level 3 resulted in a 14% reduction (Ranjbar et al., 2022). Finally, in the Netherlands, Goverde et al. (2013) found a reduction in capacity consumption of 13.8% using ERTMS/ETCS Level 2 with the current block section design, and 15.5% with a shorter block section design, compared to NS'54/ATB-EG.

Despite these theoretical benefits, the study of Landex, Wittrup, et al. (2019) warns that capacity gains may be limited in practice. In this study, it is noted that when the conventional signalling system is replaced 1:1 with ERTMS/ETCS, capacity may decrease due to more conservative braking curves.

2.1.4. Application to research

The train compression method, as described in UIC leaflet 406, assumes ideal conditions. As such, this method approximates the theoretical capacity of a track, i.e. the maximum number of trains that can run under ideal conditions. For this study, however, theoretical capacity is not relevant since it does not reflect real-world conditions where variability and disruptions are present. Therefore, practical capacity is more relevant for this study, as this gives a more realistic picture of what the track can handle. Practical capacity considers margins for small disruptions or differences in driving behaviour, and is therefore more aligned with day-to-day operations. Since ERTMS/ETCS Level 2 enables more precise braking, it is expected that certain block section design strategies under ERTMS/ETCS Level 2 will improve the practical capacity, which is also in line with the found literature of Landex, Jensen, et al. (2019), Ranjbar et al. (2022), and Goverde et al. (2013).

Although the train compression method was originally designed to approximate theoretical capacity, it can also be used to understand infrastructure utilisation. By interpreting the results as a measure of capacity utilisation, bottlenecks can be recognised and different block section design strategies can be compared. In this study, the method is therefore not used to calculate an absolute capacity maximum, but rather to provide insight into differences in utilisation and flexibility between different block section designs.

The practical capacity will be determined by using the train compression method for each study area of the current infrastructure design (with NS'54/ATB-EG) as well as for each strategy per study area (with ERTMS/ETCS Level 2). This enables a comparison between the different block section design strategies.

2.2. *Disruptions in railway operations*

As rail transport grows and the intensity of its use increases, the sensitivity of the network to disturbances and disruptions becomes greater (Bešinović, 2020; Törnquist, 2007). Bešinović (2020) describes disturbances as day-to-day schedule variations, disruptions as external conditions such as infrastructure failure, and disasters as external natural conditions such as earthquakes. The latter two often result in temporary closures of lines or stations, while incidents such as suicides, demonstrations or strikes can also affect service frequency (Bešinović, 2020).

This sub-section explores the operational consequences of railway disruptions and how timetable design can provide built-in resilience to reduce their impact. It also examines the effect of different signalling and train protection systems on performance and response in disruptive conditions.

2.2.1. *Operational impact of disruptions*

The location, timing and duration of disruption may differ per disruption, but there may also be variation in the approach to how the disruption is resolved. For example, if a failure occurs during rush hour, the line could be partially repaired to allow train traffic but with reduced frequency. In this case, the failure could be repaired at night. However, if a similar failure were to occur in the evening or on a less busy route, the decision may be made to close the route completely until repairs are completed at night (Golightly & Dadashi, 2017).

In addition, the type of disruption may also determine the impact on the timetable. For instance, when there is a blockage on the track, it is almost immediately known whether or not trains can continue running, but when there is a staff shortage, it may still be possible to run trains. This depends on how many staff members are available or on standby (Goos et al., 2009).

For a minor disruption where the train is slightly delayed, it is generally not perceived as bad service by passengers. If major disruptions occur too often, however, this does change and they may eventually switch to another mode of transport. Because of this, it is important that during such a (major) disruption, the timetable returns to the original timetable as quickly as possible so that passengers experience as little disruption as possible (Goos et al., 2009).

The magnitude of the impact of a disruption also depends on the headway between trains on the same track. A disruption has more impact on the route when trains run closer together than when trains have more time between them (Goos et al., 2009).

The examples above illustrate how a disruption can vary in type, severity and operational impact. To understand how a railway system can absorb and recover from such events, the concept of resilience becomes essential. According to Bešinović (2020), the resilience of a railway system is defined as the ability of a railway system to provide effective services in normal conditions, as well as to resist, absorb, accommodate and recover quickly from disruptions or disasters. Furthermore, Bešinović (2020) describes the resilience curve of a railway transport system, which can be seen in Figure 9. Robustness in this model is defined as the ability to cope with several daily (smaller) delays due to disruptions. Vulnerability is the performance of the system during a disruption. Survivability is described as the ability of a system to switch from planned system performance to a disruptive state. Response is what actions are taken when a disruption occurs

to mitigate the damage. Finally, recovery is the ability of the system to return from the disruptive state to its original state. When recovery begins, it marks the end of the disruptive state.

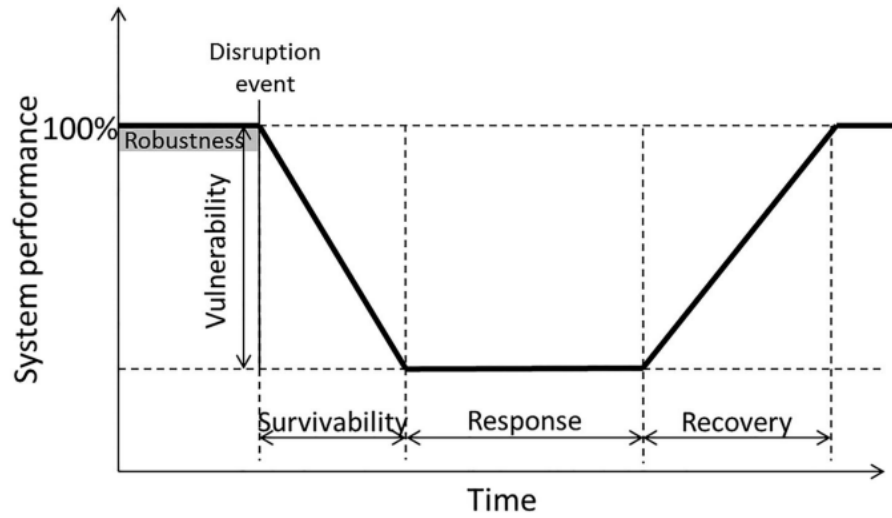


Figure 9: Resilience curve of Bešinović (2020)

In addition, Figure 10 presents a conceptually similar resilience curve, but with a more quantitative focus. Nicholson et al. (2015) defines resilience as the required time of a system to recover from disruptions and quantifies the maximum deviation from the schedule. This curve is based on maximum deviation, recovery time, deviation range and recovery threshold. In this model, the maximum deviation is the value that deviates the most from that of the non-disruptive state. The deviation area is the area under the deviation curve of the disruptive state. Finally, the recovery time is defined as the time between the deviation of a disruption rising above a threshold and the deviation of the disturbance falling below this threshold, which is the recovery threshold.

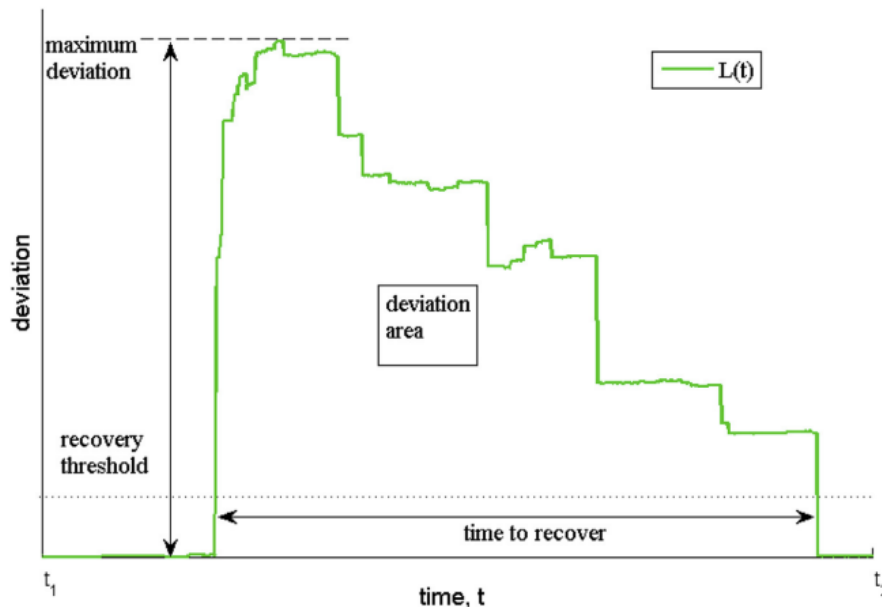


Figure 10: Resilience curve of Nicholson et al. (2015)

2.2.2. Resilience in timetable design

Trains may experience (minor) delays in the timetable. Robust timetables are designed to cope with these delays. This can be done by strategically distributing built-in time reserves across train paths so that small deviations do not disrupt the entire timetable. However, no timetable is robust enough to cope with severe disruptions, such as train failures, speed restrictions or infrastructure

failures. In such a scenario, multiple adjustments are required which result in severe delays and longer travel times (Corman et al., 2014).

During such disruptions, the capacity of one or multiple railway lines can be significantly reduced for an extended period. How much this capacity is reduced depends on the different signalling and ATB systems, as well as the traffic control decisions (Goverde et al., 2013). The built-in time reserves that usually absorb minor delays are insufficient to cope with the effects of major disruptions, allowing delays to spread across the network. In response, a new traffic plan needs to be developed. This may involve rerouting trains, changing stopping patterns, cancelling services or short-turning trains (ending a train's journey earlier than planned, usually at a station shortly before its final destination), to free up line capacity for other services (Corman et al., 2014).

Timetable design takes into account the fact that trains do not always run exactly as scheduled. This can be due to different factors such as passengers getting on and off the train, driver behaviour, train composition and weather conditions. When insufficient buffer is taken into account, these small variations can turn into delays that disrupt the timetable. This underlies the importance of designing a timetable that is resilient in such variations. To design a reliable timetable, a minimum amount of running time supplement is taken into account to accommodate variations in travel time. This supplement can also be used to reduce or even eliminate delays by allowing trains to run faster. In addition to the running time supplement, a buffer time is also taken into account. This buffer time is also included to prevent the succeeding train from being immediately hindered or forced to brake due to a (slightly) delayed preceding train (ProRail, 2013).

The buffer time is set to 60 seconds in the Netherlands (ProRail, 2013). According to Goverde (2018), the running time supplements between two stops is at least 5% and typically 10%. This running time supplement is implemented at the maximum speed of the track section in question. So for example, with a track section speed of 100 km/h, the train is assumed to be travelling between 90 and 95 km/h when making the timetable. In case of delays, this margin allows the train to speed up and potentially recover lost time.

2.2.3. Impact of different signalling systems in relation to disruptive conditions

In the current NS'54/ATB-EG system, there are two types of signals: operated and P-signals. Operated signals are placed at switches and are controlled by the traffic control system by the dispatcher. This dispatcher sets the route of travel by ensuring that the switches are correctly positioned, and thus (s)he does not determine the aspect (colour) of the signal (Veiligheid & vakmanschap railvervoer, 2023). The second type is the P-signal (*Dutch: 'permissief', permission*), which is used to indicate whether the block to be entered is unoccupied (Infrasite.nl, n.d.).

During periods of disruptions, train drivers should stop at the next signal they encounter and contact the dispatcher for further instructions. The dispatcher may authorise the train driver to proceed to the next operated signal. If there are P-signals between two operated signals, the train may pass them without further communication to the dispatcher. Moreover, if communication between the train driver and dispatcher is not possible, the train may also pass the P-signals. For both scenarios, the train driver must contact the dispatcher again at the next operated signal (Infrasite.nl, n.d.).

During this procedure, strict safety measures must be followed. For instance, the train must not exceed a speed of 40 km/h. At this speed, the train can stop within the distance that the driver can see if the track is not clear. In addition, the driver must take into account the failure of a level

crossing, as they are connected to the P-signals, and must be careful at these crossings. Finally, of course, the dispatcher should not give permission to pass a red P-signal if (s)he is aware of dangers behind it (Overheid.nl, 2023).

The NS'54 signalling system under ATB-EG has similarities with the Stop Marker Boards and Location Marker Boards in ERTMS/ETCS Level 2, particularly in their operation under both normal and disruptive conditions. As mentioned in section 1.2.2.2, SMBs and LMBs function identically during non-disruptive situations. However, in the event of a disruption, a key difference emerges: with ERTMS/ETCS Level 2 a train must stop at the first SMB encountered and receive an European Instruction which provides authorisation to proceed. Once authorised, they may pass intermediate LMBs without further contact with the dispatcher and continue towards the next SMB. This mirrors the procedure under NS'54/ATB-EG, where trains are allowed to move to the next operated signal as soon as they have permission and pass the intermediate P-signals without further communication.

This operational resemblance shows that NS'54/ATB-EG and ERTMS/ETCS Level 2 follow similar procedures during disruptions. However, due to the technical differences between both systems, the performance during such disruptions can differ. Several studies have investigated these effects in more detail.

The study of Goverde et al. (2013) examined the impact of different block section designs under disruptive conditions. The study showed that there is a considerable gain for ERTMS/ETCS Level 2 compared to NS'54/ATB-EG in such conditions. This improvement is attributed to shorter braking distances at lower speeds, which stabilise headway times and improve overall throughput.

The results of Goverde et al. (2013) are in line with the results of Simons (2019), who analysed the impact of ERTMS/ETCS Level 2 during seven different disruptive conditions across three signalling designs: the current NS'54/ATB-EG layout, ERTMS/ETCS Level 2 using the current layout, and ERTMS/ETCS Level 2 using reduced block section lengths. The study found that the ERTMS/ETCS Level 2 with the current block section design was 10% more resilient than the NS'54/ATB-EG situation, applying block sections of 200 metres under ERTMS/ETCS Level 2 increased resilience by 25%.

Similarly, Landex, Wittrup, et al. (2019) concluded that block sections with ERTMS/ETCS Level 2 are generally less restrictive due to the continuous update of movement authority. They expected that this results in fewer delays when the current signalling system is compared with ERTMS/ETCS Level 2 with the same block section design. However, they also note that, with the same block layout, the critical block could remain the same across the different signalling systems, the minimum line headway may remain unchanged.

2.2.4. Application to research

Based on the information provided in this section, NS'54/ATB-EG is expected to perform worse under disruptive conditions than ERTMS/ETCS Level 2 when using the same block layout. However, this advantage may decrease when more SMBS are introduced with alternative block section designs, as the procedure for requesting an European Instruction takes additional time. In contrast, designs that incorporate more LMBs are expected to improve resilience by enabling faster recovery.

Although both system experience a significant capacity reduction during major disruptions (Corman et al., 2014; Goverde et al., 2013), ERTMS/ETCS Level benefits from continuous real-time communication between train and track. This enables more dynamic traffic control

interventions and potentially faster dispatching decisions compared to the NS'54/ATB-EG system, where communication is less integrated.

The degree of capacity loss during disruptions is not only determined by the signalling and ATB systems. Traffic control and timetable design decisions also play a crucial role (Goverde et al., 2013). This is not considered within this study. This study thus focusses specifically on how signalling and ATB choices, in particular the design of block sections and the use of SMBs or LMBs, affect track resilience and capacity during disruptions.

2.3. Research gap

Current research on ERTMS/ETCS Level 2 block section design strategies has several limitations, leaving important areas unexplored, such as resilience during disruptions (with only three studies to this). The first major limitation is that existing studies often focus on a single block section design strategy throughout the research process (Cansu et al., 2023; Landex, Jensen, et al., 2019; Landex, Wittrup, et al., 2019; Vignali et al., 2020). By not comparing multiple design strategies, these studies fail to assess trade-offs between different approaches, particularly in how they perform under varying operational conditions. This narrow focus limits the ability to compare findings across different rail systems and operational intensities.

Another important gap is that many studies have limited their analysis to one specific study area (Goverde et al., 2013; Ranjbar et al., 2022; Vignali et al., 2020). This does not take into account the variation in traffic volume (used capacity) in different regions. Therefore, the results cannot fully reflect how different train volumes can affect the performance of block section strategies. By not considering a wider range of operational contexts, these studies provide limited insights into how design strategies perform with different traffic volumes.

Although ERTMS/ETCS Level 2 has been extensively studied, limited attention has been given to the operational handling of End of Authorities (EoAs) during disruptions, particularly regarding the use of Location Marker Boards. Most existing studies focus on general capacity improvements, while the impact of requesting European Instructions at every SMB during disruptions remains unexplored. This lack is a critical gap in the literature, as the use of LMBs could provide alternative approaches to dealing with capacity during disruptions, especially compared to SMBs. Given the flexibility and minimal infrastructure requirements of LMBs, further investigation into their performance during disruptive conditions is needed. This study aims to explore these gaps by comparing multiple ERTMS/ETCS Level 2 block section designs across three different corridors with varying traffic volumes, using simulations to evaluate their effectiveness under disruptive and non-disruptive conditions.

3. Research structure

In this chapter, the research aim is outlined, where the key components are highlighted for clarity. The four research questions, discussed in the following section, are designed to support the achievement of this aim. After this, the scope of the study is defined, and this chapter ends with an overview of the methodology steps taken during this research.

3.1. Research aim

This study aimed to **evaluate the performance¹ of multiple ERTMS/ETCS Level 2 railway block section design strategies² under both normal³ and disruptive⁴ conditions.**

¹ Performance refers to Key Performance Indicators. These were identified through a literature review and validated through stakeholders interviews.

² In this study, a block section design strategy refers to rails between the stations of the study area, including the station itself.

³ In this study, normal conditions were defined as the standard operating conditions of a railway network in which all systems operate according to schedule. This is characterised by trains running on time without large delays or interruptions, and by well-functioning infrastructure, such as tracks, signals and stations, which allows for smooth and uninterrupted train traffic.

⁴ Disruptive conditions refer to instances of unexpected breakdowns or failures in the railway network in this study. Examples of these incidents include infrastructure failures, accidents, extreme weather conditions, or operational issues (Goos et al., 2009). Such incidents may result in delays, a reduction in the frequency of trains, detours or cancellations. The extent of the disruptions may vary, but could also show network-wide effects, resulting in a deviation from the planned timetable and the necessity for alternative routes to minimise the impact on passengers and freight (Corman et al., 2014).

3.2. Research questions

In order to achieve the research aim, four research questions were formulated. The first research question focussed on the various Key Performance Indicators related to train disruptions that could potentially be used for the trade-off analysis.

1. Which Key Performance Indicators (KPIs) are most applicable in a trade-off analysis related to train disruption and are of interest to the different stakeholders in this domain?

The second research question related to the performance of the different strategies. These strategies range from theoretical extremes to more practical and balanced approaches, and were developed in the early stages of the research. Furthermore, the strategies were presented to the stakeholders during the interviews, and possible input from this was incorporated to refine the strategies were relevant. Each strategy was tested during normal and disruptive conditions with varying train volumes.

2. What is the performance of the various railway block section design strategies during normal and disruptive conditions in combination with varying train volumes?

The next step of the research focussed on testing the block section design strategies using Location Marker Boards instead of Stop Marker Boards during disruptions. The research question aimed to determine whether the use of LMBs could lead to an improvement in performances during disruptions compared to SMBs.

3. What is the performance when the railway block section design strategies use Location Marker Boards (LMBs) instead of Stop Marker Boards (SMBs) during disruptions?

Finally, a comparison between the different strategies was made based on trade-off analysis.

4. Based on the KPIs of research question 1 and simulation results of research question 3 & 4, which trade-offs must be considered when selecting a block section design?

3.3. Research scope

This study focussed on comparing the effects of the current NS'54/ATB-EG system with the proposed ERTMS/ETCS Level 2 implementation. The analysis included simulating different train volumes, allowing a more comprehensive evaluation and ex-ante assessment of different design strategies under various operational scenarios. Each study area has been assessed using consistent criteria within a trade-off analysis, ensuring a balanced comparison of the proposed strategies and their impact on line capacity, resilience and disruption management.

Multiple traffic control rules could be applied during a disruption. Adjustment measures, such as cancelling trains, turning at stations other than planned, or left-track driving, were outside the scope in this study. As a result, this study used the First in, First Out (FIFO) strategy. The trains that arrived first somewhere in a block section were also the first to leave. When several trains were waiting at a station, the longest waiting train received priority. This approach was consistent during disruptions and required no additional regulations.

The study used the 2025 timetable. The decision to use the 2025 timetable is based on the fact that there were still too many uncertainties in the timetables for the upcoming years. In addition, from the 2025 timetable it is known at what times the different freight trains paths are reserved.

Furthermore, this study assumed that the whole investigated area was equipped with ERTMS/ETCS Level 2, meaning that the station areas and open line use the system. This also meant that no transition between NS'54/ATB-EG and ERTMS/ETCS Level 2 was needed, as opposed to the current situation in the Netherlands. Because of this, a comparison between a 100% NS'54/ATB-EG and a 100% ERTMS/ETCS Level 2 could be made.

3.4. Methodology

Figure 11 provides the different steps of the methodology, each of which contributed to answering the research questions described in section 3.2. In this figure, each row corresponds to a separate research question. In addition, multiple lines from the interview box (first box of RQ2) direct to different boxes. These lines are labelled with text indicating the specific information needed to carry out the next step. In this report, each step of the methodology and corresponding results is explained in a separate chapter.

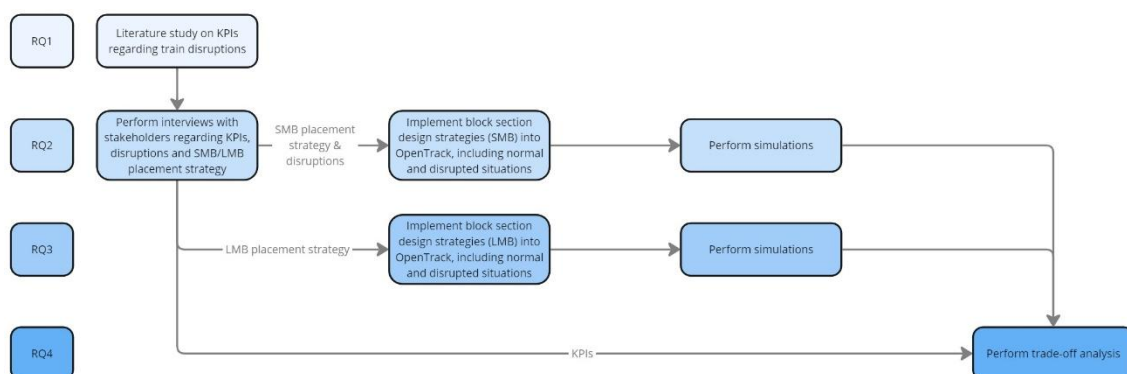


Figure 11: Flowchart of methodology

4. Study area

This study focussed on three different study areas: Zwolle – Deventer, Amersfoort Centraal – Apeldoorn, and Arnhem Centraal – Nijmegen, all located in the eastern and mid-eastern regions of the Netherlands, as can be seen in Figure 12. These areas were selected based on a number of criteria that match the purpose of this study:

1. Variation in traffic volumes

In order to evaluate how block section design strategies perform under different levels of capacity consumption, it is important to include lines with varying volumes.

- Low: Zwolle – Deventer includes a single-track section (between Olst and Deventer), which limits capacity and makes the line vulnerable to disruptions.
- Medium: Amersfoort Centraal – Apeldoorn carries regular freight traffic (two freight trains per direction per hour), increasing heterogeneity and operational complexity.
- High: Arnhem Centraal – Nijmegen is one of the busiest rail routes in the Netherlands, offering insights into high-demand scenarios (ProRail, 2021b).

2. Disruption relevance and alternative routing

These areas are especially important for eastern and northern Netherlands, where alternative routes are limited during disruptions. This makes resilience relevant in these regions.

3. Diversity in traffic type and operational characteristics

The selected lines differ in train composition (intercity, regional, freight), train speeds, and timetable, which allows for broader applicability and comparison of performance per strategy.

4. Similar length for comparability

All three lines are roughly similar in length, allowing for fair comparisons between the different lines.

Based on these criteria, the three selected study areas allowed for performance comparisons. This study specifically focussed on line-level performance, since including full network interactions would require numerous assumptions regarding routing, prioritisation and disruption propagation. To avoid this complexity and ensure a clear and controllable analysis, the selected areas offer defined boundaries. This made it possible to compare block section strategies in a consistent and realistic way, while keeping the focus on the line itself.

By including a mix of line types, the study aimed to cover a range of scenarios. Furthermore, by comparing strategies across different locations and levels of capacity consumption, insights could be obtained that are transferable to other lines, assuming similar conditions. For example, a strategy that performs well under high intensity may not be effective in a lower intensity context, or vice versa.



Figure 12: Overview of selected study areas

4.1. Low volume: Zwolle – Deventer (blue)

The low volume study area is the Zwolle – Deventer line of 29.9 kilometres. An intercity train runs every half hour in both directions, with intermediate stops at Olst and Wijhe. The section between Deventer and Olst is single track. This restriction limits the frequency to two trains per hour in each direction, so that only the intercity train can operate on this line. During normal circumstances, no freight trains operate on this line.

4.2. Medium volume: Amersfoort Centraal – Apeldoorn (red)

The medium volume line in this study is the Amersfoort Centraal – Apeldoorn route, which has a length of 43.8 kilometres. Intercity and freight trains operate on this line. The intercity train runs with a frequency of five trains per hour in each direction, and the freight trains two times per hour in each direction. Furthermore, two regional trains also operate on this line, although they only use a part of the route since they operate between Amersfoort Centraal and Ede-Wageningen/Barneveld Zuid.

4.3. High volume: Arnhem Centraal – Nijmegen (green)

The high volume route in this study is the 18.5 kilometres Arnhem Centraal – Nijmegen line, which is served by regional, intercity and freight trains. The route accommodates six intercity and four regional trains, which both operate on the whole line. In addition, two regional trains also operate on this line between Arnhem Centraal and Tiel. While the intercity trains operate as a non-stop

service between Arnhem Centraal and Nijmegen, the regional trains that run from Arnhem Centraal to Nijmegen make intermediate stops at Arnhem Zuid, Elst, and Nijmegen Lent, while the regional trains between Arnhem Centraal and Tiel only stop at Elst. Additionally, a freight train runs once per hour per direction between these cities.

5. Key Performance Indicators assessment

Building upon the theoretical concepts discussed in Chapter 2, such as railway capacity, resilience, and operational effects of ERTMS/ETCS Level 2, this chapter identifies and validates the Key Performance Indicators (KPIs) used to evaluate different block section design strategies, which provides the answer to research question 1. These KPIs provide a quantifiable means to assess the impacts of design choices, and are essential for the trade-off analysis presented later in this study.

5.1. Methodology

The first phase of this research focussed on identifying Key Performance Indicators (KPIs) related to train disruptions, which provided a measure for assessing the impact of different block section strategies under ERTMS/ETCS Level 2. To select suitable KPIs for a trade-off analysis related to train disruptions, specific criteria were established. A KPI was considered suitable if it met the following criteria:

- **Relevance:** The KPI should cover operational aspects affected by block section design strategies.
- **Quantifiability:** The KPI should be measurable in a clear, consistent and objective way that allows comparisons between different strategies.
- **Stakeholder value:** The KPI could be of interest for the different stakeholders.
- **Practical usability:** The KPI should be understandable and interpretable such that it can be used in decision-making processes.

After this, the found KPIs from the literature review were verified through semi-structured interviews. In semi-structured interviews, the main interview topics were identified in advance, while the format also allowed the flexibility to delve deeper into specific topics raised by interviewees. The main themes of these interviews are described below and the full interviews can be found in Appendix A: Interviews. The interviews were conducted with a diverse group of stakeholders to bring out different perspectives, including representatives from ProRail, NS, Keolis, and Haskoning. These stakeholders manage, use or research the railway network in the Netherlands. Table 2 shows which topics were discussed with which stakeholder.

Table 2: Overview which topics were discussed with which stakeholder

Stakeholder	Interview topic		
	Validation of KPIs	Block section design strategies marker boards	Disruptions
ProRail			
Railway signalling engineer	☒	☒	☒
Capacity management	☒	☒	☒
Dispatchers	☒	☒	☒
System specialist ERTMS	-	-	-
ERTMS Programme Management	☒	☒	☒
NS	☒	☐	☒
Keolis	☒	☐	☒
Arriva	☒	☐	☒
Haskoning	☐	☒	☒

As Table 2 shows, none of the topics were discussed with the ProRail system specialist ERTMS. This is because this interviewee is mainly specialised in the field of ERTMS/ETCS Hybrid Train Detection (formerly known as Level 3). This interview therefore served to provide a more complete picture of the area of ERTMS/ETCS domain as a whole.

5.1.1. Validation of Key Performance Indicators

As mentioned in the first step of the methodology, KPIs related to train disturbances were first identified based on a literature review. During the semi-structured interviews, these KPIs were presented to the stakeholders. Their responses helped refine the selection of KPIs so that they would align with actual operational needs. Capturing this practical expertise at the beginning of the study allowed a trade-off between theoretical strategies and their application in real railway operations.

5.2. Results

This section presents the results of which Key Performance Indicators have been selected to evaluate the block section design strategies. This is based on a combination of literature review and stakeholder interviews.

5.2.1. Literature review

Several studies have investigated performance indicators in a railway network during disruptions and/or disturbances. The performances included vary from study to study and is explained in this section.

The study by Nicholson et al. (2015) presents a comprehensive framework for assessing the performance of railway operations for both minor and major disruptions based on identified Key Performance Indicators (KPIs). These KPIs provide a quantitative basis for comparing different operational strategies, both in simulations and real-time operations. These KPIs can be grouped into three categories:

- **Operational performance**
 - Transport volume: the total number of passenger and freight kilometres travelled across a network, reflecting the capacity utilisation of the system
 - Journey time: the average time required for train journeys between selected origin-destination pairs
 - Connectivity: the average transfer time of all transfers at a station for journeys that both depart and arrive during the simulation period
 - Punctuality: the sum of departure delays at selected stations
- **Resilience**
 - Resilience: the required time of a system to recover from disruptions and quantifies the maximum deviation from the schedule
- **Sustainability**
 - Energy consumption: the energy required per service for all services
 - Resource usage: track and rolling stock utilisation, providing insight into system efficiency and infrastructure constraints

The paper highlights the importance of these KPIs in providing rail operators with decision-support tools to reduce delays and improve system robustness and resilience.

The paper of Jensen et al. (2014) puts two indicators of robustness into perspective.

1. **Capacity consumption – UIC 406.** As described in section 2.1.2 is the UIC 406 method used to improve the efficiency of train traffic by reducing the intervals or gaps between consecutive trains. Based on these compressed train paths the capacity consumption

can be determined, which is percentage of the infrastructure's utilisation within a specified period.

2. **Robustness indicator including passenger travel time.** The weighted travel time extension (WTTE) can also be used as a measure of robustness. This is calculated as the relative difference between the total weighted real travel time and the nominal (planned) travel time of passengers. To obtain the total weighted real travel time either real delays have to be used or a simulation of delays has to be conducted. The lower the value of the indicator, the more robust the timetable is.

In the paper of Dewilde et al. (2014), this WTTE is further explained. Based on extensive studies, weights are assigned to different wasted travel times to represent the passengers' perception of wasted travel times. Delays have a weight of 3, supplements that result in extra unnecessary dwell times a weight of 2, and transfers a weight of 2. Transfers mean that the passenger has to wait on the platform until the connecting train arrives.

The total weighted real travel time for all passengers is computed using the described weights. The total weighted real travel time is normalized by subtracting the nominal travel time of all passengers from it and dividing this result by the same nominal travel time. This ratio gives a measure for the weighted travel time extension. The weighted travel time extension equals:

$$WTTE = \frac{\text{total weighted real travel time} - \text{nominal travel time}}{\text{nominal travel time}} \quad \text{Eq. 1}$$

At last, Ranjbar et al. (2022) investigate the impact of capacity of various signalling systems, which include ETCS Hybrid Level 3, ETCS Level 2 and the Swedish ATC2 signalling system. The comparison between the different systems is based on the occupation time of a block section, capacity consumption, minimum headway, and ratio of headway (compared to ATC2). Within this paper the occupation time is defined as the total time a block section is occupied by a train within a defined time period, capacity consumption is the ratio between occupation time to a defined time period, minimum headway is the required time interval between two consecutive trains, and the ratio of headway compares the minimum headway of ETCS Level 2 and ETCS Hybrid Level 3 to the Swedish ATC2 signalling system. These indicators were specifically chosen as they are important performance considerations and decision-making indicators.

5.2.2. Interviews

The interviews reveal that different stakeholders consider different aspects of the performance of block section design strategies to be important. While there are similarities in general goals, such as aiming for a reliable and efficient railway system, the emphasis varies depending on the stakeholder's role.

- ProRail, as infrastructure manager, primarily focusses on the efficient use of infrastructure, aiming to increase capacity where possible while keeping infrastructure costs manageable. Simplicity of design is an important consideration: if a layout is not intuitive, for example for a train driver, it may lead to confusion at block boundaries, potentially causing unnecessary stops or unsafe behaviour. From the perspective of dispatchers, it was also highlighted that resilience and workload during disruptions are important, particularly when designs include a high density of SMBs that must be handled under disruptive conditions.
- Operators, including NS, Arriva, and Keolis, place more weight on the robustness of the timetable. Their key concerns revolve around punctuality, connectivity, capacity, travel time, weighted travel time extension, and overall passenger experience. One example mentioned is the importance of reliable connections. This includes both keeping total

transfer times low and ensuring that trains do not depart earlier than scheduled, potentially breaking important passenger connections.

- It is also pointed out that safety is not a consideration but a requirement. If the design meets the design requirements, safety is assumed to be guaranteed. However, it is important that SMBs are located where it is safe to stop. At the same time, over-design should be avoided, as it may undermine the comprehensibility or usability of the system.

5.2.3. Selection of KPIs

During the interviews, the stakeholders highlighted the different aspects they considered important. Some KPIs are slightly modified or refined to better fit the scope of this study, and additional explanations are included where relevant. Based on the insights gained from the interviews, the following Key Performance Indicators are selected for this study:

- Capacity consumption (UIC 406) and therefore minimum headway
- Resilience
- (Weighted) travel time
- Punctuality
- Infrastructure costs

Resilience

Exactly how resilience should be measured was not explicitly addressed during the interviews. Moreover, various definitions and interpretations of resilience exist in the literature (Bešinović, 2020; Nicholson et al., 2015). In this study, two indicators are selected to quantify resilience: the recovery and disruption period.

The recovery period is defined as the time from the start of the disruption until a train returns to operation within a predefined margin of the timetable at the location of failure (Bešinović, 2020). For this, thresholds of 3 and 5 minutes are used to assess how quickly the system returns to near-normal performance. NS and ProRail use a passenger punctuality margin to determine how many trains arrive on time. As of the new timetable this year, this margin went from 5 minutes to 3 and 10 minutes (Leblanc, 2025). As a result, this study chooses to include both the 3-minute and 5-minute margins.

The disruption period, on the other hand, is measured from the onset of the disruption until the first train fully returns to the timetable at the location of failure.

Figure 13 shows a time-distance diagram to illustrate both concepts. The red line represents the train in which the disruption occurs. The first dot on the 'location of failure' line marks the start of the disruption. The blue line represents the first train to recover within the 3- or 5-minute delay threshold (recovery period), and ends at the second dot. The green line indicates the first train to resume operations entirely according to the original timetable (disruption period), and ends at the third dot.

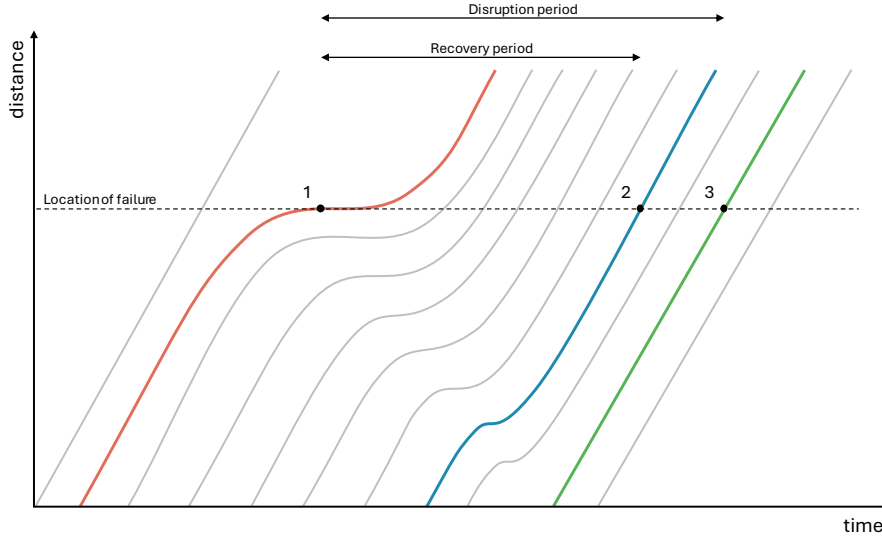


Figure 13: Illustration of the recovery and disruption period

(Weighted) travel time

The mean travel time is a straightforward indicator that reflects the overall performance of the railway system. It can be calculated per strategy, but also broken down by train types. This allows for an analysis of which train series are more affected or benefit more from a given strategy.

The Weighted Travel Time Extension (WTTE), however, requires a more complex approach. In order to use the method of Dewilde et al. (2014) as explained in Section 5.2.1, passenger data should be used in order to assess the actual impact of delays in the passenger perspective. Since such data was not available for this study, a substitute method was developed using the seating capacity of the various train types used in the simulation and a disruption factor.

To better reflect how delays are perceived by passengers, findings from Warffemius (2015) were used as a basis. This study found that one minute of delay is perceived as three to five minutes of additional travel time. Based on this, a disruption factor was defined, which represents the ratio between the actual delay and the scheduled travel time, which can be seen below:

$$delay_i = \max(0, travel\ time\ delayed_i - travel\ time\ baseline_i) \quad Eq. 2$$

Where:

- $travel\ time\ delayed_i$ Travel time with disruption for train series i
- $travel\ time\ baseline_i$ Travel time without disruption for train series i

With this $delay_i$ the $disruption\ factor_i$ can be calculated for the affected train i , which represents the relative impact of a disruption:

$$disruption\ factor_i = \min\left(1, \frac{delay_i}{travel\ time\ baseline_i}\right) \quad Eq. 3$$

After this, the $weighted\ delay_i$ per affected train i is calculated by multiplying the $delay_i$ with the $disruption\ factor_i$ and $seating\ capacity_i$:

$$weighted\ delay_i = delay_i \cdot seating\ capacity_i \cdot disruption\ factor_i \quad Eq. 4$$

The total Weighted Travel Time Extension $WTTE_i$ can then be calculated as the ratio between the total weighted delay and the total nominal weighted travel time:

$$WTTE_i = 1 + \frac{\sum_i weighted\ delay_i}{\sum_i travel\ time\ baseline_i \cdot seating\ capacity_i} \quad Eq. 5$$

This results in a weighted performance metric in percentages that captures both the magnitude of delays and the potential number of passenger impacted.

Travel time deviation compared to NS'54/ATB-EG

Although punctuality was identified during the interviews as a relevant Key Performance Indicator, it is not included in this study. The KPI would be used during undistruptive conditions, where punctuality typically approaches 100%. This makes it an uninformative metric in order to assess different block section designs. Instead, this study focusses on travel time deviation compared to the NS'54/ATB-EG reference case. By comparing these deviations, potential gains in operational efficiency can be identified.

Infrastructure costs

One of the interviews revealed that costs can be assessed indirectly by looking at the number of SMBs in the design.

Although overall passenger experience is an important KPI for railway operators, it was not included in this study. The main reason is that it is out of the scope of this study and the lack of accessible and detailed passenger data.

Furthermore, this study makes a deliberate distinction between the KPIs used under different conditions. In undisturbed scenarios, the capacity, average travel time, infrastructure costs, and travel time deviation compared to the NS'54/ATB-EG scenario are evaluated. In disruptive scenarios, the focus shifts to resilience and the Weighted Travel Time Extension (WTTE).

5.3. Conclusion

The goal of this first part of this study was to identify and validate relevant Key Performance Indicators (KPIs) that could be used to evaluate different block section design strategies under ERTMS/ETCS Level 2, particularly during train disruptions. A combination of a literature review and semi-structured interviews with various stakeholders formed the basis for selecting these KPIs.

From the literature, several KPIs were identified, such as capacity consumption, travel time, punctuality and energy usage. These were further refined during the interviews. During these interviews, the stakeholders provided insights into which aspects they considered important. ProRail emphasised capacity, costs and resilience, while operators prioritised travel time, resilience, and punctuality. Dispatchers highlighted the impact of disruptions and the associated workload when designs include a high density of SMBs.

Based on the literature and the insights from the interviews, the following Key Performance Indicators were selected for this study:

- Capacity consumption (UIC 406), including minimum headway
- Resilience, measured by recovery and disruption periods
- (Weighted) travel time
- Travel time deviation
- Infrastructure costs

6. Implementation of block section design strategies

In this chapter, the second research question is answered. The first part outlines the methodology used to implement various block section design strategies under ERTMS/ETCS Level 2. It begins with a description of the selected block section design strategies and the regulations that comes with this. This is followed by an explanation of the disruption scenarios, their locations, and their implementation into OpenTrack. The methodology ends with an overview of the assumptions that are made. The second part of this chapter presents the results of the implementation of the block section design strategies into OpenTrack in non-disruptive and disruptive conditions. The chapter ends with a conclusion.

6.1. Methodology

In this research, OpenTrack was used to conduct the simulations. OpenTrack is a micro-simulation software designed for railway planning. It simulates and calculates train movements based on input such as rolling stock, infrastructure, and timetables, while taking into account the constraints of the signalling system and schedule (OpenTrack, 2024).

6.1.1. Block section design strategies

This section describes the block section design strategies that were used in this study. The aim of these strategies was to explore a range of different possible implementations, ranging from theoretical extremes to more practical and balanced approaches. For example, the ETCS minimum distance strategy represents a capacity-maximising extreme, while the harmonic strategy reflects a more pragmatic and cost-aware approach.

The first strategy serves as a baseline and provides a reference for comparison between the current system with NS'54/ATB-EG as well as the other strategies, while the second strategy was expected to serve as an upper bound in terms of performance. The other strategies were expected to fall somewhere in between these two strategies.

Furthermore, the strategies (1, 2, 4, and 5) were also discussed during the interviews with ProRail and Haskoning. These parties either design, operate or advise on railway infrastructure. During the interviews, they were asked whether additional strategies should be considered. As a result of these interviews, strategy 3 was added. This strategy has strategy 2 as base, whereby marker boards that have no to little impact on the capacity were removed. This strategy minimises the costs, but tries to keep the capacity as high as possible.

When applying the different design strategies for block sections, there may be locations where placing a SMB is not feasible due to regulations or physical constraints. This may mean adjusting the placement of the SMB or changing the design of the block section to meet local regulations or operational requirements. Since each location and strategy is different, each scenario was evaluated on a case-by-case basis to ensure that deviations from the planned design were addressed with tailor-made solutions.

Strategy 1 – Current block section design

The first strategy involved using the existing block section design without any changes. This served as a baseline for comparison with other ETCS strategies and NS'54/ATB-EG. An important limitation to take into account was that, due to design regulations, a SMB could not always be placed in the same locations as existing signals. As already explained above, a tailor-made approach was needed to solve this.

Strategy 2 – Minimum distance

The second strategy consisted of placing SMBs along the entire route at the minimum distance allowed, which is every 200 metres. This dense placement of SMBs was tested in OpenTrack to evaluate the effects on train traffic and performance.

Strategy 3 – Cost-efficient minimum distance strategy

During one of the interviews, a strategy emerged that uses the principles of the minimum distance strategy, but considers which marker boards have little or no effect and can therefore be removed. As a result, it is likely that many marker boards could be removed, which would save a lot of money. The removal of marker boards was based on the timetable and reviewed on the space-time diagrams.

Strategy 4 – Harmonic

The fourth strategy was the harmonic strategy, where block sections were designed to be small near stations and gradually increase in length on the open line. This approach improves flexibility around stations and reduces costs by minimising the number of smaller block sections in less critical areas.

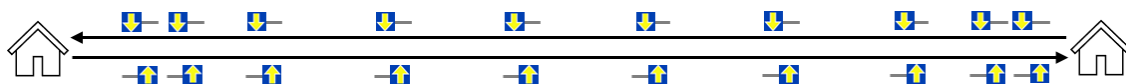


Figure 14: Example of harmonic strategy

This design is based on the headway between two consecutive trains with identical characteristics. In this study, a headway of four minutes was used, meaning that when the first train departs from the origin, the second train departs four minutes later. This time interval was maintained throughout the route. Both trains were assumed to be of the same type and to follow the same stopping pattern, including any intermediate stops.

This headway considers possible intermediate stops of the trains and time the system needs to communicate, such as the release of a route. These stops take extra time because of the deceleration, actual stopping of the train and (de)boarding of passengers, and then acceleration again.

Strategy 5 – ProRail design manual ERTMS

ProRail, together with Movares and Arcadis, has developed a strategy to speed up the introduction of ERTMS by focussing on the rapid design of block layouts. The design starts by identifying the constraints on the open line, such as switches, level crossings and bridges, and then moves on to the stations. With this strategy, it is expected to be possible to design >80% faster and require <20% extra attention (Movares et al., 2024).

The design manual does not include all the design rules of ProRail. As a result, assumptions have been made about which rules are important at this design stage and which are not. In addition, generic maximum block lengths have been established based on the speed of the line section and the headway.

6.1.1.1. Marker board placement regulation

To design the block sections, regulations must be followed. In this study, some regulations from the design regulations of ERTMS/ETCS Level 2 in the Netherlands by ProRail (2021) were taken into account. While not all rules could be fully included due to complexity and scope, the key principles considered are summarised below:

- Minimum block length is 200 metres, which can be reduced to 100 metres in consultation with ProRail.

- Maximum block length is 5000 metres, which can be enlarged upon agreement with ProRail.
- SMBs at stations are placed as close as possible to the end of the platform, with the possibility to extend the location up to 50 metres if operational hindrance is expected.
- SMBs are positioned based on the type of switch movement (driving along/against the switch).
- SMBs are placed at a minimum distance beyond the level crossing/movable bridge, which is 425 metres for passenger lines, and 750 metres for freight. A minimum of 100 metres overshoot length between the SMB and the edge of the movable part of the bridge is applied. Figure 15 shows the minimum distance between the SMB and level crossing. The distances are the same for the moving bridges.

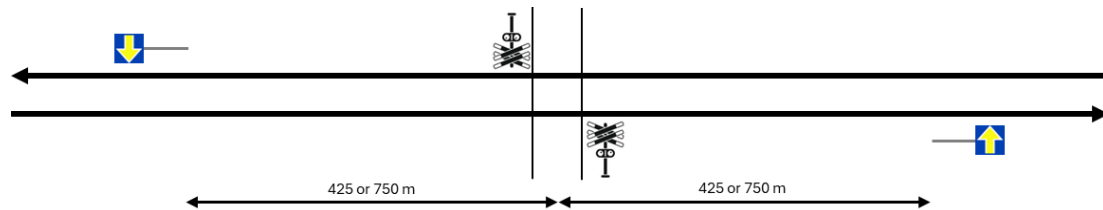


Figure 15: Minimum distance between SMB and level crossing

6.1.2. Disruptions

Besides identifying KPIs and verifying the block section designs, the interviews were also conducted in order to identify the most common disruptions under ERTMS/ETCS Level 2 and their (average) duration. Since no data became available based on the interviews, data of rijdendetreinen.nl was used.

6.1.2.1. Disruption data based on rijdendetreinen.nl

Rijden de Treinen (n.d.) gathers information regarding travel and background information of the Dutch railways. The website saves data regarding train operations and disruptions since 2011. Based on this data, the most frequent occurring disruptions in the Netherlands have been identified. However, the disruption statistics are mainly based on NS'54/ATB-EG. Using these statistics to model disruptions in OpenTrack could lead to unrealistic scenarios when assessing ERTMS/ETCS Level 2.

ERTMS/ETCS Level 2 is already implemented on a few routes in the Netherlands, such as the Betuweroute, and the high speed line (HSL) between Belgian border – Rotterdam and Rotterdam – Schiphol. In Table 3 the most frequent occurring disruptions for the Netherlands and for HSL can be found, based on Rijden de Treinen (n.d.).

Table 3: Most frequent occurring disruptions and their durations in the Netherlands and on the high speed rail based on Rijden de Treinen (n.d.)

Frequency	The Netherlands	High speed line (HSL)
1	Train failure – 42 min	Train failure – 47 min (Breda – Rotterdam) & 56 min (Rotterdam – Schiphol)
2	Collision – 2 hours, 1 min	Stranded train – 1 hour, 3 min (Breda – Rotterdam) & 50 min (Rotterdam – Schiphol)
3	Failure in signalling system – 2 hours, 47 min	Failure of switches – 2 hours, 15 min (Breda – Rotterdam) Disruption elsewhere – n/a (Rotterdam – Schiphol)

According to Rijden de Treinen (n.d.), the difference between a train failure and a stranded train is that a stranded train cannot continue its journey, while a failed train will eventually be able to get away on its own. An additional train may be needed to clear a stranded train that has broken down, however this depends on the cause and location of the train. The same applies to a collision, where an extra train is often needed to transfer passengers in order to continue the journey. The simulation of an additional train to remove the stranded train or an additional train for passengers is beyond the scope of this study and therefore these disruptions were not simulated.

From the disruption shown in Table 3, only the train failure is simulated. Other disruptions, such as collisions or stranded trains, were excluded because they depend on interventions by the dispatcher such as the need of additional trains.

To maintain consistency, the duration of the disruption was scaled to reflect the timetable intensity of each study area. For example, a 50-minute disruption has a much greater impact on a busy corridor such as Arnhem Centraal – Nijmegen than on a less congested line like Zwolle – Deventer. Rather than modelling different operational responses per study area (e.g. cancelling trains between Arnhem Centraal and Nijmegen), a fixed rule was applied: in each case, the disruption duration was set to approximately 1.5-2 times the train frequency of the direction that the disruption takes place. This ensures that the system is sufficiently stressed, but the system still recovers relatively quickly and, as a result, may not require disruption measures in reality.

A second type of disruption considered in this study is specific to ERTMS/ETCS Level 2: a communication failure caused by temporary loss of contact between the train and the Radio Block Centre (RBC). In such cases, the train does not receive any movement authorities anymore and has to stop at the next Stop Marker Board to receive an European Instruction from the dispatcher. It usually takes about 5 minutes to contact the dispatcher and confirm whether the train may pass the next marker board (van der Hoeven & de Jong, 2024). Once authorisation is granted, the train continues at a restricted speed of 40 km/h to the next SMB. This procedure is repeated for each subsequent SMB until the disruption is resolved.

In the simulations, the section affected by the communication failure is assumed be at least one kilometre long, ensuring that the trains encounter multiple SMBs in some strategies. If LMBs are present in the disruptive area, the train may pass them at 40 km/h, without requesting a European Instruction.

6.1.2.2. *Locations of disruptions*

Disturbances can occur at any point along the track. In this study, two types of disruptions were considered, each requiring a different simulation approach. To ensure consistency and allow a fair comparison between the different block section design strategies, fixed disruption locations were selected for each study area. These locations were determined by analysing corridor characteristics such as infrastructure layout, train frequency, and operational bottlenecks. Based on these factors, a range of locations were defined per corridor:

- **Zwolle – Deventer:** In this corridor, the disruption was placed on the single-track section between Olst and Deventer.
- **Amersfoort Centraal – Apeldoorn:** For this corridor, the disruption was placed closer to Amersfoort. This allows observation of a more extended propagation effect, since the reduced traffic load provides more space for delay buildup and potential recovery.
- **Arnhem Centraal – Nijmegen:** Given the intensity of train traffic on this corridor, the disruption was placed after the rail connection to Tiel, closer to Nijmegen. This setup was intended to avoid immediate interference with trains heading to and from Tiel. Otherwise,

the disruption would have caused widespread delays, extending beyond the simulation window and making meaningful recovery measurement impossible.

The locations for the failed train were determined using a random number generator, constrained by a predefined range specific to each corridor (as discussed above). Several factors influence the actual impact of a disruption, such as:

- The distance the train must travel under restricted speed (40 km/h ‘on sight’)
- The duration the train remains stopped
- The overall traffic density on the line

Since disruptions are inherently unpredictable, using randomisation allowed for unbiased and varied placement of the disturbance within logical bounds.

In the case of communication failures, all Stop Marker Boards within this range were identified, after which those with (approximately) the same location were selected across all strategies to ensure consistent comparison. Although each location was selected with contextual logic, it is important to note that the precise location and duration of a disruption are not essential to the study. The primary objective is to assess how different block section designs affect the recovery process, and not to simulate real-world disruptions in detail.

Additionally, it was assumed that no operational adjustments (e.g. rerouting or timetable changes) were made in response to disruptions. Therefore, simulating a very long disruption would be unrealistic with this assumption, as such cases would lead to these adjustments in real-life.

6.1.2.3. *Disruption modelling in OpenTrack*

In OpenTrack, disruptions can be modelled in various ways depending on the nature of the disruption. A train failure was modelled by programming a standstill at a pre-defined time and location. If the train stops in the middle of a block section and the train can continue its journey again, the train must continue with 40 km/h until it enters the next block section. This has to do with the fact that a train's MA is withdrawn after a certain time of inactivity.

Disruptions caused by train failures can vary in impact depending on the train's location. For example, a train failure on a shunting yard or on a side track usually does not cause major problems. However, a train failure on the open line or on a platform causes disruptions. This is because trains cannot pass the failed train or they may have to use the track of the opposite direction (Rijden de Treinen, 2024).

Furthermore, communication failures, such as no connection between RBC and train, are modelled by forcing the train to stop at the next Stop Marker Board (SMB). Upon stopping, the train driver must contact the train dispatcher, a process that is assumed to take five minutes (van der Hoeven & de Jong, 2024). After receiving an European Instruction, the train may proceed at 40 km/h until the next SMB, where the process may repeat if communication has not been restored.

6.1.3. *Assumptions*

When designing block layouts, the braking capabilities of trains are taken into account. However, there is often a difference between the theoretical braking curve and actual driver behaviour. It is expected in reality that drivers brake more conservatively than technically possible with ERTMS/ETCS Level 2. Although ERTMS/ETCS Level 2 allows for more efficient braking behaviour and potentially shorter travel times, this study assumes a conservative braking curve.

As discussed in Section 6.1.1.1, extensive design regulations exist for the implementation of ERTMS/ETCS Level 2. Due to the complexity and scope of these requirements, not all rules could be incorporated into this study. As a result, the proposed block section design strategies may not be fully compliant with real-world regulations and may therefore be not feasible in practice.

There are currently no formal Dutch regulations regarding the implementation of Location Marker Boards. Therefore, it is assumed that the same placement criteria apply to Location Marker Boards as to Stop Marker Boards (SMBs). The only difference lies in operational behaviour during disruptions: trains are allowed to pass LMBs at 40 km/h without needing a European Instruction, whereas SMBs do require this. This is based on the regulations of Switzerland regarding LMBs (Bundesamt für Verkehr BAV, 2024).

In the event of a disruption, it is assumed that trains resume operations according to the First In, First Out (FIFO) principle. This means that trains have to wait at a designated location until they can start travelling again. These designated locations can be at a station or somewhere between stations.

In cases where a disruption causes a 30-minute delay and the train frequency is also every 30 minutes, it may be more practical to cancel one train instead of running two trains close together. The decision to cancel a train depends on the train frequency in the study area, the duration of the disruption, and the dispatcher. However, during this study the focus lies on assessing how resilient each block section design is in handling disruption. This caused that during disruptions within this study, no trains were cancelled or other disruption measures were applied.

Lastly, freight paths represent allocated time slots for freight operations but are not always used in practice. In this study, it is assumed that all freight trains for which a path is reserved will operate as scheduled. This results in a higher operational density than may occur in reality but ensures that the infrastructure and timetable are stress-tested under full utilisation conditions.

6.2. Results

This section presents the results of the implementation of the different block section design strategies. The results are divided into two main parts: operations under non-disruptive conditions, and performance during disruptive conditions. Key Performance Indicators are evaluated across all strategies and study areas.

6.2.1. Non-disruptive conditions

Costs

Table 4 provides an overview of the number of Stop Marker Boards used in each strategy across the three study areas. As shown, NS'54/ATB-EG and the ETCS current block section design use the same number of infrastructure elements for every route. This is because both strategies are based on the same block layout.

The ETCS minimum distance strategy consistently shows the highest number of SMBs in all study areas. This strategy is based on short block sections to minimise train headways, resulting in a high density of infrastructure elements. The ETCS design manual also uses a large number of SMBs. This is partly due to the fact that the design manual leaves room for interpretation, which caused that the assumption was made that a SMB should be placed after every level crossing. Since the Zwolle – Deventer route includes a large number of level crossings, this assumption led to a large increase in SMBs. It is likely that in practice many of these SMBs could be removed.

Additionally, the design manual indicates that on routes where frequently freight trains run, block lengths should be reduced. This applies to both the Amersfoort Centraal – Apeldoorn and Arnhem Centraal – Nijmegen routes, which explains the higher number of SMBs for those areas.

Interestingly, the ETCS cost-efficient strategy uses the fewest elements in two out of three study areas, except Arnhem Centraal – Nijmegen. Since the route lacks capacity, many blocks remained necessary since otherwise the capacity decreases too much.

Finally, the ETCS harmonic strategy falls somewhere in the middle of all three routes. It typically uses slightly more elements than NS'54/ATB-EG or ETCS current block section design, but fewer than the ETCS minimum distance and design manual strategies. This is because the block layout of NS'54/ATB-EG was used as a basis and based on this, it was examined where extra blocks were needed in order to maintain the needed headway.

Table 4: Number of Stop Marker Boards used per strategy and study area

Strategy	Zwolle – Deventer	Amersfoort Centraal – Apeldoorn	Arnhem Centraal – Nijmegen
NS'54/ATB-EG	Signals: 46	Signals: 78	Signals: 61
ETCS current block section design	SMBs: 46	SMBs: 78	SMBs: 61
ETCS minimum distance	SMBs: 197	SMBs: 324	SMBs: 183
ETCS cost-efficient	SMBs: 31	SMBs: 58	SMBs: 162
ETCS harmonic	SMBs: 41	SMBs: 83	SMBs: 72
ETCS design manual	SMBs: 101	SMBs: 155	SMBs: 97

Capacity consumption

Table 5 shows the capacity consumption for each of the strategies across the three study areas. A lower percentage indicates that more capacity is available. In other words, lower values are preferred. It is important to note that these capacity values are based on the practical capacity, which includes buffer times and runtime supplements, as explained in Section 2.2.2.

For the Zwolle – Deventer section, the difference between the strategies are marginal. Only the ETCS harmonic strategy stands out with a slightly lower capacity consumption. This can be explained by the design choice near the transition from single to double track, where the trains meet each other, the block lengths were minimised. This makes it possible to clear the single section as soon as possible. Aside from that, the NS'54/ATB-EG strategy performs best, though only by a very small margin.

More variation is observed in the Amersfoort Centraal – Apeldoorn study area. The ETCS minimum distance strategy performs best, closely followed by the other ETCS strategies. The ETCS cost-efficient strategy, however, shows notably higher capacity consumption. This likely results from the removal of too many blocks, reducing the ability to operate trains closely together. Although the results between most strategies do not differ substantially, the result of the ETCS cost-efficient strategy does indicate that using fewer blocks can have a disadvantage on capacity.

Arnhem Centraal – Nijmegen shows the greatest variation between strategies. Several strategies even exceed 100% capacity consumption, meaning that during the compression method it could not be compressed, but additional time was added to the timetable in order to allow trains to operate without hindrance. Only the ETCS minimum distance and ETCS design manual strategies just fall below the 100%, making these strategies the only one with a bit of margin in the timetable.

Both strategies are based on shorter block lengths, which explains their improved performance. It is noticeable that the ETCS cost-effective strategy performs worse than the ETCS minimum distance, although it still contains relatively many short blocks.

Table 5: Capacity consumption per strategy and study area

Strategy	Zwolle – Deventer	Amersfoort Centraal – Apeldoorn	Arnhem Centraal – Nijmegen
NS'54/ATB-EG	79,49%	82,19%	107,39%
ETCS current block section design	79,56%	81,74%	102,72%
ETCS minimum distance	79,53%	81,39%	99,66%
ETCS cost-efficient	79,53%	86,08%	102,18%
ETCS harmonic	78,61%	82,22%	106,68%
ETCS design manual	79,76%	82,77%	99,12%

Travel time – total mean travel time per strategy

Figure 16 shows the average travel time of the different strategies, where A is from Zwolle to Deventer and B is from Deventer to Zwolle. In both directions it can be seen that the travel times under all ETCS strategies are slightly longer than under NS'54/ATB-EG.

This can be explained by the braking behaviour between the two directions. On the Zwolle – Deventer section, the train under NS'54/ATB-EG already follows the track's speed profile quite closely. Although ERTMS/ETCS Level 2 allows to brake independently of the location of the SMB (unlike with the NS'54/ATB-EG situation), the benefit is limited here because the NS'54/ATB-EG braking behaviour was already well aligned. Since in this study the ERTMS/ETCS Level 2 braking curves are slightly more conservative compared to the NS'54/ATB-EG braking curve, which results in a small increase in travel time.

In the opposite direction, the difference in travel time between NS'54/ATB-EG and the ETCS strategies is smaller. With NS'54/ATB-EG, the train starts braking earlier due to signal placement, which results in a less efficient use of the speed profile. Although ERTMS/ETCS Level 2 allows to brake later compared to the NS'54/ATB-EG situation, the resulting time gain is not sufficient to reduce the overall travel time and compensate for the braking curve.

Moreover, there is relatively little train traffic on this route. As a result, no problems occur regarding short headways that have to be met, nor do trains run with hinderance. This means there is little to improve when trains run according to schedule.

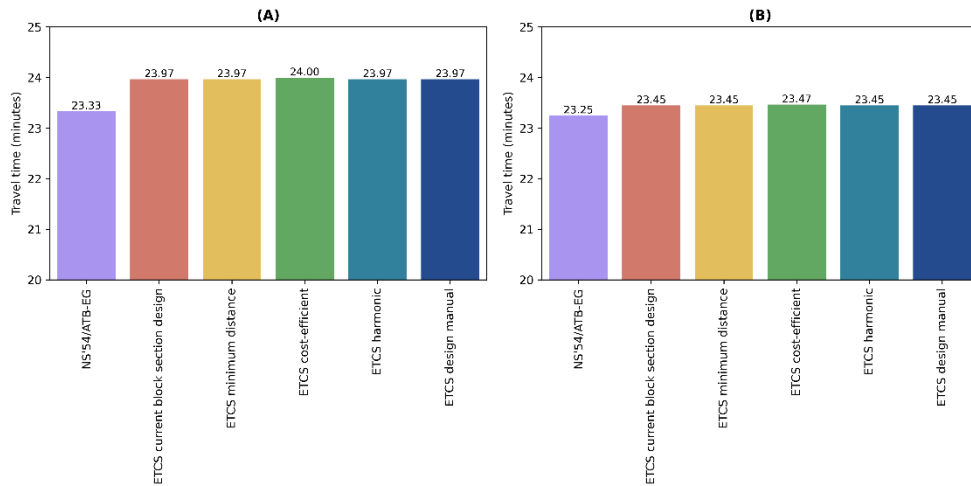


Figure 16: Mean travel time per strategy (8:00-9:00) (A) Zwolle - Deventer (B) Deventer - Zwolle

As shown in Figure 17, the ETCS strategies outperform NS'54/ATB-EG in terms of average travel time in this study area. This improvement can be attributed to the higher traffic intensity compared to the Zwolle – Deventer route. Due to this higher intensity, there is more interaction between the trains, resulting in (potentially) more hindrance. With ERTMS/ETCS Level 2, train can brake later and make more efficient use of the available track space. This leads to fewer hinderances, and combined with the more optimal braking moments results in shorter average travel times. The time-distance diagrams (see Appendix B.2. Amersfoort Centraal – Apeldoorn) illustrate this effect clearly.

On the Apeldoorn – Amersfoort Centraal route, the effect of the different ETCS strategies is more evident. Trains experience more hindrance, especially around Amersfoort Centraal. As a result, the benefits of using ERTMS/ETCS Level 2 are larger.

In addition to these operational factors, the difference in average travel time between directions can be explained by the presence of freight trains. On this route, freight trains travelling from Amersfoort Centraal to Apeldoorn have scheduled stops, which are taken into account when calculating the average travel time. In the opposite direction, freight trains do not have such scheduled stops, resulting in shorter average travel time in that direction.

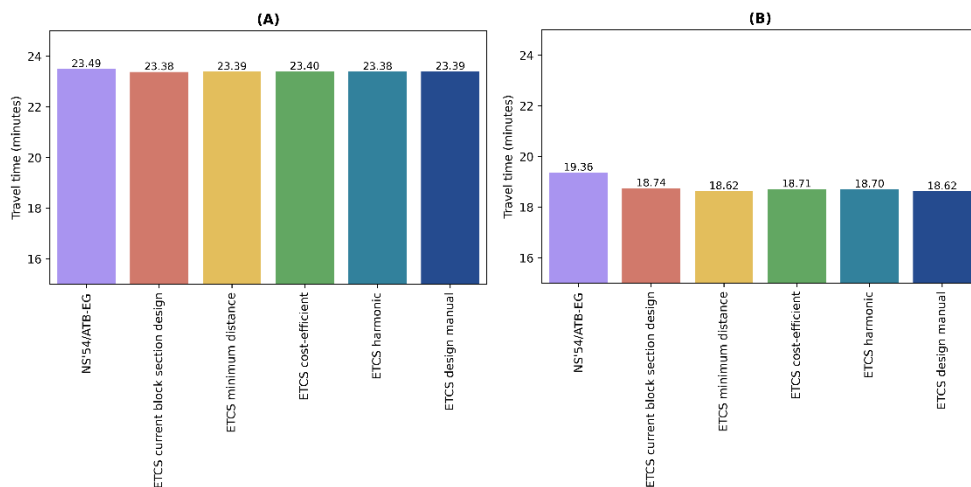


Figure 17: Mean travel time per strategy (8:00-9:00) (A) Amersfoort Centraal - Apeldoorn (B) Apeldoorn - Amersfoort Centraal

The results of the mean travel time of Arnhem Centraal – Nijmegen section are comparable to Figure 17B (see Appendix C.1. Travel time – total mean travel time per strategy). As the time-

distance diagrams show in Appendix B.3. Arnhem Centraal – Nijmegen, hindrances occur in both directions of travel in this study area. With any ETCS strategy, the travel time is reduced because train can run closer to each other.

Travel time – mean travel time per strategy and train type

Figure 18A shows the average travel time per strategy and train type between Arnhem Centraal and Nijmegen during undistruptive conditions. What is immediately noticeable is that for almost all train types the travel time decreases when implementing an ETCS strategy, with the exceptions of the freight train with the ETCS current block section design and harmonic strategy. The time-distance diagrams (see Appendix B.3. Arnhem Centraal – Nijmegen) show that, in these cases, the regional train departs slightly later from Nijmegen Lent due to the less favourable braking curve under ERTMS/ETCCS Level 2. As a result, the headway between the freight train and the regional train is reduced, requiring the freight train to apply stronger braking.

Figure 18B shows the mean travel time per train type between Nijmegen and Arnhem Centraal. In this figure, it can also be seen that the travel time decreases when implementing ERTMS/ETCS Level 2 compared to the NS'54/ATB-EG situation. However, this does not apply to the freight train with the ETCS current block section design, harmonic and design manual strategies. In these strategies, the regional train, which runs ahead of the freight train, travels slightly slower than in the NS'54/ATB-EG situation, forcing the freight train to apply stronger braking. The block section design is more favourable with the ETCS minimum distance and cost-efficient strategies, meaning that this problem does not occur.

The regional train shows a small decreases but remains relatively constant across the ETCS strategies. As for the intercity train, travel times decrease for all ETCS strategies. However, the ETCS harmonic strategy shows a smaller reduction compared to the other ETCS strategies. This can be explained by the longer block lengths used in this strategy, which forces trains to brake earlier when another train travels in front of it.

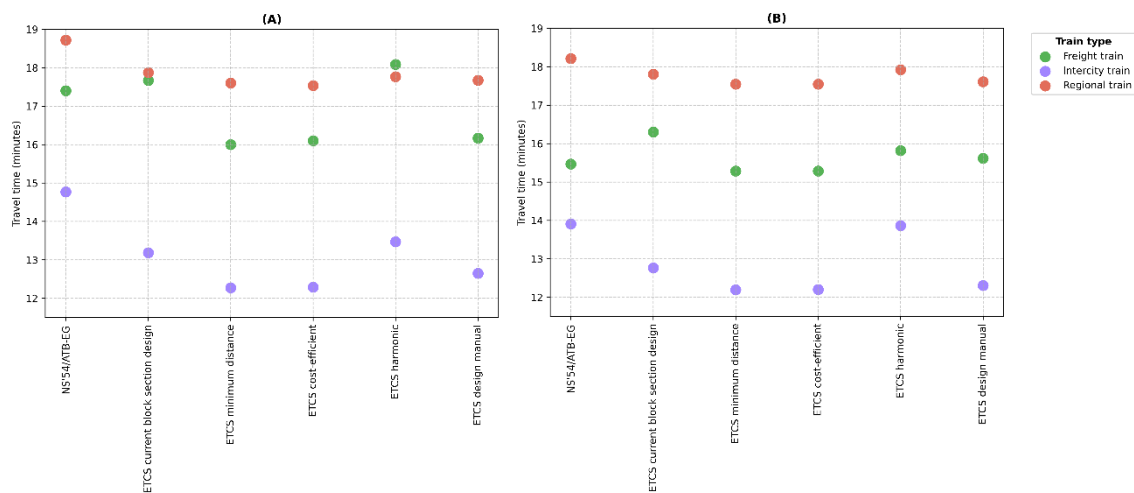


Figure 18: Mean travel time per strategy and train type (8:00-9:00) (A) Arnhem Centraal – Nijmegen (B) Nijmegen – Arnhem Centraal

As for the other study areas (see Appendix C.2. Travel time – mean travel time per strategy and train type), the results for Zwolle – Deventer and vice versa are the same as for Figure 16 as only one type of train operates here. For Amersfoort Centraal – Apeldoorn, only small differences can be seen between the NS'54/ATB-EG situation and ETCS strategies. There is no particular train type or strategy that has a large advantage of the implementation of ERTMS/ETCS Level 2 on this route. These findings are in line with the results for the overall average travel time in Figure 17A. Compared to the opposite direction, the figure reveals more variation between both strategies

and train series. The reason is that trains in this direction encounter more hindrance, creating opportunities for improvement relative to the current NS'54/ATB-EG situation. A similar conclusion was drawn for this situation as was from Figure 17B.

Travel time deviation compared to NS'54/ATB-EG

Figure 19 shows the travel time deviation compared to the NS'54/ATB-EG situation for the Amersfoort Centraal – Apeldoorn study area. As shown in Figure 19A, the ERTMS/ETCS Level 2 situation freight trains have a slight increase in travel time. This is caused by the fact that they run without any hindrance, which means that the train can break less strong with ERTMS/ETCS Level 2, resulting in an increase in travel time. Intercity trains also run unhindered, except for the one that follows a freight train. Just before arriving in Apeldoorn, this intercity train must brake because of the freight train. In the ETCS cost-efficient scenario, the braking point occurs earlier compared to the other strategies. This explains the difference in travel time deviation for the intercity trains. For regional trains, a travel time gain is found with the implementation of ERTMS/ETCS Level 2, regardless of the block section design strategy. These findings are supported by Figure 33 in Appendix C.2. Travel time – mean travel time per strategy and train type, which show that in general the travel times with the ETCS strategies do not have large differences compared to the NS'54/ATB-EG situation.

As for Figure 19B, the figure shows notable fluctuations in travel time deviation of freight trains. Based on these results and the time-distance diagrams in Appendix B.2. Amersfoort Centraal – Apeldoorn, it can be concluded that when freight trains experience hindrance, they brake more strongly when longer blocks are used, explaining the greater variation in travel times. Block section designs with longer blocks, such as ETCS current block section design, cost-efficient, and harmonic, show less travel time improvement compared to strategies with shorter blocks, such as ETCS minimum distance and ETCS design manual. For regional and intercity trains, the travel time deviation is quite consistent across all ETCS strategies. This indicates that the selected block section designs have little to no impact on the travel time under normal operating conditions.

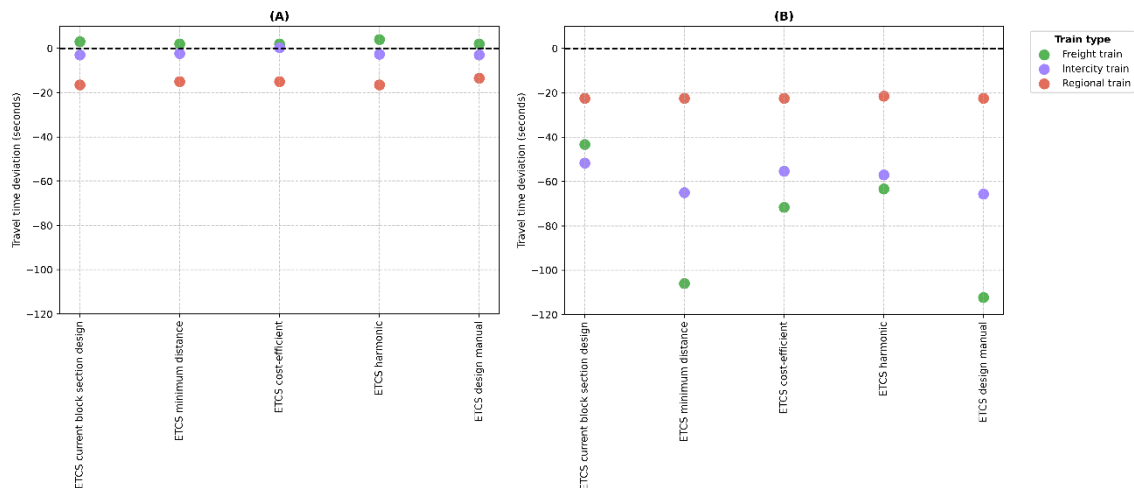


Figure 19: Travel time deviation (8:00-9:00) (A) Amersfoort Centraal – Apeldoorn (B) Apeldoorn – Amersfoort Centraal

The relatively lower performance of the ETCS harmonic strategy can be explained by its initial design approach. It was developed to optimise train movements based on paired operations of the same train types, such as two intercity trains. However, this strategy did not explicitly consider combinations of heterogeneous trains, such as freight trains followed by passenger trains. This design limitation may have led to suboptimal spacing of block sections which causes

more frequent hinderance between differing train types in practice. A similar trend is observed in the Arnhem Centraal – Nijmegen study area.

Appendix C.3. Travel time deviation compared to NS'54/ATB-EG provides the results of the other study areas. For the Zwolle – Deventer route, the same trend is observed as previously noted: the implementation of ERTMS/ETCS Level 2 leads to an increase in travel time in this study area. In the Arnhem Centraal – Nijmegen study area, the same fluctuations in travel time deviation for the freight trains can be seen, especially for the ETCS current block section design and harmonic strategies. These results are consistent with the conclusion drawn from the Amersfoort Centraal – Apeldoorn case, where freight trains were found to brake more strongly when operating with longer block sections.

6.2.2. Disruptive conditions – train failure

In this scenario, a train failure occurs. For each study area, this occurs at a different location, as mentioned in Section 6.1.2.2. For example, this occurs between Deventer and Zwolle on the single-track section. Due to the frequency of two trains per hour (every 30 minutes), this means that one train blocks the entire time of 1.5 times the interval: 45 minutes. As this is single track, this blockage affects train traffic in both directions. This causes not only delays towards Zwolle, but also towards Deventer.

On the Amersfoort Centraal – Apeldoorn section, the disruption duration is set at 15 minutes because six trains run from Apeldoorn to Amersfoort Centraal within an hour. Since the disruption occurs in that direction, the study area is referred to as Apeldoorn – Amersfoort Centraal throughout this section. No noticeable disruption occurs in the opposite direction.

The Arnhem Centraal – Nijmegen route has a high service frequency (13 trains within an hour seen from Arnhem Centraal). A multiplication factor of 2 is applied for this scenario, resulting in a total disruption time of 9 minutes. This is done since the disruption time would otherwise be similar to the communication disruption, which is explained in Section 6.2.3. The disruptive train is travelling from Arnhem Centraal to Nijmegen; no impact is observed in the opposite direction.

For the interpretation of the results of the recovery period – whenever the recovery periods have the same time for both thresholds, the same train is assigned as 'recovered'. Furthermore, if the last delayed train has a delay of 9 minutes and the next train is already back on schedule, the recovery period is based on the train with the 9-minute delay.

Resilience – recovery period

The recovery period is defined as the time from the start of the disruption until a train returns to operation within a predefined margin (3 or 5 minutes) of the timetable at the location of disruption. The train disruption in the Zwolle – Deventer study area, occurs with a train travelling from Deventer to Zwolle. This failure takes place on the single track section of the study area, which causes that also the traffic from Zwolle to Deventer experience hinderance.

As Table 6 shows, the recovery periods is the same for both thresholds. As seen form this table, the ETCS cost-efficient strategy has a slightly larger recovery period compared to the other strategies. This can be explained by the reduced number of blocks in this strategy. With fewer blocks, trains have to wait longer before receiving a movement authority, leading to a slower restart of operations.

Table 6: Recovery period for the train failure of Deventer – Zwolle

Strategy Recovery threshold	NS'54/ ATB-EG	ETCS – current block section design	ETCS – minimum distance	ETCS – cost- efficient	ETCS – harmonic	ETCS – design manual
3 & 5 min	01:11:39 (100%)	01:10:11 (-2.05%)	01:09:01 (-3.68%)	01:12:18 (+0.91%)	01:09:33 (-2.93%)	01:10:11 (-2.05%)

For trains travelling in the opposite direction, the recovery threshold does matter. It also shows that strategies such as ETCS minimum distance and design manual perform slightly better than others, although the differences remain relatively small. This difference can be explained by the fact that with the ETCS minimum distance, the train can slightly earlier continue its journey again compared to the ETCS design manual.

The ETCS cost-efficient strategy, on the other hand, shows the longest recovery times for both thresholds. This is in line with the results of the traffic of the other direction.

Table 7: Recovery period for the train failure of Zwolle – Deventer

Strategy Recovery threshold	NS'54/ ATB-EG	ETCS – current block section design	ETCS – minimum distance	ETCS – cost- efficient	ETCS – harmonic	ETCS – design manual
3 min	01:54:17 (100%)	01:53:27 (-0.73%)	01:52:17 (-1.75%)	01:55:37 (+1.17%)	01:53:13 (-0.93%)	01:53:27 (-0.73%)
5 min	01:05:04 (100%)	01:01:44 (-5.12%)	01:01:30 (-5.48%)	01:05:42 (+0.97%)	01:02:55 (-3.30%)	01:01:44 (-5.12%)

The recovery period results of the train failure between Arnhem Centraal and Nijmegen clearly highlight the performance gap between NS'54/ATB-EG and all ETCS strategies (Table 8). While NS'54/ATB-EG requires nearly an hour to return to operations that are within a 3-minute threshold of the timetable, all ETCS strategies achieve recovery in approximately 30-38 minutes. This illustrates an improved recovery capability of ERTMS/ETCS Level 2 in disruption events under high-frequency conditions.

The performance difference can be attributed to the fact that trains under ERTMS/ETCS Level 2 can operate much closer together than in the NS'54/ATB-EG situation. As a result, a train is more can meet the recovery threshold earlier.

Table 8: Recovery period for the train failure of Arnhem Centraal – Nijmegen

Strategy Recovery threshold	NS'54/ ATB-EG	ETCS – current block section design	ETCS – minimum distance	ETCS – cost- efficient	ETCS – harmonic	ETCS – design manual
3 min	00:59:40 (100%)	00:37:55 (-36.45%)	00:30:00 (-49.72%)	00:30:42 (-48.55%)	00:30:06 (-49.55%)	00:30:49 (-48.35%)
5 min	00:46:27 (100%)	00:32:59 (-28.99%)	00:30:00 (-35.41%)	00:30:42 (-33.91%)	00:30:06 (-33.20%)	00:30:49 (-33.66%)

The recovery periods of Amersfoort Centraal – Apeldoorn (see Appendix D.1. Resilience – recovery period) show that the greatest improvements can be made by using ETCS minimum distance, harmonic and design manual. This is consistent with the findings for the other two study areas.

Resilience – disruption period

The disruption period is defined as the time from the beginning of the disruption until the first train is able to pass the disruptive section completely on schedule (so recovery threshold = 0 minutes). It is not important to look at it from a particular direction, as it is important to know when a disruption starts and when it ends, so that all trains can run fully according to schedule.

Table 9 presents a summary of disruption periods per strategy and study area. What stands out is that for the Zwolle – Deventer route, the disruption periods for all ETCS strategies are approximately the same as for NS'54/ATB-EG, except for the ETCS minimum distance strategy. This route operates on a half-hourly timetable per direction. Consequently, when a train cannot yet be marked as 'on schedule', the train half-hour later is analysed, extending the disruption period by another half-hour. As the results show, when using short blocks, the disruption can be resolved roughly 30 minutes earlier than with the other strategies.

As the table shows, the ETCS minimum distance, harmonic and design manual strategies perform best in the event of a disruption between Apeldoorn and Amersfoort Centraal, NS'54/ATB-EG and ETCS current block section design fall in the middle range, while ETCS cost-efficient strategy performs the worst. The longer disruption period for the ETCS cost-efficient strategy is due to the fact that more trains experience delays when this strategy is applied, which is caused by the longer and less convenient placed blocks used with strategy.

At last, both ETCS harmonic and ETCS design manual show a small increase in disruption period compared to the NS'54/AT-EG situation with the disruption between Arnhem Centraal and Nijmegen. This is caused by the fact that in all three situations, the same train is marked as 'on schedule' but in the ERTMS/ETCS Level 2 situations the braking curve causes a small increase in travel time and thus disruption period. In contrast, the ETCS current block section design, ETCS minimum distance, and ETCS cost-efficient strategies show shorter disruption times (between 44 and 49 minutes).

Table 9: Disruption periods of the train failure per strategy and study area

Strategy	Zwolle – Deventer	Apeldoorn – Amersfoort Centraal	Arnhem Centraal – Nijmegen
NS'54/ATB-EG	02:21:16 (100%)	00:49:46 (100%)	00:59:40 (100%)
ETCS current block section design	02:21:28 (+0.14%)	00:48:52 (-1.81%)	00:49:06 (-17.71%)
ETCS minimum distance	01:59:12 (-15.62%)	00:43:07 (-13.36%)	00:44:33 (-25.34%)
ETCS cost-efficient	02:21:28 (+0.14%)	01:03:21 (+27.29%)	00:44:40 (-25.14%)
ETCS harmonic	02:21:51 (+0.41%)	00:43:07 (-13.36%)	01:00:00 (+0.56%)
ETCS design manual	02:21:28 (+0.14%)	00:43:07 (-13.36%)	01:00:00 (+0.56%)

Weighted Travel Time Extension (WTTE)

The WTTE results of the train failure between Apeldoorn and Amersfoort Centraal, shown in Figure 20, confirm the earlier findings from the recovery and disruption periods. The strategies with the lowest WTTE values are ETCS minimum distance and ETCS design manual.

The ETCS cost-efficient strategy shows the highest WTTE value. This corresponds with its longer recovery and disruption period. According to the time-distance diagrams (Appendix B.2. Amersfoort Centraal – Apeldoorn), two intercity trains experienced more hindrance in this scenario compared to the other strategies. This can be explained by the block layout: longer block sections lead to longer occupation times, forcing consecutive trains to brake earlier and therefore also become delayed.

NS'54/ATB-EG also scores relatively high in terms of WTTE, which is consistent with the middle position in terms of recovery time. The results show that NS'54/ATB-EG performs slightly worse than the ETCS current block section design, as trains experience more delay in the former scenario. At last, the ETCS harmonic strategy is between the two extremes, which is in line with the fairly average performance in the earlier resilience analysis.

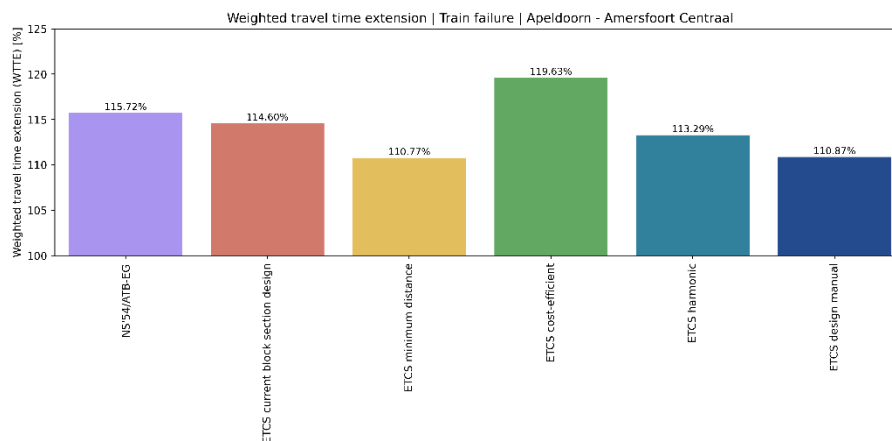


Figure 20: WTTE values of train failure | Apeldoorn – Amersfoort Centraal

In both the Zwolle – Deventer and Arnhem Centraal – Nijmegen study areas, strategies with smaller blocks result in lower WTTE scores. This is in line with the results of the Amersfoort Centraal – Apeldoorn section.

6.2.3. Disruptive conditions – communication failure

In the event of a communication failure, no connection is possible between the train and the Radio Block Centre (RBC) for at least one kilometre. Upon reaching the next marker board, the train driver must contact the dispatcher to request an European Instruction. Once permission is granted, the train may proceed at a speed of 40 km/h to the next SMB. If communication has not been restored by then, the procedure must be repeated.

The communication failure is initiated in the direction as the order in which the study area is presented. For example, the communication failure starts for a train travelling from Apeldoorn to Amersfoort Centraal. This is why the study area is referred to in this order for the communication failure.

Resilience – recovery period

Table 10 shows the recovery period of the communication failure with SMBs for the Arnhem Centraal – Nijmegen study area. As can be seen from this table, the recovery periods for NS'54/ATB-EG, ETCS current block section design, ETCS harmonic and ETCS design manual are approximately equal, each around 30 to 31 minutes. This indicates that these strategies are able to resume normal operations relatively quickly after this communication failure involving SMBs.

In contrast, the ETCS minimum distance and ETCS cost-efficient strategies show longer recovery periods, with ETCS minimum distance is by far the longest of all strategies. This is due to the use

of many short block sections, which require the train to stop before each SMB and request an European Instruction from the dispatcher to proceed. This time-consuming process slows the affected train and delays recovery across the entire system.

The ETCS cost-efficient strategy tries to reduce the number of SMBs compared to the ETCS minimum distance strategy. With this strategy, blocks are removed that are not needed in order to save costs and maintain a headway of four minutes. However, as Arnhem Centraal – Nijmegen is a busy route, a limited number of SMBs could be removed without increasing the headway. Consequently, this strategy retains a relatively high number of SMBs, meaning that trains must stop frequently, leading to longer recovery periods. However, these periods are still shorter than under the ETCS minimum distance strategy.

In the NS'54/ATB-EG situation, trains have to stop one time to contact the dispatcher, whereas in the ETCS design manual situation, this happens twice. Nevertheless, the ETCS design manual still outperforms NS'54/ATB-EG. This is explained by the shorter block lengths, allowing trains to run closer together once the disrupted train resumes its journey.

Table 10: Recovery period for the communication failure with SMBs of Arnhem Centraal – Nijmegen

Strategy Recovery threshold	NS'54/ ATB-EG	ETCS – current block section design	ETCS – minimum distance	ETCS – cost- efficient	ETCS – harmonic	ETCS – design manual
3 min	00:31:29 (100%)	00:30:06 (-4.39%)	01:18:53 (+150.56%)	00:44:22 (+40.92%)	00:30:37 (-2.75%)	00:30:13 (-4.02%)
5 min	00:31:29 (100%)	00:30:06 (-4.39%)	01:14:22 (+136.21%)	00:36:55 (+17.26%)	00:30:37 (-2.75%)	00:30:13 (-4.02%)

Additionally, Table 11 shows that the Nijmegen – Arnhem Centraal direction also experiences additional travel times from the communication failure on the opposite track. However, this only happens in the NS'54/ATB-EG situation. In this case, delays around Nijmegen cause to delay departures from Nijmegen and increasing overall travel time.

Table 11: Recovery period for the communication failure with SMBs of Nijmegen – Arnhem Centraal

Strategy Recovery threshold	NS'54/ ATB-EG	ETCS – current block section design	ETCS – minimum distance	ETCS – cost- efficient	ETCS – harmonic	ETCS – design manual
3 min	00:30:32	-	-	-	-	-
5 min	00:25:38	-	-	-	-	-

For the communication failure between Apeldoorn and Amersfoort Centraal, the ETCS minimum distance and cost-efficient strategies show a higher recovery period compared to the NS'54/ATB-EG situation (see Appendix E.1. Resilience – recovery period). In addition, the ETCS design manual strategy also shows an increase. For both the ETCS minimum distance and design manual strategies, this is due to the need for more frequent stops to request an European Instruction. In the ETCS cost-efficient strategy, longer blocks increase the headway between trains, providing less flexibility to resolve the disruption and thus an increase in recovery period.

Unlike in the Arnhem Centraal – Nijmegen study area, where ETCS design manual outperformed NS'54/ATB-EG, this is not the case on the Amersfoort Centraal – Apeldoorn study area. Here, the disrupted train must stop three times instead of two, due to the presence of a level crossing. This additional stop reduces the effectiveness of the strategy in this situation.

For the disruption between Deventer and Zwolle, ETCS cost-efficient and harmonic strategies result in a longer recovery period than the other strategies. This is caused by a bottleneck at Zwolle, where the disrupted train arrives just as another train is scheduled to depart for Deventer. The combination of a single-track section and shared platform use leads to delays in both directions, increasing the overall recovery time.

Resilience – disruption period

Table 12 provides an overview of the disruption periods of the communication failure for all three study areas. These periods largely confirm the findings from the recovery period analysis.

In the Zwolle – Deventer study area, most strategies (NS'54/ATB-EG, ETCS current block section design, minimum distance, and design manual) minimise the disruption to the affected train. However, a different pattern is observed with the ETCS cost-efficient and ETCS harmonic strategies. In these cases, the disruption extends beyond the initially affected train and impacts train running in the opposite direction as well. As explained in the recovery period, this is due to a bottleneck near Zwolle. When the delayed train arrives at Zwolle, it causes a domino delay for the next train departing towards Deventer. That in turn creates an additional delay because of limited margin in the timetable in Deventer, where the returning train is once again delayed as a result.

For the Amersfoort Centraal – Apeldoorn, NS'54/ATB-EG, ETCS current block section design, and harmonic again perform best, with disruption periods lasting under 20 minutes. ETCS cost-efficient and design manual show moderate increases of about 43 minutes. ETCS cost-efficient and ETCS design manual show a moderately longer disruption period of about 43 minutes. With the ETCS cost-efficient strategy, the train must travel for a longer distance at 40 km/h after receiving a new movement authority due to the use of longer blocks. The ETCS minimum distance again show the longest disruption period, lasting more than an hour. As in the recovery period, this is due to the high number of required stops to contact the dispatcher at each SMB.

On the Arnhem Centraal – Nijmegen route, the ETCS current block section design performs best, with the shortest disruption period of about 44 minutes. ETCS cost-efficient and ETCS design manual also perform well, each with disruption times of just under 49 minutes. On the other hand, ETCS minimum distance show the longest disruption durations, reaching up to 89 minutes. This again highlights the inefficiency caused by frequent stops to request European Instructions from the dispatcher. ETCS harmonic also performs relatively poorly compared to the better performing ETCS strategies, with a disruption period similar to that of NS'54/ATB-EG. This suggests that its block section design may not be optimal under disruptive conditions.

Table 12: Disruption periods of the communication failure with SMBs per strategy and study area

Strategy	Zwolle – Deventer	Apeldoorn – Amersfoort Centraal	Arnhem Centraal – Nijmegen
NS'54/ATB-EG	00:29:24 (100%)	00:19:47 (100%)	00:59:21 (100%)
ETCS current block section design	00:29:09 (-0.85%)	00:18:53 (-4.55%)	00:44:22 (-25.25%)
ETCS minimum distance	00:29:09 (-0.85%)	01:03:22 (+220.30%)	01:29:06 (+50.13%)
ETCS cost-efficient	01:19:38 (+170.86%)	00:43:07 (+117.94%)	00:59:06 (-0.42%)
ETCS harmonic	01:21:00 (+175.51%)	00:19:31 (-1.35%)	00:48:53 (-17.64%)
ETCS design manual	00:29:09 (-0.85%)	00:43:07 (+117.94%)	00:48:53 (-17.64%)

Weighted Travel Time Extension (WTTE)

The WTTE results for the communication failure on the Arnhem Centraal – Nijmegen section are presented in Figure 21. These results are largely in line with the findings from the resilience analysis. With the WTTE results, the extent of the delay and the seating capacity of each affected train is taken into account.

The ETCS minimum distance strategy stands out with the highest WTTE score (158.89%), followed by the ETCS cost-efficient strategy (119.96%). In these strategies, the affected train must stop at multiple SMBs to receive an European Instruction, causing delays. This not only results in delays for the disruptive train itself, but also causes knock-on effects for following trains.

In contrast, the design strategies NS'54/ATB-EG, ETCS harmonic and ETCS current block section all show lower WTTE values. These strategies recover relatively quickly and cause less severe delays to fewer following trains, resulting in lower WTTE.

The ETCS design manual strategy scores slightly higher than these three (109.18%), matching the average performance in terms of disruption and recovery. Although this strategy does not require as many stops as ETCS minimum distance, it still causes more delays compared to NS'54/ATB-EG or ETCS harmonic strategies, leading to a higher WTTE.

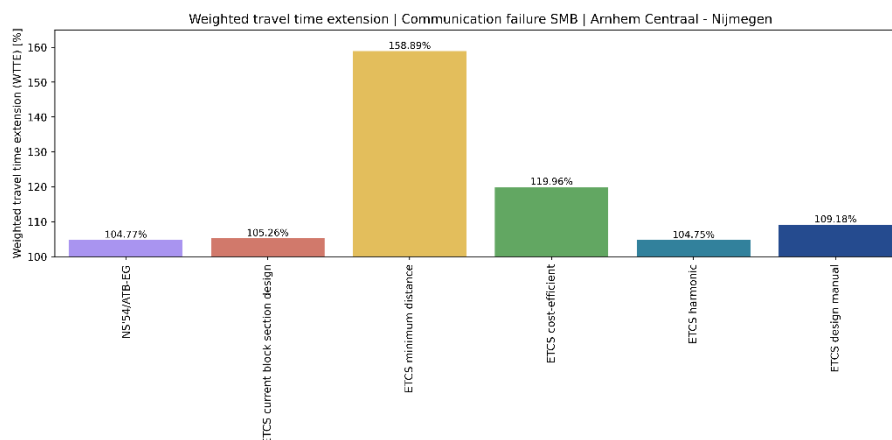


Figure 21: WTTE values of communication failure with SMBs | Arnhem Centraal – Nijmegen

The results of the other study areas show that ETCS minimum distance and design manual have the highest WTTE values, as seen in Appendix E.2. Weighted Travel Time Extension (WTTE). This is in line with the results of Arnhem Centraal – Nijmegen, where strategies containing a higher number of SMBs also resulted in higher WTTE values.

6.3. Conclusion

The chapter ends with the conclusion of the presented results. The findings are grouped into three categories: non-disruptive conditions, disruptions due to train failure, and disruptions caused by communication failure.

6.3.1. Non-disruptive conditions

During undisturbed conditions, four KPIs were analysed: costs, capacity consumption, average travel time, and travel time deviation compared to NS'54/ATB-EG. Although, these indicators show consistent trends across all three study areas, their impact varied per corridor.

Costs

Overall, similar trends could be observed across the three study areas. The trend suggests that the impact of each strategy on infrastructure elements is consistent regardless of route characteristics. ETCS minimum distance and design manual required the most infrastructural elements, indicating higher implementation costs. Conversely, ETCS cost-efficient uses the least, but this trade-off comes with performance consequences, especially under disruption.

Capacity consumption

Regarding capacity consumption, it can be seen that the effectiveness of ERTMS/ETCS Level 2 block section design strategies depends on the characteristics of the route. This includes traffic density, timetable, and possible infrastructure constraints. The strategy should therefore be adapted to these characteristics.

In general, on routes where the train volume is low, the added value of implementing ERTMS/ETCS Level 2 is limited, since the capacity consumption does not improve (a lot). In contrast, on high-frequency routes such as Arnhem Centraal – Nijmegen, ERTMS/ETCS Level 2 clearly increases capacity. The extent of this improvement also depends on the chosen strategy. The ETCS minimum distance tends to perform best, especially on corridors where the train volume is high.

Travel time (deviation)

The impact of ERTMS/ETCS Level 2 block section design strategies on travel time is strongly dependent on corridor characteristics such as traffic density. On low-frequency routes like Zwolle – Deventer, improvements are minimal or even negative due to already efficient operations under NS'54/ATB-EG. In contrast, busier corridors such as Arnhem Centraal – Nijmegen, benefit from shorter block sections, which enable shorter headways and reduced delays because of more efficient braking. This results in fewer delays and travel time reductions.

These effects also vary by train type. Passenger trains generally profit from the implementation of ERTMS/ETCS Level 2, while freight trains are more sensitive to block section lengths. Designs with shorter blocks, such as the ETCS minimum distance and design manual strategies, show the most improvements in travel time deviations and therefore travel time.

6.3.2. Disruptive conditions – train failure

During the disruptive conditions, three KPIs were analysed: recovery period, disruption period and the Weighted Travel Time Extension. The recovery period and disruption period are part of the resilience.

Recovery period

The results shows that recovery performance varies per strategy and study area, due to corridor characteristics such as traffic intensity. In general, strategies with shorter block sections, particularly ETCS minimum distance and design manual, enable faster recovery after disruptions. In contrast, strategies with longer blocks, such as ETCS cost-efficient, recover more slowly and are more sensitive to delays.

Disruption period

The results show that the choice of block section design strategy has an impact on the disruption period. The ETCS minimum distance strategy consistently performs best across all study areas, highlighting the advantage of short block lengths in enabling earlier recovery. Strategies with longer block sections, such as ETCS cost-efficient, consistently show longer disruption periods, suggesting that reduced infrastructure may limit the flexibility that is wanted and needed during disruptions. Interestingly, some strategies like ETCS harmonic and design manual recover the overall flow quickly but still record longer disruption periods. This underlines the difference between general system recovery and the precise moment the first train runs fully on schedule again.

WTTE

The WTTE results closely mirror the patterns observed in the recovery and disruption period analyses. In all three study areas, the minimum distance ETCS strategy consistently provides the lowest WTTE values, confirming its strong overall resilience performance. In contrast, the cost-efficient ETCS strategy generally performs worst, especially on the Zwolle – Deventer, and Amersfoort Centraal – Apeldoorn corridors.

In all cases, NS'54/ATB-EG tends to have a higher WTTE value than the better-performing ETCS strategies, while the ETCS harmonic and design manual strategies have a consistent middle position. Overall, the WTTE results confirms that shorter and more optimally placed blocks help to minimise the impact of passenger delays during disruptions.

6.3.3. Disruptive conditions – communication failure

Just as for the train failure, the same three KPIs were analysed.

Recovery period

The recovery results for the communication failure scenario with SMBs show clear differences between the strategies, strongly influenced by the block layout and operational regulations due to SMBs. On the corridors with a higher volume, the ETCS strategies with more SMBs placed, show a longer recovery period. This is caused by the need to stop frequently and receive an European Instruction by the dispatcher at each SMB. On the corridor with low train volume, most strategies recover at roughly the same time, except for ETCS cost-efficient and harmonic, which experiences hindrance near Zwolle due to unfortunate timing of train movements.

Disruption period

The disruption period results for the communication failure with SMBs further reinforce the patterns observed in the recovery analysis. On all three routes, strategies with fewer SMBs, such as ETCS current block section design and ETCS harmonic, consistently show shorter disruption durations. This suggests that limiting the number of times a train must stop and request a new European Instruction contributes to faster restoration of regular operations.

In contrast, the ETCS minimum distance strategy consistently performs the worst across all study areas. Despite its advantages in other contexts, the large number of SMBs leads to frequent stops to contact the dispatcher, resulting in extended disruption periods.

WTTE

The WTTE results for communication failures with SMBs confirm that a short recovery or disruption period does not always result in minimal passenger impact. While strategies like NS'54/ATB-EG, ETCS current block section design, and ETCS harmonic consistently show low WTTE values, others show higher scores, despite rather quick recovery and disruption periods.

This difference lies in the pattern and severity of delays. While strategies like ETCS minimum distance and design manual recover quickly and show short disruption periods (as what was shown between Zwolle and Deventer), the affected trains experience greater delays individually, leading to higher delay factors. In the other study areas, it could be seen that when multiple trains experience moderate delays, the WTTE value increases more than when one train gets heavily affected.

Across all study areas, the ETCS minimum distance strategy consistently scores the highest WTTE values, highlighting its vulnerability to communication disruptions when using SMBs.

7. Implementation of Location Marker Boards

This chapter provides an answer to the third research question, which relates to the performances of Location Marker Boards during disruptive conditions. In the first part of the chapter, the methodology is explained. After this, the results are presented which compare the performance of Location Marker Boards to Stop Marker Boards. The chapter ends with a conclusion.

7.1. Methodology

This aspect of Location Marker Boards (LMBs) is crucial as there is currently no regulation for this in the Netherlands. Therefore, their impact, especially during disturbances, is largely unknown. In Switzerland, however, LMBs are implemented and regulated. For the purpose of this study, Swiss regulations are assumed. According to these regulations, the train must stop at the next marker board when a disruption occurs, regardless of whether it is an SMB or an LMB. After receiving permission to proceed by requesting a European Instruction, the train may pass LMBs at a speed of 40 km/h until it reaches the next SMB (Bundesamt für Verkehr BAV, 2024).

7.1.1. Strategy implementation into model

As previously discussed in Section 1.2.2.2, the operational behaviour of LMBs under non-disruptive conditions is identical to that of the SMBs. However, when disruptive conditions occur, different rules apply. In the case of a failure, the driver must call the dispatcher at every SMB to receive a new movement authority. In contrast, when LMBs are used, the train may continue its journey at 40 km/h and does not have to stop until the next SMB to request a new European Instruction from the dispatcher (if the disruption is still ongoing).

7.2. Results

The implementation of LMBs is only relevant for the communication failure scenario, as this is a scenario where the disruption takes place over a certain stretch of the track, instead of one specific location (as happened with the train failure).

Whether LMBs could be used within the disrupted area depended on the block section layout of each ETCS strategy. As described earlier, the communication failure affects at least one kilometre of track. For LMBs to be implemented in such a case, these must be one or more SMBs located within that one-kilometre stretch following the initial stop. Only those SMBs can be replaced by LMBs. However, in some ETCS strategies, the block section in which the failure occurs is already longer than one kilometre. In these cases, there are no intermediate SMBs present within the disruption zone that could be replaced with LMBs, making LMB implementation inapplicable for those strategies.

As a result, LMBs could not be implemented for every strategy and study area. For the ETCS minimum distance and ETCS design manual strategies, LMBs could be applied in all three study areas. For the ETCS cost-efficient strategy, this was only possible on the Arnhem Centraal – Nijmegen route. Since the rest of the results of these simulations are identical to those from the communication failure scenario using only SMBs, they will not be repeated in this chapter. However, the comparison between the effects of SMB versus LMB is made for the strategies and study areas where it was possible to implement them.

Resilience – recovery period

Table 13 presents the recovery periods for the communication failure between Arnhem Centraal and Nijmegen, comparing the use of SMBs and LMBs. As shown, the implementation of LMBs results in a reduction in recovery periods across all three strategies. This pattern is consistent

with the findings for the Apeldoorn – Amersfoort Centraal section and can be attributed to the fact that train no longer need to stop and wait for a European Instruction at every SMB. Instead they can continue travelling at a reduced speed of 40 km/h, which improves the recovery performance.

The strategies using LMBs outperform the other strategies where no LMBs could be implemented (see Section 6.2.3), regardless of whether the 3-minute or 5-minute recovery threshold is applied.

Table 13: Comparison between recovery periods for the communication failure with SMBs and LMBs of Arnhem Centraal – Nijmegen

Strategy Recovery threshold	Use of SMBs			Use of LMBs		
	ETCS – minimum distance	ETCS – cost- efficient	ETCS – design manual	ETCS – minimum distance	ETCS – cost- efficient	ETCS – design manual
3 min	01:18:53 (+150.56%)	00:44:22 (+40.92%)	00:30:13 (-4.02%)	00:18:53 (-40.02%)	00:29:11 (-7.31%)	00:19:00 (-39.65%)
5 min	01:14:22 (+136.21%)	00:36:55 (+17.26%)	00:30:13 (-4.02%)	00:18:53 (-40.02%)	00:18:53 (-40.02%)	00:19:00 (-39.65%)

As for the other study areas, the comparison of the recovery period reveal that the recovery period does not change for the Zwolle – Deventer study area. These results suggest that the recovery period cannot improve more for this disruption scenario. Furthermore, the results of Apeldoorn – Amersfoort Centraal show that the usage of LMBs improve the recovery period, just as the results of Arnhem Centraal – Nijmegen show.

Resilience – disruption period

Table 14 compares the disruption periods when using either SMBs or LMBs during a communication failure. As explained above, the results for the Deventer – Zwolle corridor show that the use of LMBs has no impact on the disruption period. However, for the Apeldoorn – Amersfoort Centraal and Arnhem Centraal – Nijmegen corridors, the results do indicate a reduction in disruption period when LMBs are implemented. This suggests that affected trains are able to return to the timetable much earlier than in the SMB scenarios.

Table 14: Comparison between disruption periods for the communication failure with SMBs and LMBs per strategy and study area

Strategy	Deventer – Zwolle		Apeldoorn – Amersfoort Centraal		Arnhem Centraal – Nijmegen	
	Use of SMBs	Use of LMBs	Use of SMBs	Use of LMBs	Use of SMBs	Use of LMBs
ETCS – minimum distance	00:29:09 (-0.85%)	00:29:09 (-0.85%)	01:03:22 (+220.30%)	00:18:53 (-4.55%)	01:29:06 (+50.13%)	00:29:11 (-50.83%)
ETCS – cost-efficient	00:29:09 (-0.85%)	00:29:09 (-0.85%)	00:43:07 (+117.94%)	00:18:53 (-4.55%)	00:48:53 (-17.64%)	00:29:11 (-50.83%)
ETCS – design manual	-	-	-	-	00:48:53 (-17.64%)	00:29:11 (-50.83%)

Weighted travel time extension (WTTE)

Figure 22 shows the WTTE values for the Arnhem Centraal – Nijmegen route with the implementation of LMBs. As expected, ETCS minimum distance, cost-efficient, and design manual demonstrate a notable reduction in WTTE values compared to the results with SMBs.

- The WTTE for ETCS minimum distance drops from 158.89% to 103.40%

- ETCS cost-efficient decreases from 119.96% to 102.81%
- ETCS design manual drops from 109.18% to 103.53%

These results confirm the benefits of using LMBs during communication failures: fewer trains are delayed, and those that are experience shorter delays. Notably, all three strategies now outperform those still using SMBs in terms of WTTE, highlighting the operational advantage of this implementation.

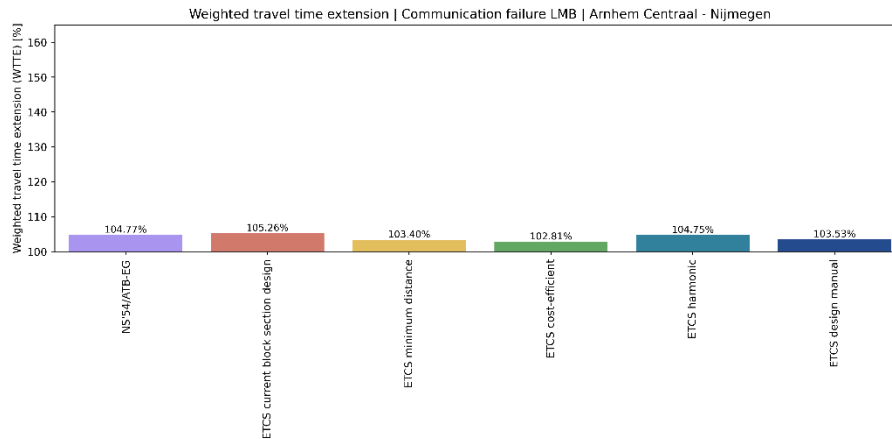


Figure 22: WTTE values of communication failure with LMBs | Arnhem Centraal – Nijmegen

The WTTE results for the other study areas also show a clear reduction in the ETCS minimum distance and design manual strategies. These results are consistent with those explained for the Arnhem Centraal – Nijmegen study area.

7.3. Conclusion

The results clearly show that replacing Stop Marker Boards with Location Marker Boards during communication failures improves the performance of block section design strategies. Using LMBs leads to faster recovery and shorter disruptions, especially on corridors with higher train densities. This is because train can pass LMBs as reduced speed without contacting the dispatcher.

The results of the Weighted Travel Time Extension show the a great improvement for strategies with high SMB densities, such as ETCS minimum distance and design manual. These results confirm that LMBs reduce the severity of delays.

Overall, the findings confirm that LMBs contribute to better resilience during disruptions. They minimise delay propagation by allowing trains to continue at reduced speed without requesting an European Instruction. This makes LMBs a valuable addition, especially for densely operated routes and/or strategies with closely spaced maker boards.

8. Trade-off analysis

This chapter provides the answer of the fourth and final research question regarding the trade-off that must be considered when selecting a block section design strategy. Just as the other chapter, first the methodology is discussed, then the results are presented, and it ends with a conclusion.

8.1. Methodology

The final step in the method was to conduct a trade-off analysis, which aimed to give insight into which trade-offs were needed to be made between the different Key Performance Indicators. The analysis was done based on Pareto fronts, which provide a quick overview which choices can be made and what effects this would give. The analysis integrates the results of simulations under both normal and disturbed conditions to provide a complete picture of system performance.

The KPIs that are discussed are the ones that have been determined based on the literature review and interviews, as described in Section 5.3.

8.2. Results

The results do not include a comparison with WTTE, as these results are very similar in behaviour to those of recovery time.

Costs versus capacity consumption

The results of the Pareto front analyses show that, across all study areas, increasing the number of blocks does not automatically lead to lower capacity consumption. In other words, adding more blocks does not always translate into increased capacity. However, the opposite effect is more evident: removing too many blocks can result in higher capacity consumption compared to the current situation, as illustrated in Figure 23.

Additionally, it can be observed that the implementation of ERTMS/ETCS Level 2 generally leads to lower capacity consumption. This is due to the improved braking location and flexibility of the system, which allows the decrease the headway. This trend is visible across the different strategies, as shown in Figure 24.

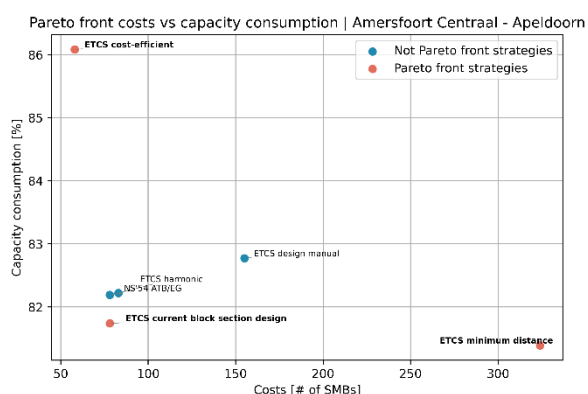


Figure 23: Pareto front of the costs versus capacity consumption during non-disruptive conditions | Amersfoort Centraal – Apeldoorn

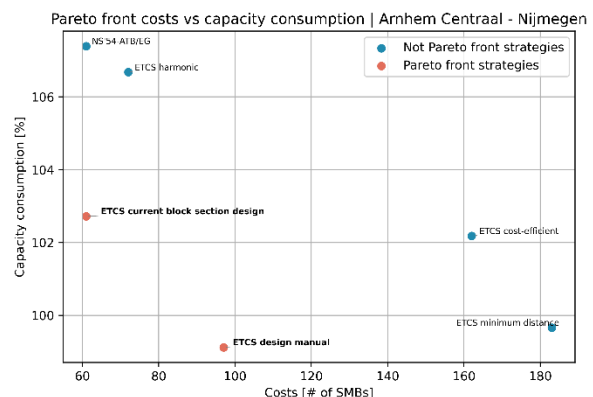


Figure 24: Pareto front of the costs versus capacity consumption during non-disruptive conditions | Arnhem Centraal – Nijmegen

Recovery period versus costs

Figure 25 presents the Pareto front for resilience versus costs on the Zwolle – Deventer route under a train failure scenario. Most ETCS strategies (except for ETCS cost-efficient) outperform the NS'54/ATB-EG baseline in terms of recovery period. The figure illustrates the trade-off

between investment and operational performance. For instance, the ETCS minimum distance strategy shows the shortest recovery period, but this comes with a higher costs due to the large number of SMBs required. On the other end, the ETCS harmonic recovers just over 30 seconds slower, but does this less SMBs and thus lower costs.

A similar pattern is observed across the other study areas and disruption types: strategies with denser block sections (such as ETCS minimum distance or design manual) tend to achieve the fastest recovery, while the more cost-efficient designs slightly increase recovery times but provide cost savings.

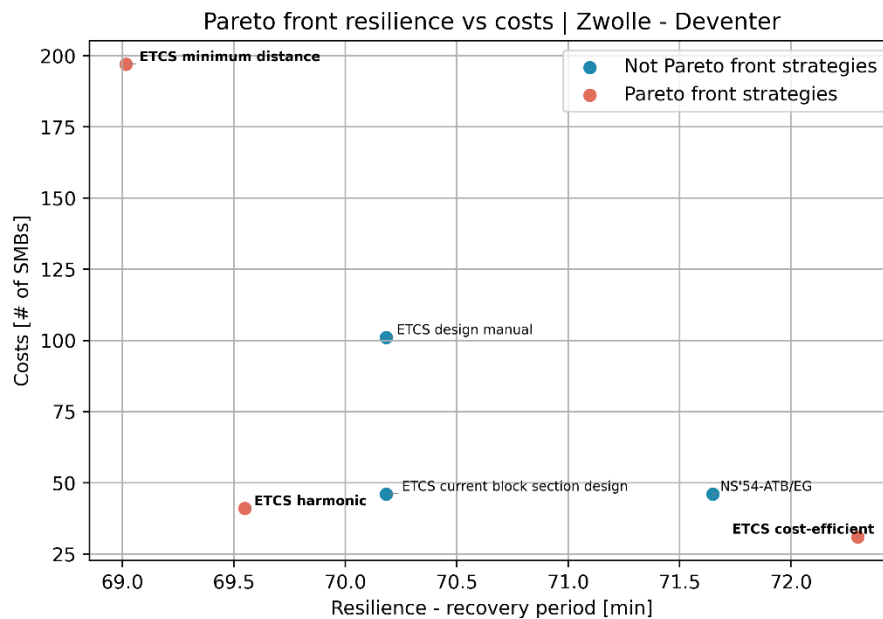


Figure 25: Pareto front of resilience versus costs during a train failure | Zwolle – Deventer

Recovery period versus capacity consumption

Figure 26 shows the Pareto front for the recovery period versus capacity consumption on the Amersfoort Centraal – Apeldoorn route during a train failure. This figure illustrates a clear trade-off between a short recovery period and higher available capacity (thus lower capacity consumption). For example, the ETCS minimum distance strategy achieves the highest capacity but at the costs of a slightly longer recovery period compared to ETCS current block section design. In contrast, the ETCS design manual strategy provides the shortest recovery period, but sacrifices (slightly) in terms of capacity.

Different patterns emerge when examining the other two corridors. Arnhem Centraal – Nijmegen route, most ETCS strategies achieve similar recovery periods (excluding NS'54/ATB-EG), yet display variation in capacity consumption. This indicates that even if strategies perform equally well in terms of recovery, they may do so at different levels of infrastructure efficiency. In contrast, for the Zwolle – Deventer corridor, capacity consumption is very similar across all strategies. This makes it more difficult to identify meaningful trade-offs in this case, since the differences are too small to strongly favour one strategy over another based on this comparison alone.

Pareto front resilience vs capacity consumption | Amersfoort Centraal - Apeldoorn

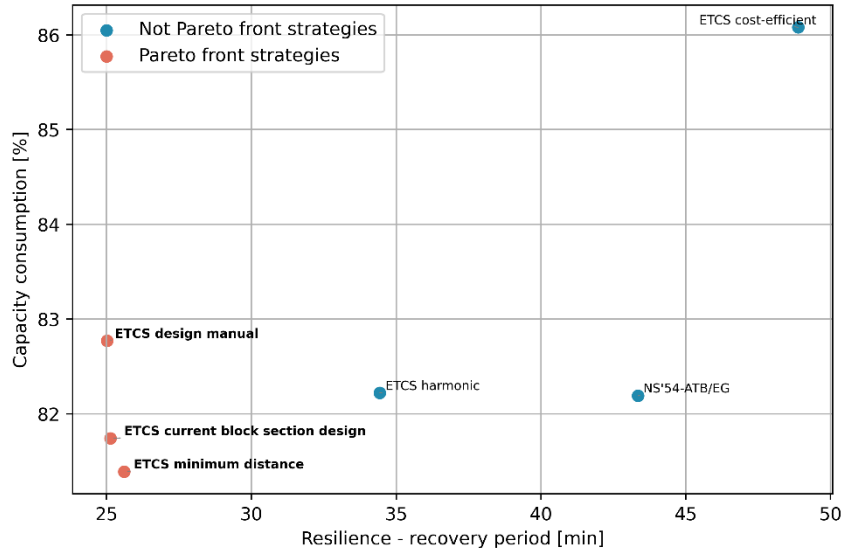


Figure 26: Pareto front of resilience versus capacity consumption during a train failure | Amersfoort Centraal – Apeldoorn

Figure 27 shows the Pareto front for recovery period versus capacity consumption for the communication failure with LMBs on the Arnhem Centraal – Nijmegen corridor. The results reveal the same as explained above with the train failure: strategies with lower capacity consumption also achieve a shorter recovery period. However, this is in contrast with the communication failure scenario with SMBs, where the same strategies showed much longer recovery periods due to the need for dispatcher involvement at every SMB, as illustrated in Figure 28.

The implementation of LMBs not only reduces capacity consumption but also improves resilience, especially for strategies like ETCS minimum distance and ETCS design manual.

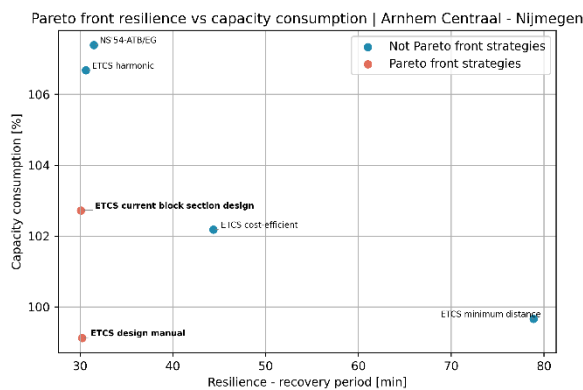


Figure 27: Pareto front of resilience versus capacity consumption during a communication failure with SMBs | Arnhem Centraal – Nijmegen

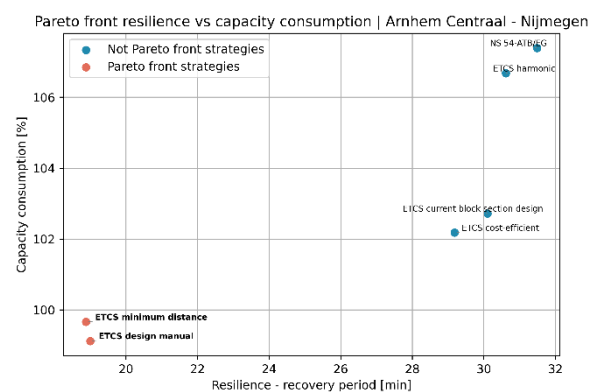


Figure 28: Pareto front of resilience versus capacity consumption during a communication failure with LMBs | Arnhem Centraal – Nijmegen

Costs versus travel time

Figure 29 shows the cost versus travel time for the Arnhem Centraal – Nijmegen corridor. It clearly shows that placing more SMBs leads to a reduction in travel time. This highlights an important trade-off: parties must determine whether lower travel times or lower infrastructure costs are more important for their objectives.

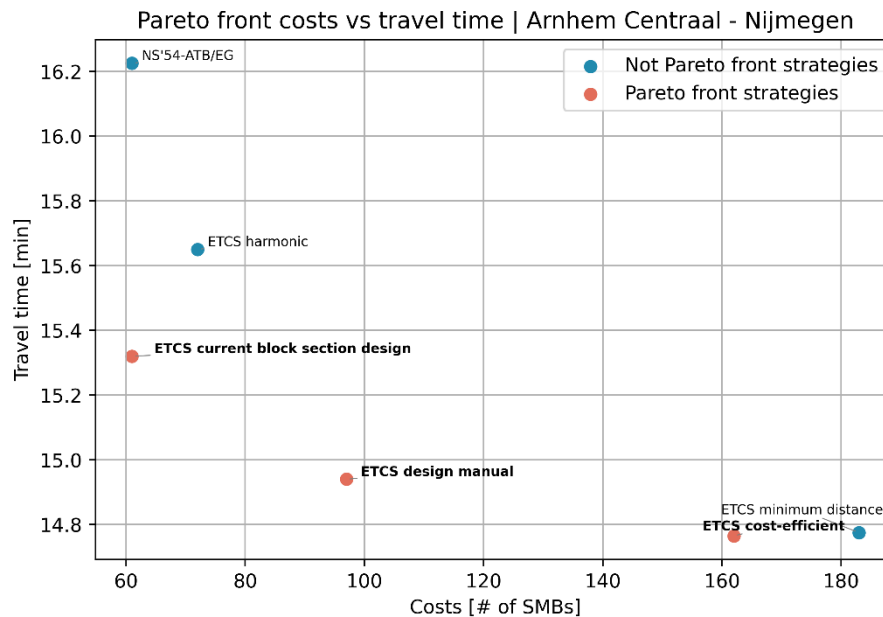


Figure 29: Pareto front of the costs versus travel time during non-disruptive conditions | Arnhem Centraal – Nijmegen

8.3. Conclusion

The trade-off analysis based on the KPIs and simulation results shows that there is no single railway block section design strategy that can be universally identified as the best. Each strategy has its own strengths and weaknesses, which is clearly reflected in the Pareto fronts. Overall, the transition from NS'54/ATB-EG to ERTMS/ETCS Level 2 leads in general to improvements in terms of capacity consumption, travel time, and recovery periods after disruptions. However, the degree of improvement and the associated costs depend strongly on the specific block section design chosen.

In terms of capacity consumption, the results show that simply placing more block sections does not automatically lead to a capacity improvement. Nonetheless, removing too many blocks clearly increases capacity consumption. The introduction of ERTMS/ETCS Level 2 generally reduces capacity consumption thanks to improved braking precision and flexibility.

Regarding resilience, strategies such as ETCS minimum distance and ETCS design manual achieve the shortest recovery periods after disruptions, but at the cost of higher infrastructure investments. In contrast, cost-efficient designs achieve modest cost savings but at the expense of slightly longer recovery periods. The choice thus strongly depends on whether resilience or cost minimisation is prioritised.

For capacity versus recovery period, results show that even if multiple strategies achieve similar recovery times, they can differ considerably in infrastructure efficiency. Particularly on high-intensity routes such as Arnhem Centraal – Nijmegen, optimising both aspects becomes critical.

In scenarios with communication failures, the type of marker board used (SMB vs LMB) plays an important role. Implementing LMBs improves both recovery and disruption periods and reduces WTTE scores, especially for block section designs which includes many SMBs.

Finally, travel time analyses reveal that placing more block sections leads to shorter travel times, particularly on routes where trains experience hindrances. Yet, this improvement comes with higher infrastructure costs, forcing a trade-off decision between operational performance and investment.

In summary, the optimal strategy is context-dependent. Routes with high traffic density and complex timetables benefit most from strategies like ETCS minimum distance, while on quieter corridors or where cost control is more critical, strategies such as ETCS cost-efficient or harmonic may be more appropriate.

9. Discussion

This chapter discusses the limitations in design and model that may have had an influence on the results of this study. In addition, the results are put in perspective in relation to existing literature.

9.1. Design limitations

Designing a block section layout under ERTMS/ETCS Level 2 is far from straightforward. To guarantee safety across Europe, the EU has established extensive design regulations, which have been further extended by ProRail with additional requirements. Together, these rules form a very detailed and comprehensive framework. Within this study, therefore, by no means all the rules have been used here. This means that the designs created in this study could only give a possible picture of what might be possible with very many exceptions. One such simplification is that the entire network is assumed to be equipped with ERTMS/ETCS Level 2, meaning that no transitions between NS'54/ATB-EG and ERTMS/ETCS Level 2 were considered.

Additionally, interviews revealed that implementing the minimum distance strategy is unlikely to be feasible in practice due to issues with the voltage stability of the overhead line system. If a train were to stop frequently due to shorter blocks, this could cause overheating of the overhead wires, leading to potential damage.

Furthermore, the design of the ETCS cost-efficient strategy did not consider the minimum headways between trains. With this design, only whether the block layout works properly in terms of timetable was taken into account. By also testing the block layout for minimum headways, it could be that fewer blocks should have been removed on certain sections. As a result, the capacity consumption, recovery and disruption periods might be lower, for example.

Last in terms of strategy design, the current block layout was used as the base for the ETCS harmonic strategy. This layout has been tested for minimum headways under ERTMS/ETCS Level 2, but not comprehensively: it was tested for particular combinations such as two regional trains of two intercity trains, but not for mixed traffic such as regional and intercity trains or different platform combinations. This design limitation could partly explain the relatively weaker performance of the ETCS harmonic strategy.

9.2. Model limitations

Although this study aimed to create as complete a picture as possible of the effects of different block layouts under ERTMS/ETCS Level 2, some limitations remain. Not all possible block configurations were tested, meaning that an even better performing layout might exist that was not considered. Additionally, while three different study areas were investigated, the sample size remains small to make generalised statements with certainty about the best strategies for different corridor types.

In addition, this study assumed an unlimited availability of rolling stock. In practice, train arriving at a station (such as Veendam or Enschede) must change ends on the train. As a result, the same train is used for the next journey. However, this was not taken into account during the simulations in this study. Especially during disruptive situations, this matters since here, before the original departure time, a train is ready for departure but it does not actually exist in reality.

Finally, the model assumed a more conservative ETCS braking curve. In reality, trains with ERTMS/ETCS Level 2 can brake harder than what was simulated. However, it is expected that train drivers will initially continue to brake conservatively, similar to current NS'54/ATB-EG situation.

Since little operational data is currently available on how drivers will actually brake with ERTMS/ETCS Level 2, this remains a source of uncertainty.

9.3. Results in perspective

Although the study faced certain design and model limitations, the results were largely consistent with findings in from existing literature. This section reflects on the results by placing them in the context of the initial hypotheses and existing literature.

9.3.1. Non-disruptive conditions

Based on the found literature in Chapter 2, several hypotheses were formulated. One of these was that the implementation of ERTMS/ETCS Level 2 would lead to increased capacity under undistruptive conditions, which was also found in the studies of Landex, Jensen, et al. (2019), Ranjbar et al. (2022), and Goverde et al. (2013). The results of this study confirmed this hypothesis for corridors where trains frequently experience delays. In such cases, ERTMS/ETCS Level 2 reduces headways between trains and therefore increase capacity.

However, this effect was not observed in the low-volume study area, where a slight decrease in capacity was found. This reduction is attributed to the braking curve applied in this study, which is slightly less favourable than that of the traditional NS'54/ATB-EG system. This issue was previously noted by Landex, Wittrup, et al. (2019), however, this only addressed the 1:1 replacement of the block sections, whereas this research shows that the capacity reduction can occur across all ERTMS/ETCS Level 2 strategies on low-traffic routes.

Furthermore, this study is based on a conservative braking curve, under the assumption that train drivers will continue braking in much the same way after the introduction of ERTMS/ETCS Level 2. In practice, trains could brake more efficiently, which could improve performance. As a result, when less conservative braking behaviour is adopted, a reduction in capacity consumption on low-density corridors might still be achievable.

Finally, it was hypothesised that the ETCS minimum distance strategy would yield the best performance overall. The results, however, shows this was not always the case. While this strategy performed well, it was outperformed in some scenarios such as capacity consumption. Nevertheless, it ended up as the second-best strategy, with only a small difference in performance compared to the top performer. This is striking, given the expectation that a highly detailed block layout, proving the most information, would lead to the best performance. The reason for this difference is unclear, but is may be due to suboptimal block placement, or an error in the simulation or calculations.

9.3.2. Disruptive conditions

A hypothesis was also formulated for the disruptive conditions: it was expected that NS'54/ATB-EG would perform worse than ERTMS/ETCS Level 2 when using the same block layout. This expectation is supported by the findings of Corman et al. (2014) and Goverde et al. (2013). The results show that this is true, however, the differences in results are relatively small.

It was further hypothesised that the advantage of ERTMS/ETCS Level 2 could be reduced by alternative block section strategies, since trains must stop at each SMB to request an European Instruction. This hypothesis can be divided between the two types of disruption. For the train failure, a consistent reduction in recovery and disruption time was observed with ERTMS/ETCS Level 2 across all strategies. In this case, the affected train only had to contact the dispatcher once, regardless of the signalling system, meaning the disadvantage of multiple dispatcher contacts to pass SMBs did not apply. In contrast, during a communication failure, the hypothesis

proved valid. Block layouts with SMBs showed longer recovery and disruption periods than those with fewer SMBs. The need for multiple dispatcher contacts clearly impacted performance in this scenario.

It was also expected that the use of LMBs would improve resilience by allowing trains to proceed at reduced speed without requesting European Instructions. The results confirmed this expectation: LMBs led to shorter disruption and recovery periods, particularly on busier corridors.

This study did not consider traffic control measures during disruptions. However, the study of Goverde et al. (2013) demonstrated that such measures can have an influence on capacity consumption and resilience. Therefore, the exclusion may limit the applicability of the results.

10. Conclusion

This chapter gives the main conclusions per research question and an overarching conclusion.

1. Which Key Performance Indicators (KPIs) are most applicable in a trade-off analysis related to train disruption and are of interest to the different stakeholders in this domain?

Based on the literature review and input from the interviews with the different stakeholders, the following KPIs were used for this study:

- Capacity consumption (UIC 406), including minimum headway
- Resilience, measured by recovery and disruption periods
- (Weighted) travel time
- Travel time deviation
- Infrastructure costs

These KPIs were considered most appropriate because they capture both operational performance during normal conditions and system behaviour under disruptive conditions. They reflect key stakeholder interests such as capacity, cost efficiency, travel time, punctuality and resilience. Moreover, the selected KPIs can be used for the trade-off analysis by linking infrastructure investments to operational outcomes under normal and disruptive conditions.

2. What is the performance of the various railway block section design strategies during normal and disruptive conditions in combination with varying train frequencies?

The performance of the various block section design strategies under ERTMS/ETCS Level 2 varies between normal and disruptive conditions and depends strongly on traffic density and disruption scenario.

Under normal conditions, ERTMS/ETCS Level 2 strategies generally offer improved capacity and travel time benefits on busier corridors (as seen on the Amersfoort Centraal – Apeldoorn and Arnhem Centraal – Nijmegen routes), while gains are limited on lightly loaded routes (which was visible on the Zwolle – Deventer route). The ETCS minimum distance and design manual strategies typically achieve the best capacity consumption and travel time results but at higher infrastructure costs.

During disruptive conditions caused by a train failure, strategies with shorter block lengths (ETCS minimum distance and design manual) enable faster recovery and smaller disruption periods, leading to better resilience and lower Weighted Travel Time Extension values. In contrast, the cost-efficient strategy consistently recovers slower and shows worse resilience under high traffic volumes.

During communication failures, however, the operational disadvantages of dense block layouts become apparent: strategies with many Stop Marker Boards, such as ETCS minimum distance, suffer from long recovery and disruption periods. Here, strategies with fewer SMBs, like ETCS current block section design and harmonic, perform better.

Overall, no single strategy performs best in all scenarios. The choice of an optimal strategy depends on balancing infrastructure costs, capacity needs, resilience requirements, and operational vulnerability to different disruption types.

3. What is the performance when the railway block section design strategies use Location Marker Boards (LMBs) instead of Stop Marker Boards (SMBs) during disruptions?

The results show that the performance of railway block section design strategies improves when Location Marker Boards are used instead of Stop Marker Boards during disruptions. Especially on busier corridors like Amersfoort Centraal – Apeldoorn and Arnhem Centraal – Nijmegen, LMBs lead to faster recovery times, shorter disruption periods, and reduced passenger delays (lower WTTE values). On less busy routes, such as Zwolle – Deventer, LMBs have less impact on recovery and disruption periods but still improve overall travel times by reducing individual train delays.

Overall, the implementation of LMBs enhances system resilience by allowing trains to continue at reduced speed without dispatcher involvement to request an European Instruction, making them particularly valuable for dense networks and strategies with many marker boards.

4. Based on the KPIs of research question 1 and simulation results of research question 3 & 4, which trade-offs must be considered when selecting a block section design?

The trade-off analysis shows that there is no single railway block section design strategy that performs best in all situations. Each strategy has specific strengths and weaknesses depending on the corridor characteristics and operational priorities.

In general, the transition from NS'54/ATB-EG to ERTMS/ETCS Level 2 improves capacity consumption, travel time, and resilience. However, achieving the best overall performance requires careful balancing between investment costs and operational benefits. Strategies like ETCS minimum distance and ETCS design manual provide the highest capacity and fastest recovery times, making them ideal for busy corridors with high traffic density. In contrast, strategies such as ETCS cost-efficient and harmonic offer lower infrastructure costs but result in slightly longer recovery and disruption periods, which may be acceptable on routes with lower traffic volumes. The implementation of Location Marker Boards (LMBs) further enhances resilience, especially for designs with initially high Stop Marker Board (SMB) densities.

In conclusion, the optimal strategy is context-specific and depends on whether capacity, resilience, travel time, or cost-efficiency is prioritised.

Aim: to evaluate the performance of multiple ERTMS/ETCS Level 2 railway block section design strategies under both normal and disruptive conditions.

The study evaluated the performance of various ERTMS/ETCS Level 2 block section design strategies using Key Performance Indicators derived from literature and stakeholder input. Under normal conditions, results showed that the effectiveness of a strategy depended heavily on corridor characteristics such as traffic density. ERTMS/ETCS Level 2 strategies generally improved capacity and travel times compared to the NS'54/ATB-EG system, especially on high-density routes.

In disruptive conditions, block section designs with shorter blocks, such as ETCS minimum distance and ETCS design manual, generally showed faster recovery and shorter disruption periods, increasing resilience. However, in scenarios involving communication failures, strategies with fewer marker boards (such as ETCS current block section design and harmonic) performed better unless Location Marker Boards were implemented, which improved system performances.

The trade-off analysis revealed that no single design strategy can be considered universally superior. Instead, the optimal choice depends on the specific operational context.

Based on the results of this study, it would be suggest to prioritise the implementation of ERTMS/ETCS Level 2 on the corridors with higher traffic volumes, since more benefits were shown for these areas. Whereas for the lower volume areas, little to no improvements were seen in both normal and disruptive conditions.

In addition, the implementation of Location Marker Boards shows great potential during disruptive conditions. Although their exact implementation falls outside the scope of this study, incorporating LMBs is strongly recommended in future designs.

11. Recommendations

This study focussed only on analysing the effects of different block layouts. With the implementation of ERTMS/ETCS Level 2, it becomes possible to increase the maximum track speed to 160 km/h, whereas with NS'54/ATB-EG the speed limit is 140 km/h. In this study, block layouts were tested based on the current track section speeds, without adjusting them to future possible speed increases. Higher permitted speeds could possibly affect the performance of block section designs and may therefore change the outcomes observed in this study. It is recommended to explore the interaction between block section design and increased speeds in future research.

Furthermore, this study made limited adjustments to block densities around stations, only with the harmonica strategy. More detailed research on block layouts in and around railway yards was not conducted, partly because the study considered only individual corridors (e.g., Apeldoorn – Amersfoort Centraal) and not extended multi-station sections (e.g., Apeldoorn – Amersfoort Centraal – Utrecht). A broader corridor approach could offer more insights into optimising block designs across multiple stations, improving overall throughput and helping to identify potential bottlenecks at key nodes.

No adjustment measures were included in this study. Further studies should incorporate such measures, as real-world operations often involve dynamic interventions during disruptions. Although this study assumed that disruptions would resolve within a reasonable time without adjustments, modelling such adjustments could reveal additional differences in for example the resilience of block section design strategies.

In the study of Quaglietta (2014), an optimisation strategy was used to find an balance between capacity and costs, potentially leading to an outcome similar as in Figure 30. Although this study intended to investigate such a strategy, it was not fully developed due to time constraints. It is recommended that future work explore this optimisation strategy, possibly combining them with the other strategies of this study as a constraint.

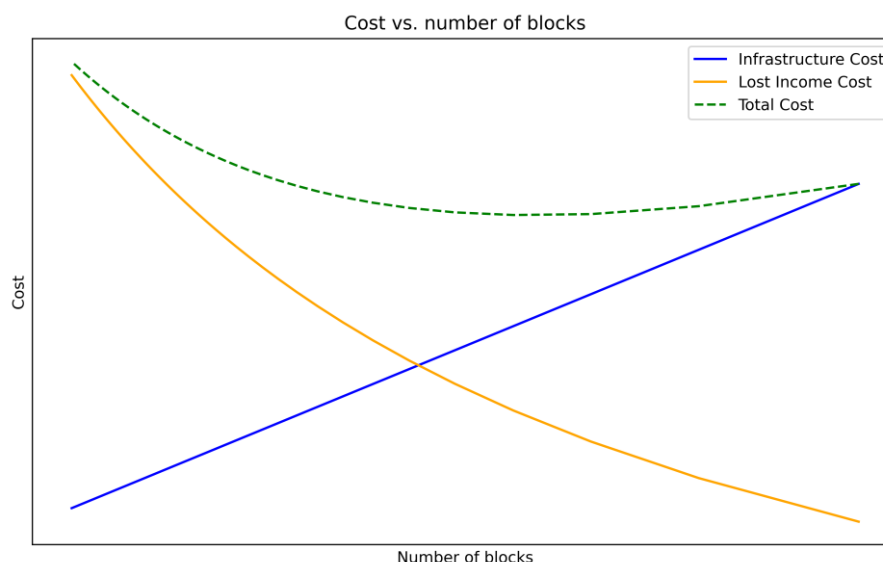


Figure 30: Possible optimisation between capacity and costs

Finally, the introduction of ERTMS/ETCS Level 2 could allow more stations in the Netherlands to function as node, similar to existing hubs like Zwolle and Zutphen. As this study focussed primarily on operational and infrastructure aspects, timetable-driven opportunities were not considered. Future research could explore how the increased flexibility of ERTMS/ETCS Level 2 can enhance network connectivity from a timetable perspective.

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Appendix A: Interviews

A.1. ProRail

Railway signalling engineers

Voor dit interview is er met twee railverkeerskundigen van ProRail gesproken. Binnen hun functie toetsen zij spoorontwerpen van ingenieurbureaus, variërend van grote infrastructurele projecten tot kleinere aanpassingen, bijvoorbeeld bij wissels of stations. Hun beoordeling richt zich onder andere op de opvolgtijd en de positionering van seinen, waarbij ze toetsen of de plaatsing voldoet aan de remwegvereisten en binnen de ontwerpvoorschriften valt.

KPI's

Vanuit de geïnterviewden zijn de volgende KPI's als belangrijke aandachtspunten beoordeeld:

- Capaciteit, met name of de blokindeling toereikend is om de geplande, onverstoord dienstregeling te kunnen rijden.
- Kosten, voornamelijk in termen van aanleg- en onderhoudskosten van fysieke elementen (zoals SMB's en assentellers).
- Zelfverklarendheid, oftewel: is de blokindeling logisch en intuïtief voor zowel ontwerpers als machinisten?
- Doelmatigheid, bijvoorbeeld: vervult elk sein of SMB daadwerkelijk een functionele rol?
- Veiligheid, met name bij gevaarpunten zoals wissels, beweegbare bruggen en overwegen, waarbij veiligheid als randvoorwaarde wordt beschouwd via de ontwerpvoorschriften.

Kosten kunnen indirect worden beoordeeld door te kijken naar het aantal elementen in een ontwerp. Andere kostencomponenten, zoals energieverbruik of materieelinzet, vallen buiten het domein van het infrastructurele ontwerp.

Blokindeling

De geïnterviewden benadrukten dat bij de uitrol van ERTMS een één-op-één overname van een bestaande blokindeling (zoals bij het ERTMS Kijfhoek – Belgische grens project) meestal niet logisch is. In dat specifieke geval werd aanvankelijk de bestaande blokindeling behouden omdat er niet werd overgestapt op assentellers. Uiteindelijk werden assentellers toch toegevoegd, wat het oorspronkelijke ontwerp deels overbodig maakte.

Verder werd benoemd dat een 200-meter-strategie op trajecten met hoge snelheden (130-140 km/h) vaak geen functionele meerwaarde heeft: treinen rijden te snel om daadwerkelijk voordeel te halen uit zulke korte blokken. Daarnaast werd benoemd dat een strategie met zeer korte blokken (bijvoorbeeld elke 200 meter) in de praktijk snel vastloopt, met name op emplacementen, gezien de aanwezige dwangpunten voor het ontwerp.

Wat betreft het gebruik van LMB's is er binnen ProRail besloten hier geen gebruik van te maken op de manier hoe dit in dit onderzoek toegepast wordt. ProRail wil mogelijk gebruik maken van virtuele seinen, wat in de praktijk eenzelfde effect heeft als een LMB. Het verschil tussen een LMB en virtueel sein is dat er bij met gebruik van een virtueel sein enkel een assenteller wordt neergelegd, en met een LMB wordt er nog een bord geplaatst naast de assenteller om de nieuwe blokgrens aan te geven. Daarbij is nog onduidelijk hoe betrouwbaar het systeem onder verstoorde omstandigheden zal zijn en wat dit betekent voor de werkdruk van de treindienstleiders. Dit maakt het moeilijk om een "ideaal ontwerp" te formuleren.

Verstoring

Volgens de geïnterviewden hoeft bij verstoringanalyse niet altijd gekeken te worden naar de oorzaak van de verstoring. Het simuleren van vertraagde treinen, bijvoorbeeld door een langere

halteertijd vanwege een reizigersincident, is een goede manier om de robuustheid van een ontwerp of dienstregeling te toetsen. Het voordeel is dat zulke vertragingen willekeurig kunnen plaatsvinden, wat representatief is voor alledaagse verstoringen.

Capacity management

De geïnterviewde werkt bij ProRail binnen capaciteitsmanagement. Hij gaf tijdens het interview inzicht in hoe nieuwe systemen invloed kunnen hebben op de capaciteit van het spoor. Binnen zijn functie adviseert hij over de richting waarin het spoornetwerk zich zou moeten ontwikkelen en beoordeelt hij of het verstandig is om bepaalde technologische veranderingen, zoals ERTMS/ETCS of ATO, door te voeren.

KPI's

Bij de afweging van nieuwe technologische systemen (zoals ERTMS/ETCS of ATO) wordt enerzijds gekeken naar de vraag: is er voldoende reizigersbehoefte om een capaciteitsverhoging te rechtvaardigen? Je kan grofweg zeggen dat met ATB 12 treinen per uur over een traject kunnen rijden (inclusief haltes), met ERTMS/ETCS stijgt dit naar 14, en met ATO naar 16. Het invoeren van een nieuw systeem moet dus passen bij de vervoersvraag. Anderzijds wordt er binnen capaciteitsmanagement gekeken naar netwerktoegankelijkheid voor alle partijen, kosten-efficiëntie en het aantrekkelijk houden van het spoorvervoer.

Wat betreft de voorgelegde KPI's, zou je mee kunnen nemen hoeveel treinen er worden geraakt tijdens een verstoring en de zogeheten olievlekwerking die daaruit voortkomt. Daarnaast zijn de heterogeniteitsindexen indirect onderdeel van de UIC 406. Wanneer je beide zou gebruiken, is er een kans dat je het dubbel gaat meten.

Blokindeling

De geïnterviewde had nog twee toevoegingen op de blokindeling strategieën. De eerste strategie is om te kijken vanuit de minimale afstand strategie en van daaruit gekeken wordt welke Stop Marker Boards (SMBs) mogelijk weggelaten kunnen worden zonder noemenswaardige capaciteitsverliezen. Hierdoor wordt er (enorm) bespaard op kosten, maar blijft de capaciteit hetzelfde.

De andere suggestie voor een blokindeling strategie is gebaseerd op een praktisch dwangpunt. In de praktijk blijkt namelijk dat door ontwerptechnische dwangpunten de blokken op de vrije baan minimaal 425 meter lang zullen zijn. Dit komt onder andere door beperkingen in de openspanningsrichting van de bovenleiding. Wanneer een trein stilvalt onder de overgang van de bovenleiding en de pantograaf precies op het overgangspunt terechtkomt, kan het draad oververhit raken en beschadigen. In combinatie met de lengte van zo'n veld (60 m), een treinlengte van 340 m en een marge van 25 m komt dit uit op 425 m, ontstaat een praktische minimale blokafstand.

Binnen ProRail is besloten om niet te werken met Location Marker Boards (LMB's), omdat deze voor machinisten weinig toegevoegde waarde hebben. Wel wordt er gewerkt aan eventuele virtuele SMB's. Het fysieke bordje van een LMB heeft geen directe invloed op de capaciteit, maar doet de technologie erachter dat wél, zowel bij LMB's als bij virtuele SMB's. Een virtueel SMB fungeert als detectiegrens en wordt gekoppeld aan assentellers die bepalen of een trein een blok in- of uitrijdt. Theoretisch kan een machinist daar ook een stopopdracht krijgen indien nodig.

Verstoringen

Vertragingen hebben niet alleen impact op de reiziger, maar ook op materieel- en personeelsomlopen, wat met name voor vervoerders van groot belang is. Zowel ProRail als vervoerders zijn daarom geïnteresseerd in de faalkansen van systemen: welke storingen treden

op, hoe lang duren deze, en hoe vaak komen ze voor? De geïnterviewde heeft hier alleen geen inzicht in voor ERTMS/ETCS Level 2.

Dispatchers

Dit interview is afgenomen met twee medewerkers van ProRail die betrokken zijn bij de implementatie van ERTMS vanuit het perspectief van verkeersleiding. De eerste persoon is werkzaam binnen de afdeling logistieke ontwikkeling bij verkeersleiding, waar hij zich bezighoudt met toekomstige operationele ontwikkelingen. De tweede persoon is projectmanager ERTMS-implementatie bij verkeersleiding en richt zich specifiek op de invoering van ERTMS binnen de verkeersleidingsorganisatie, onder andere op het gebied van regelgeving, opleiding en de inzet van simulatoren.

KPI's

Wat betreft KPI's uit de literatuur vinden zij vanuit de punctualiteit en rijtijden binnen een blok belangrijk. Zelf maken zij ook gebruik van KPI's, welke over het hele gebied gaan in plaats van op baanvakniveau. Daarnaast maken zij onderscheid tussen normale en verstoorde omstandigheden. In niet-verstoorde situaties wordt bijvoorbeeld gekeken naar punctualiteit. Voor verstoorde situaties zijn er afspraken of prestatienormen, bijvoorbeeld hoe lang het duurt dat een gestrande trein weggesleept wordt. Hierbij speelt de blokindeling een belangrijke rol: het aantal tussenliggende blokken (en dus SMB's) kan direct invloed hebben op hoe snel je bij de gestrande trein bent. Dit is wel afhankelijk van de procedure die daarvoor bedacht is. Daarnaast is voor hen de gebruiksvriendelijkheid en tevredenheid van de treindienstleider van belang.

Vanuit verkeersleidingsperspectief zijn er duidelijke voorkeuren en bezwaren rondom het gebruik van Location Marker Boards (LMB's). Treindienstleiders willen deze bij voorkeur niet en dan vooral het fysieke bord niet, met name om verwarring tijdens verstoringen te voorkomen. Machinisten zouden in zo'n geval per ongeluk kunnen stoppen bij een LMB en vervolgens contact opnemen, wat onnodige vertraging kan veroorzaken. Bovendien vereist het gebruik van LMB's ook dat er specifieke procedures worden opgesteld voor verstoorde situaties, die uitvoerbaar, efficiënt, foutbestendig en gebruiksvriendelijk voor zowel machinist als verkeersleiding moeten zijn.

Blokindeling

Qua blokindeling zijn er geen nieuwe ideeën naar boven gekomen, maar wel enkele eisen die aan een indeling gesteld zouden kunnen worden. Zo moeten SMB's geplaatst worden op locaties waar dit logisch is vanuit veiligheidsoogpunt. Daarnaast speelt de afhandeling van bijvoorbeeld een gestrande trein een belangrijke rol. Bij het slepen van een trein geldt: hoe minder SMB's tussen de gestrande trein en het volgende emplacement, hoe sneller de trein verwijderd kan worden. Als richtlijn kan worden gerekend met ongeveer 10 minuten per SMB (inclusief procedure om het blok weer vrij te melden). Bij 10 SMB's kost dit dus al snel ruim een uur. Een eis die daaruit zou kunnen volgen, is dat een gestrande trein binnen een uur bij een emplacement moet kunnen zijn. Dit zou neerkomen op een maximum van ongeveer 6-7 SMB's over het gehele traject, afhankelijk van de lengte. Daarnaast speelt regelgeving rondom SMB's en LMB's een rol in de blokstrategie: mocht het zo zijn dat andere regels gelden voor LMB's, dan zou het mogelijk zijn om meer LMB's te plaatsen dan SMB's. Dit blijft echter afhankelijk van de operationele procedures die hiervoor gelden.

Verstoringen

Wat betreft verstoringen gaf men aan ervaring te hebben op basis van bestaande ERTMS-trajecten, zoals de Betuweroute en de HSL. Hieruit blijkt dat RBC-storingen relatief zeldzaam zijn (ongeveer eens per jaar) en meestal binnen 15 minuten worden opgelost. Trein-gerelateerde verstoringen, zoals communicatieproblemen door defecte antennes, komen vaker voor. Op de Betuweroute gebeurde dit bijvoorbeeld gemiddeld eens per maand.

System specialist ERTMS

De geïnterviewde houdt zich binnen ProRail bezig met ERTMS/ETCS Hybrid Train Detection, ook wel bekend als ERTMS/ETCS Level 3. Bij deze variant blijven de fysieke detectiesecties bestaan, maar kunnen ze worden onderverdeeld in kleinere, virtuele secties. Dit maakt het mogelijk om het spoor efficiënter te benutten, doordat treinen dichter op elkaar kunnen rijden.

Om Hybrid Train Detection te implementeren, moeten treinen echter beschikken over een zogenoemde trein integriteitsmodule. Omdat deze module in de trein moet worden ingebouwd, verschuiven de kosten bij dit systeem deels van ProRail naar de vervoerders. Dit is in tegenstelling tot bij ERTMS/ETCS Level 2, waar de kosten zwaarder aan ProRail kant liggen. Het feit dat de kosten en baten bij twee verschillende partijen liggen blijkt op dit moment een belangrijke belemmering voor de implementatie van Hybrid Train Detection.

Wanneer een traject uitsluitend bereden wordt door treinen die wél zijn uitgerust met deze integriteitsmodule, kunnen de virtuele blokken volledig benut worden. In dat geval kan het spoor in veel kleinere secties worden opgedeeld, wat leidt tot een capaciteitsverhoging. In de praktijk is het echter waarschijnlijk dat er ook nog treinen zonder zo'n module rijden. Dergelijke treinen zijn dan aangewezen op de fysieke blokken, wat ten opzichte van de ideale situatie van ERTMS/ETCS Hybrid Train Detection zorgt voor een lagere benutting van de capaciteit.

Zeker in de overgangsfase zal de verhouding tussen niet-integere en integere treinen een grote rol spelen. Omdat het aandeel niet-integere treinen in het begin relatief groot zal zijn, moeten de fysieke blokken in die fase beperkt blijven in lengte. Daarnaast is nog niet volledig onderzocht wat er gebeurt als een trein die als integer wordt beschouwd plotseling niet-integer wordt – bijvoorbeeld door een foutmelding in het integriteitssysteem. In dat geval blijft de trein wel operationeel, maar moet hij weer functioneren binnen de grenzen van de fysieke secties. Dit onderstreept dat het systeem in zekere zin altijd moet kunnen terugvallen op fysieke detectie, wat invloed heeft op hoe je de secties ontwerpt.

In dit systeem wordt er gestreefd naar langere fysieke secties om het aantal assentellers en daarmee de kosten te beperken. De virtuele secties daarentegen blijven volgens de huidige filosofie gelijk aan, of korter dan, de huidige sectielengtes. Op die manier wordt geprobeerd een balans te vinden tussen kostenbesparing en capaciteitswinst.

A.2. Nederlandse Spoorwegen

Advisor timetable planning

De geïnterviewde is werkzaam bij NS en houdt zich bezig met de middellangetermijnontwikkeling van de dienstregeling (2 tot 7 jaar vooruit). Dit betreft grote wijzigingen zoals frequentie-aanpassingen, lijnvoering en de invoering van nieuwe technologieën zoals ERTMS of ATO. Naast de inhoudelijke analyse van varianten, wordt ook gekeken naar nieuwe methodes en simulaties om dienstregelingen te evalueren.

KPI's

Binnen de context van blokindeling zijn kosten voor NS minder relevant, omdat deze aan de infrabeheerderzijde liggen. De enige kostengerelateerde factor voor NS is de ombouw van materieel. Natuurlijk denkt NS graag mee over het belang van het gehele spoorsysteem, maar is het ook belangrijk om de verschillende belangen te benoemen. Wel worden andere prestatie-indicatoren als zeer belangrijk gezien:

- Capaciteit – het kunnen rijden van meer of flexibeler treinen draagt direct bij aan de mogelijkheden voor een betere dienstregeling en hogere reizigerstevredenheid.

- Robuustheid – nauw verbonden met capaciteit: het systeem moet ook veerkrachtig blijven tijdens verstoringen.
- Passagiersperspectief, zoals (gewogen) reistijd en punctualiteit – dit is verweven met zowel capaciteit als punctualiteit.

Robuustheid wordt bij NS in de praktijk benaderd aan de hand van ontwerpregels zoals rijtjesspel (bijv. 7%), buffertijden (60 sec) en uitgangspunten voor de halteertijden. Deze normen zijn niet wiskundig onderbouwd, maar gebaseerd op ervaring. Bij ingrijpende dienstregeling wijzigingen is het nog onzeker of deze richtlijnen nog toereikend zijn, vooral omdat bijsturingmogelijkheden daarin niet worden meegenomen.

Daarnaast werd benadrukt dat de compressiemethode, hoewel nuttig, niet het hele systeemgedrag reflecteert, met name bij treinen die meerdere studiegebieden doorkruisen, zoals de 3600 (Zwolle – Roosendaal). Capaciteitsmetingen op basis van compressie kunnen dan per deeltraject sterk verschillen, terwijl het in werkelijkheid om één doorgaande trein gaat.

Blokindeling

De geïnterviewde had geen op- of aanmerkingen wat betreft blokindelingen.

Verstoring

De geïnterviewde gaf aan dat verstoringen door GSM-R-verbinding of treincommunicatie realistische scenario's zijn. In de praktijk wordt aangenomen dat ERTMS/ETCS Level 2 minder gevoelig is voor bepaalde storingen zoals sectieproblemen, die bij NS'54/ATB-EG vaker voorkwamen. Er is echter nog onvoldoende data om dit volledig te onderbouwen.

A.3. Arriva

Program manager ERTMS

De geïnterviewde is werkzaam bij Arriva als programmamanager ERTMS. In deze rol is hij verantwoordelijk voor de invoering van ERTMS/ETCS Level 2 in Limburg en Noord-Nederland. In Limburg blijft het baanvak zelf ongewijzigd en ligt de focus op de ombouw van de treinen, onder andere vanwege aansluiting op het Belgische spoorstelsel. In Noord-Nederland wordt wél het baanvak aangepast, wat aanleiding geeft om diverse procedures opnieuw tegen het licht te houden, zoals die rondom calamiteitenafhandeling en dataverwerking.

KPI's

Vanuit het perspectief van Arriva zijn er meerdere KPI's belangrijk bij de invoering van ERTMS/ETCS Level 2. Ten eerste wil men ondanks veranderingen in infrastructuur of systemen nog steeds de geplande dienstregeling kunnen rijden. Hierbij spelen punctualiteit (op tijd vertrekken en aankomen) en reistijd een grote rol. Daarnaast wordt gekeken naar het aangeboden transportvolume: worden reizigers niet onnodig achtergelaten op het perron, en wordt er tegelijkertijd niet met te veel lege stoelen gereden? Deze afweging raakt aan begrippen zoals gebruikte capaciteit en capaciteitsverbruik. Ook reizigerstevredenheid is essentieel, en deze wordt mede beïnvloed door de punctualiteit, informatievoorziening en het vervangend vervoer tijdens verstoringen.

Arriva moet verantwoording afleggen aan twee belangrijke partijen: de provincie en de reiziger. Waar de provincie zich richt op punctualiteit, reizigerstevredenheid en het voorkomen van overvolle treinen, kijkt de reiziger met name naar aankomsttijden (vooral in verband met aansluitingen), duidelijkheid bij verstoringen en het gemak van de reis. Volgens de geïnterviewde weegt aankomsttijd zwaarder dan vertrektijd voor de beleving van de reiziger.

Kosten spelen uiteraard ook een rol, al ligt de focus voor Arriva hierbij meer op operationele kosten zoals energieverbruik en personeel. Een aangepaste dienstregeling kan reizigerstechnisch gunstig uitpakken, maar economisch juist nadelig zijn door hogere personeelsinzet of inefficiënte benutting van materieel.

Wat betreft robuustheid wordt opgemerkt dat vervoerders deze anders benaderen dan infrastructuurbeheerders. Voor vervoerders neemt de robuustheid van een station toe naarmate de operationele complexiteit toeneemt (zoals extra wissels, mogelijkheden voor keermogelijkheden of flexibele perronindelingen). Voor ProRail geldt juist: hoe minder wissels, hoe minder kans op storingen – en dus hogere robuustheid.

De top drie KPI's volgens Arriva zijn:

1. Punctualiteit (op tijd vertrekken en aankomen)
2. Beoordeling van de reiziger
3. Kosten, in termen van gereden treinen versus gemiste capaciteit of opbrengsten

Blokindeling

Ten aanzien van blokindelingen werd benadrukt dat een gestandaardiseerde blok lengte weinig flexibiliteit oplevert, vooral niet in gebieden waar dynamiek gewenst is. De zogeheten harmonica strategie levert volgens de geïnterviewde flexibiliteit op in de omgeving van stations, en een 200 meter-strategie biedt zelfs hoge flexibiliteit op zowel vrije baan als emplacementen. Uiteindelijk verwacht hij dat de ideale blokstrategie per traject zal afhangen van de specifieke eigenschappen van het baanvak.

A.4. Keolis

Safety expert

De geïnterviewde is werkzaam als Safety-Manager bij Keolis. In deze functie is hij verantwoordelijk voor alle veiligheidsaspecten binnen het bedrijf, zowel voor het rail- als busvervoer. Zijn taken bestrijken onder andere het beoordelen van materieel, procedures en de naleving van veiligheidsnormen binnen de concessies waarin Keolis actief is.

KPI's

Binnen de context van spoorinrichting en dienstregeling benoemde de geïnterviewde drie belangrijke aandachtspunten:

- Veiligheid: zowel het materieel als de infrastructuur moeten voldoen aan de geldende veiligheidsnormen. Dit is voor Keolis een absolute randvoorwaarde.
- Kwaliteit van het vervoer: hieronder vallen aankomst- en vertrektijden, maar ook aansluitingen. Het is bijvoorbeeld onwenselijk dat een aansluitende trein vóór dienstregeling vertrekt, waardoor overstappers hun verbinding missen. Vertraging is eveneens onwenselijk, maar wordt als minder verstorend ervaren dan een 'te vroege' trein.
- Kosten van het materieel: Keolis moet investeren in treinen die voldoen aan technische en veiligheidsnormen. Daarbij speelt ook de lengte van de concessie een rol; het materieel moet in principe 'afgeschreven' zijn aan het einde van de concessieperiode om economisch verantwoord te kunnen worden ingezet.

Hoewel ERTMS/ETCS Level 2 in de toekomst de standaard zal worden, levert het systeem voor Keolis zelf weinig directe voordelen op. De enige verwachte verbetering is een afname van het aantal storingen, maar qua operationele ruimte of capaciteit zal er niet direct veel veranderen omdat de stations capaciteit (afhandel/overstap ruimte) hierdoor niet toeneemt.

Dienstregeling en afhankelijkheid van NS

De dienstregeling van Keolis wordt grotendeels bepaald door de landelijke dienstregeling van NS. Keolis moet zijn diensten rondom het hoofdnet plannen en past zijn vertrektijden en aansluitingen aan op de ruimte die beschikbaar is. Dit beperkt de speelruimte om zelfstandig blokindeling of rijtijden te optimaliseren. Wel is er aandacht voor reizigersstromen en hoe Keolis binnen de beschikbare infrastructuur toegevoegde waarde kan leveren voor de reiziger.

Blokindeling

Volgens de geïnterviewde is de capaciteit van stations vaak de beperkende factor bij het ontwerpen van blokindelingen. Wanneer een station aanzienlijk minder capaciteit heeft dan het voorafgaande baanvak, ontstaat een knelpunt. In dat geval maakt een geoptimaliseerde blokindeling op de vrije baan weinig verschil: het station blijft de bottleneck. Extra rijpaden zijn pas nuttig wanneer bijvoorbeeld trage of stoptreinen onderweg kunnen worden ingehaald.

Verstoring

Binnen Keolis is nog geen duidelijk beeld van de mogelijke verstoringen die met ERTMS/ETCS Level 2 gepaard kunnen gaan. Omdat het systeem grotendeels nog in de implementatiefase zit, is er nog weinig operationele ervaring opgedaan vanuit het perspectief van regionale vervoerders. De verwachting is dat de storingen van andere aard zullen zijn dan met NS'54/ATB-EG, maar welke dat precies zijn, is nog niet helder.

A.5. Haskoning

Railway signalling engineer (1)

De geïnterviewde is werkzaam bij ingenieursbureau Haskoning als railverkeerskundige. Hier houdt hij zich bezig met de functionele inrichting van het spoor, waaronder de lay-out van stations en de plaatsing van wissels en seinen. Wat betreft ERTMS was hij betrokken bij twee grote projecten: rondom Dordrecht (onderdeel van ERTMS Kijfhoek – EKB) en de Hanzelijn. In beide gevallen ging het om een compleet nieuw ontwerp van de spoorinrichting in combinatie met ERTMS.

Blokindeling

Voor de ERTMS-projecten waar de expert aan mee heeft meegewerkt, kwamen in de praktijk neer op een vorm die lijkt op het harmonica-model. De reden hiervoor is dat in de projecten de ontwerpen primair zijn gebaseerd op klanteneisen, waarbij vooral minimale opvolgtijden worden gevraagd. Dit leidt er automatisch toe dat de blokken rond stations (waar de snelheid lager ligt) kleiner worden dan op de vrije baan, wat precies het principe is van de harmonicastrategie.

Wanneer er gestuurd wordt op kostenminimalisatie, is het belangrijk om eerst duidelijk te hebben onder welke randvoorwaarden dit gebeurt. Een kosten minimaliserend ontwerp dat alleen de klanteneisen meeneemt, ziet er anders uit dan een ontwerp waarin ook technische randvoorwaarden gelden, zoals een minimale of maximale bloklengte. Daarbij werd aangetekend dat een dergelijke strategie ook zou moeten worden uitgebreid met een afweging van de tijd die nodig is om het ontwerp te maken. Vanuit dat oogpunt is het overnemen van huidige blokindeling (onder NS'54/ATB-EG) vrijwel helemaal overnemen naar ERTMS/ETCS Level 2 gunstig, omdat deze minder ontwerpwerk vergt en hiermee de doorlooptijd van projecten korter is.

Binnen Haskoning wordt als ontwerpindicator vaak de zogeheten ongehinderde opvolgtijd gebruikt. Dit is de minimale tijd tussen twee opvolgende treinen, zodanig dat de 2^e trein niet hoeft te remmen voor de voorganger. Die opvolgtijd is direct afhankelijk van de bloklengte, en die hangt weer samen met het gewenste aantal treinen dat je over het traject wilt laten rijden.

Een SMB plaats je idealiter daar waar een trein onder zowel verstoorde als niet-verstoorde omstandigheden veilig tot stilstand gebracht moet worden, bijvoorbeeld net vóór een emplacement. Hierdoor kan een trein in verstoorde omstandigheden in elk geval doorrijden tot het inrijsein, waarna verkeersleiding of het systeem opnieuw kan beoordelen wat er moet gebeuren. In wisselstraten wil je juist liever géén stilstaande treinen, ook niet bij verstoringen. Daarom zou hier eerder gekozen kunnen worden voor LMB's: deze creëren geen formele stopverplichting in verstoorde omstandigheden, waardoor achteropkomende treinen sneller weer ruimte krijgen. Tijdens onverstoorde omstandigheden geldt voor een LMB hetzelfde als voor een SMB.

Verstoringen

De geïnterviewde geeft aan dat er in Nederland tot nu toe vooral ERTMS-trajecten op de vrije baan zijn ingericht, en dat er nog weinig ervaring is met ERTMS/ETCS Level 2 op emplacementen. Hierdoor is nog onduidelijk hoe ERTMS/ETCS Level 2 zich in dat soort omgevingen gedraagt en welke verstoringen zich daar kunnen voordoen. Op de vrije baan zijn bekende verstoringen onder andere sectiestoringen (waarbij het systeem een sectie niet vrijgeeft), storingen aan overwegen, en gestrande treinen. Op emplacementen ontstaan verstoringen vaak in beweegbare onderdelen, zoals wissels. Hoewel de reparatietijd van bijvoorbeeld een wissel gelijk zal zijn onder NS'54/ATB-EG en ERTMS/ETCS Level 2, kunnen de procedures ná een storing (zoals het opnieuw instellen van routes of vrijgeven van secties) onder ERTMS/ETCS Level 2 meer tijd kosten. Die procedures zijn deels onbekend en worden nu op aannames gebaseerd.

Een voorbeeld daarvan is de communicatie tussen trein en RBC voor het instellen en vrijgeven van routes. Hier is het systeem afhankelijk van berekeningstijd en dataverkeer, wat extra vertraging kan opleveren. De exacte duur hiervan is nu nog niet bekend en wordt op dit moment geschat.

Railway signalling engineer (2)

De geïnterviewde is werkzaam als railverkeerskundige bij Haskoning. Binnen het ERTMS-programma was hij betrokken bij het project ESAAL, gericht op de implementatie van ERTMS op het traject tussen Schiphol, Amsterdam, Almere en Lelystad. Binnen dit project lag aanvankelijk het plan om te werken met korte blokken, omdat het traject ontworpen is voor een hoge frequentie aan treinen, en zo een hogere capaciteit gerealiseerd zou kunnen worden.

Blokindeling

Het korte blokken ontwerp van ESAAL is herzien op verzoek van NS en de verkeersleiding. De reden hiervoor is dat machinisten in verstoorde situaties bij elk SMB expliciet toestemming moeten vragen om deze te mogen passeren. Bij korte blokken leidt dit tot een hoge frequentie van toestemmingsvragen, wat de werkdruk voor zowel de machinist als de treindienstleider aanzienlijk verhoogt.

Volgens de geïnterviewde leidt de invoering van ERTMS/ETCS Level 2 niet automatisch tot capaciteitsverhoging, zeker niet op baanvakken die onder NS'54/ATB-EG al efficiënt zijn ingericht. Binnen emplacementen is er echter wel ruimte voor winst, doordat in Nederland onder ERTMS/ETCS Level 2 kleinere blokken geplaatst kunnen worden dan onder het huidige systeem.

Bij het ontwerp van blokindelingen zijn er bepaalde dwangpunten, zoals de in- en uitrijders rond stations, waar het ontwerp in de praktijk vaak al geoptimaliseerd is. Op deze locaties verandert de positionering van seinen of SMB's meestal niet, ongeacht de gekozen strategie. Voor de rest van het traject wordt vervolgens gekeken naar de gewenste capaciteit, wat bepaalt welk blokontwerp passend is.

De geïnterviewde benadrukt dat er in de praktijk sprake is van verwevenheid tussen strategieën. In sommige situaties past de huidige blokindeling goed, bijvoorbeeld als alles technisch stabiel functioneert. Bij beperkte financiële middelen is een strategie gericht op kostenminimalisatie logisch. In andere gevallen, zoals bij optimalisatie rondom drukke gebieden of knelpunten, zijn strategieën zoals minimale afstand of de harmonica-aanpak geschikter.

Tot slot werd benoemd dat een strategie met 200 meter blokken weliswaar veel flexibiliteit biedt, maar ook nieuwe knelpunten creëert, vooral bij stations. Dit probleem komt nu al naar voren binnen het hoogfrequentprogramma: bij vertraging of verstoring ontstaat een file van treinen die in de rij staan om het station binnen te kunnen rijden, wat de doorstroming aanzienlijk belemmert.

Verstoringen

Wat betreft verstoringen is nog niet alles bekend over hoe ERTMS/ETCS Level 2 zich in de praktijk zal gedragen. Wel is duidelijk dat klassieke storingen zoals defecte wissels, bovenleidingen of materieel gewoon blijven voorkomen. Nieuwe type verstoringen kunnen ontstaan vanuit het digitale karakter van ERTMS/ETCS Level 2, zoals storingen in de GSM-R-communicatie, waarbij er tijdelijk geen contact is tussen de trein en interlocking. Wanneer er 35 seconden geen contact is, krijgt de trein een snelremming.

A.6. Programmadirectie ERTMS

De geïnterviewde is werkzaam als programmamanager en strategisch adviseur binnen de Programmadirectie ERTMS. De Programmadirectie is verantwoordelijk voor het realiseren van een goed werkend vervoerssysteem onder ERTMS in Nederland, waarbij infrastructuur en vervoerders op elkaar moeten worden afgestemd. Daarnaast speelt de Programmadirectie een rol in de Europese uitrol van ERTMS, met als doel uniformiteit te bereiken in plaats van versnipperde nationale implementaties.

KPI's

De geïnterviewde vertelt dat hij binnen de Programmadirectie vanuit verschillende perspectieven naar bepaalde vraagstukken kijkt. Dit is afhankelijk van het type corridor of het doel. Ter illustratie noemde hij twee relevante corridors:

- ESAAL-corridor (Schiphol – Amsterdam – Almere – Lelystad)

Dit traject kent (zeker in de pre-coronaperiode) extreem hoge reizigersdruk. Er waren momenten waarop reizigers niet meer konden instappen, simpelweg omdat de deuren niet meer dicht konden. Hier ligt de nadruk op capaciteitsverhoging en het vergroten van de vervoersmogelijkheden.

- Internationaal railgoederenvervoer (o.a. Rotterdamse haven)

Op dit vlak is er juist sprake van marktkrimp. Het percentage goederentreinen ten opzichte van reizigerstreinen is relatief klein, maar goede achterlandverbindingen zijn en blijven cruciaal voor het (rail) goederenvervoer. Daarbij spelen internationale afstemming en kostenbeheersing een grote rol. Door gesynchroniseerde ERTMS-uitrol binnen Europa kan worden voorkomen dat goederenvervoerders continu geconfronteerd worden met verschillende ERTMS-versies, hardware-updates of aanpassingen per land, wat leidt tot hoge kosten en inefficiëntie.

In beide voorbeelden speelt het bredere idee van value for money een belangrijke rol: wat investeer je, en wat levert het op? Die vraag is volgens de geïnterviewde moeilijk te kwantificeren, omdat de impact zich vaak uitstrekt tot buiten de spoorsector zelf. Zo kan het wel of niet realiseren van ERTMS op een corridor ook effect hebben op bijvoorbeeld woningbouw, mobiliteit, en regionale werkgelegenheid.

Blokindeling

De geïnterviewde gaf aan geen specifieke toevoegingen te hebben met betrekking tot blokontwerpen. Wel benoemde hij dat met de komst van Hybrid Train Detection de relevantie van fysieke blokindelingen in de toekomst mogelijk volledig verdwijnt. Dit systeem maakt het namelijk mogelijk om de treinpositie op virtueel niveau te bepalen, waardoor vaste blokken overbodig kunnen worden.

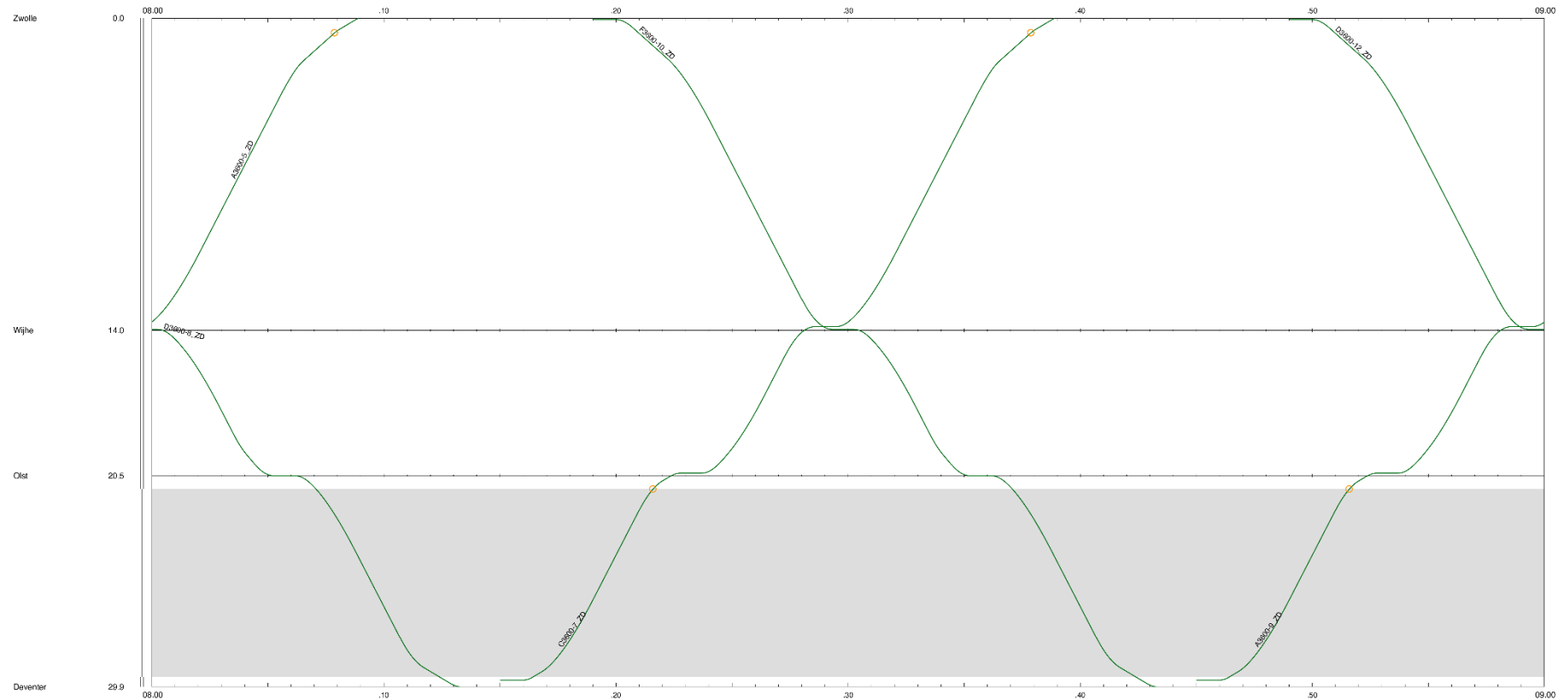
Verstoring

Hoewel de geïnterviewde niet precies kon aangeven welke verstoringen zich het meest zullen voordoen onder ERTMS, benoemde hij wel welke storingen relevant zijn voor het type onderzoek. Een belangrijk voorbeeld is het niet verlengen van de movement authority, waardoor een trein stilvalt. Daarnaast is het bij verstoringen zoals een defecte trein of een aanrijding van belang om na te denken over de mogelijke bijsturingsmogelijkheden. De mate waarin de infrastructuur en het systeem daarin flexibiliteit bieden, kan bepalend zijn voor het herstelproces.

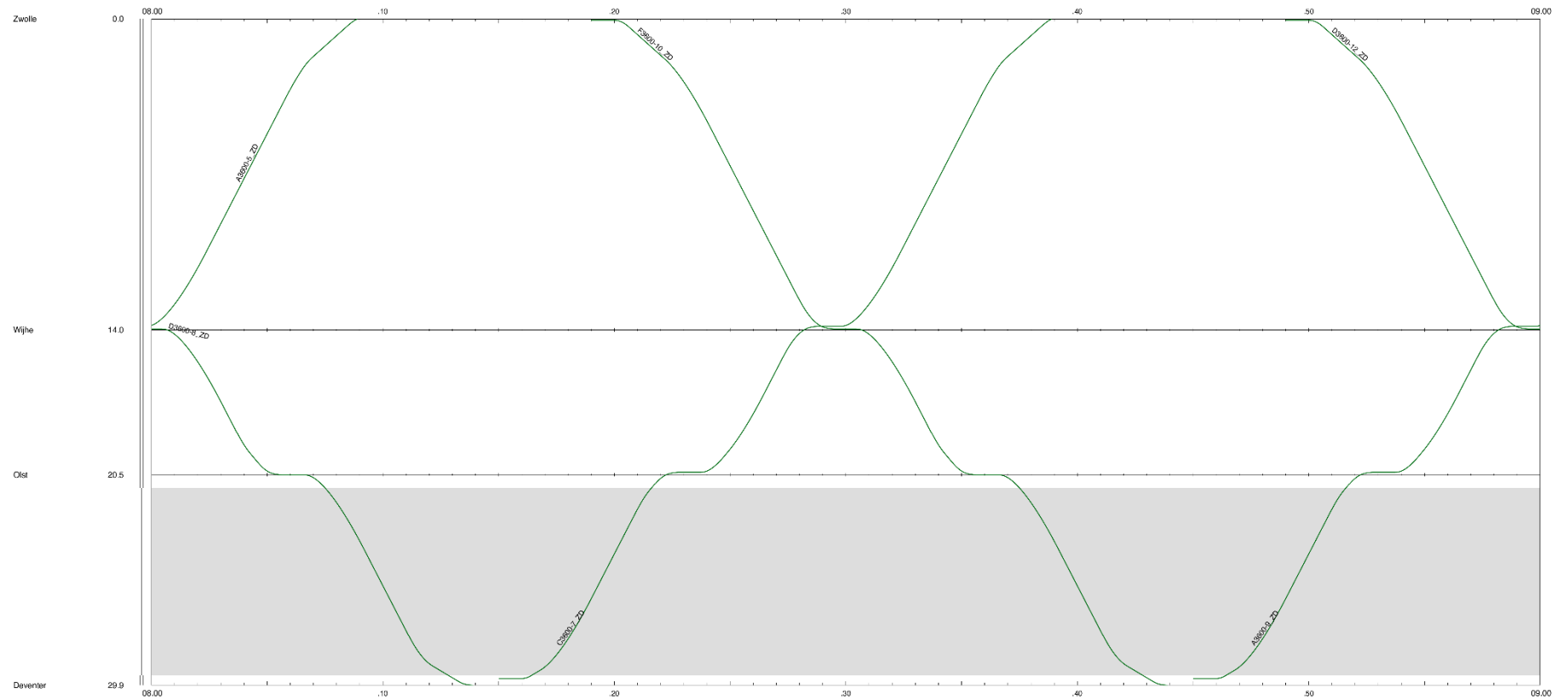
Appendix B: Time-distance diagrams

B.1. Zwolle – Deventer

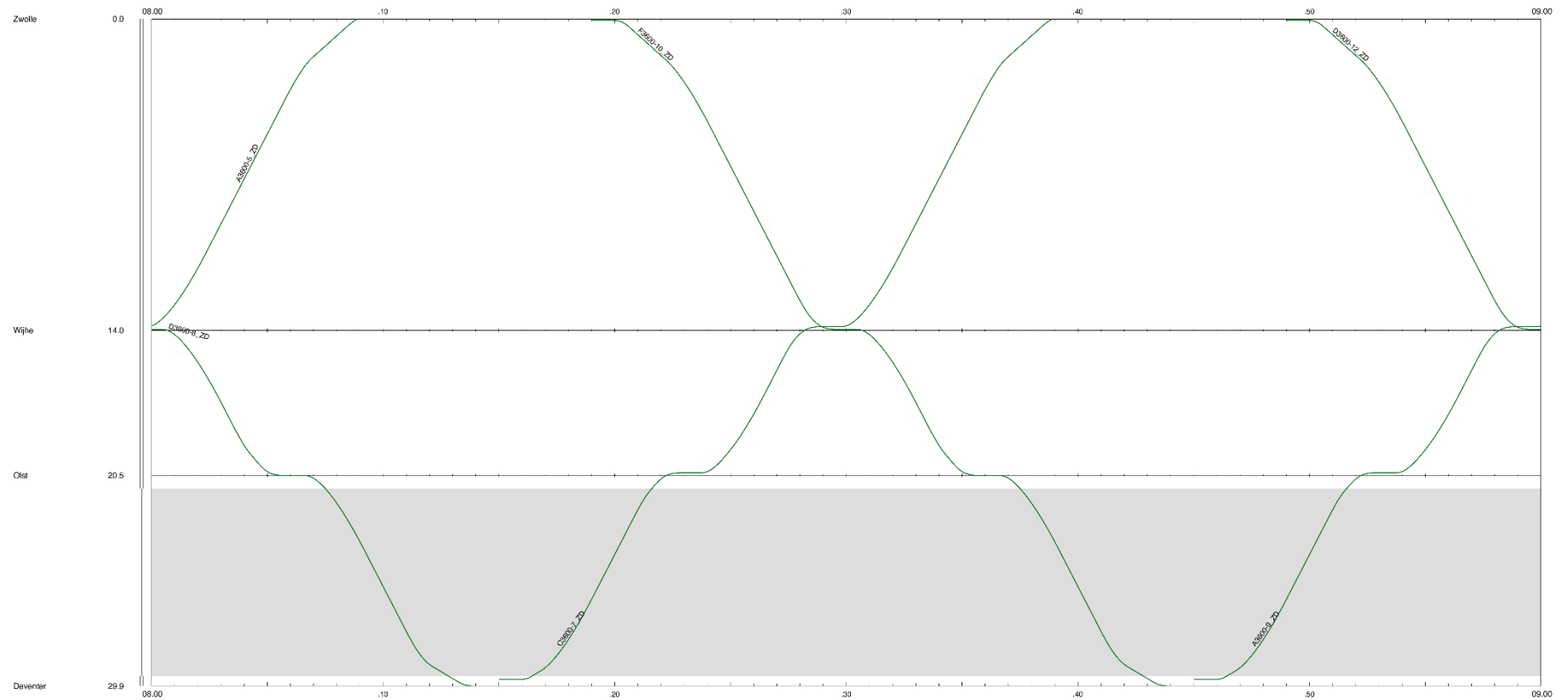
Zwolle - Deventer NS'54/ATB-EG I Current block section design



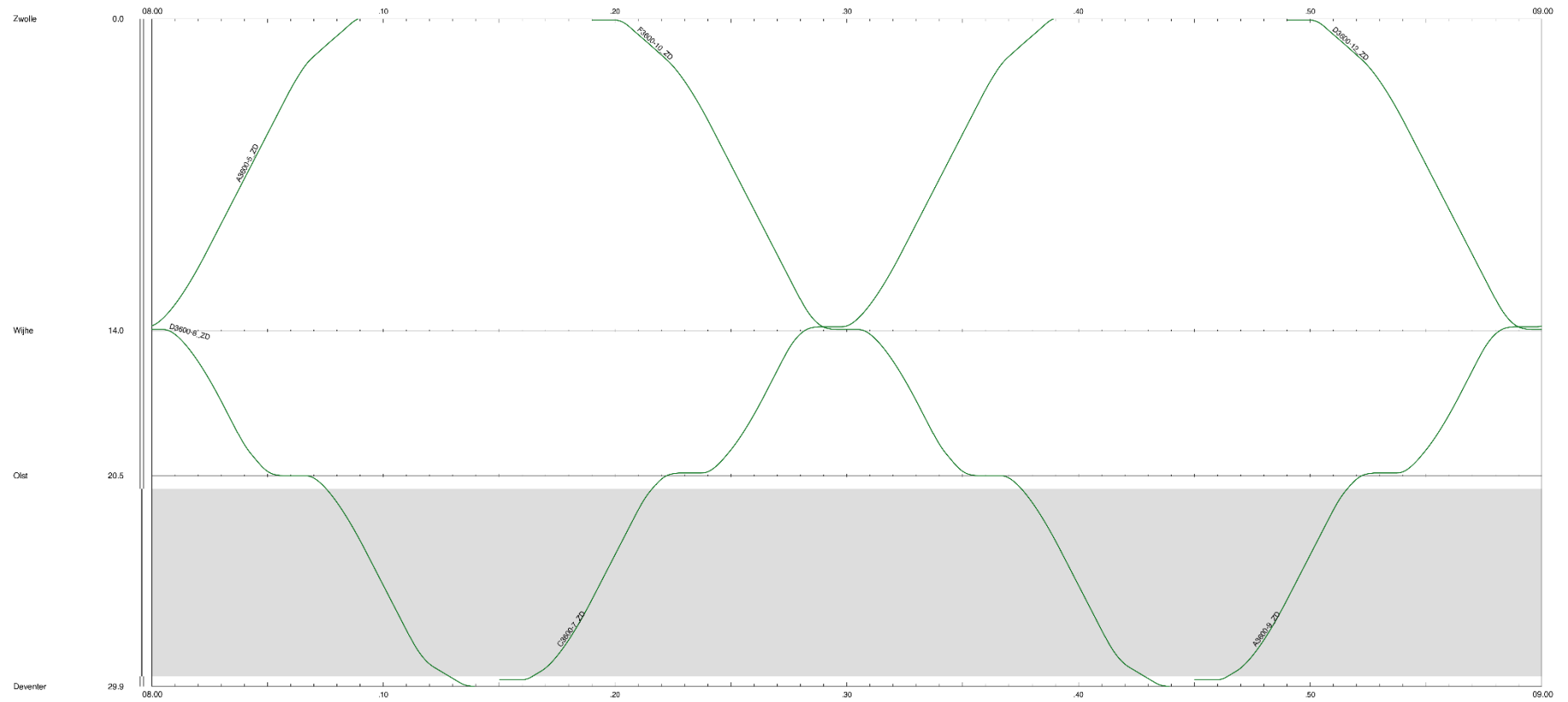
Zwolle - Deventer ERTMS/ETCS Level 2 I Current block section design



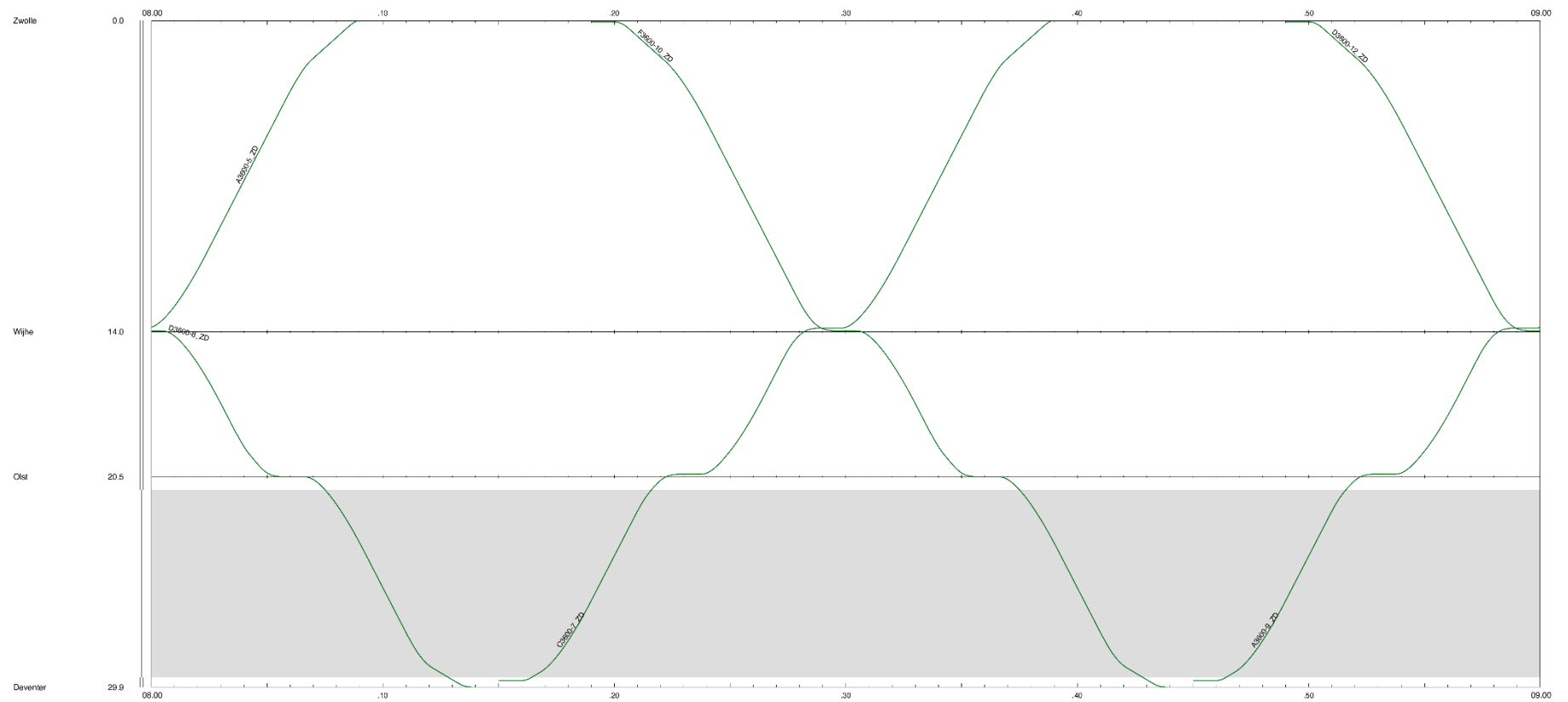
Zwolle - Deventer ERTMS/ETCS Level 2 I Minimum distance block section design



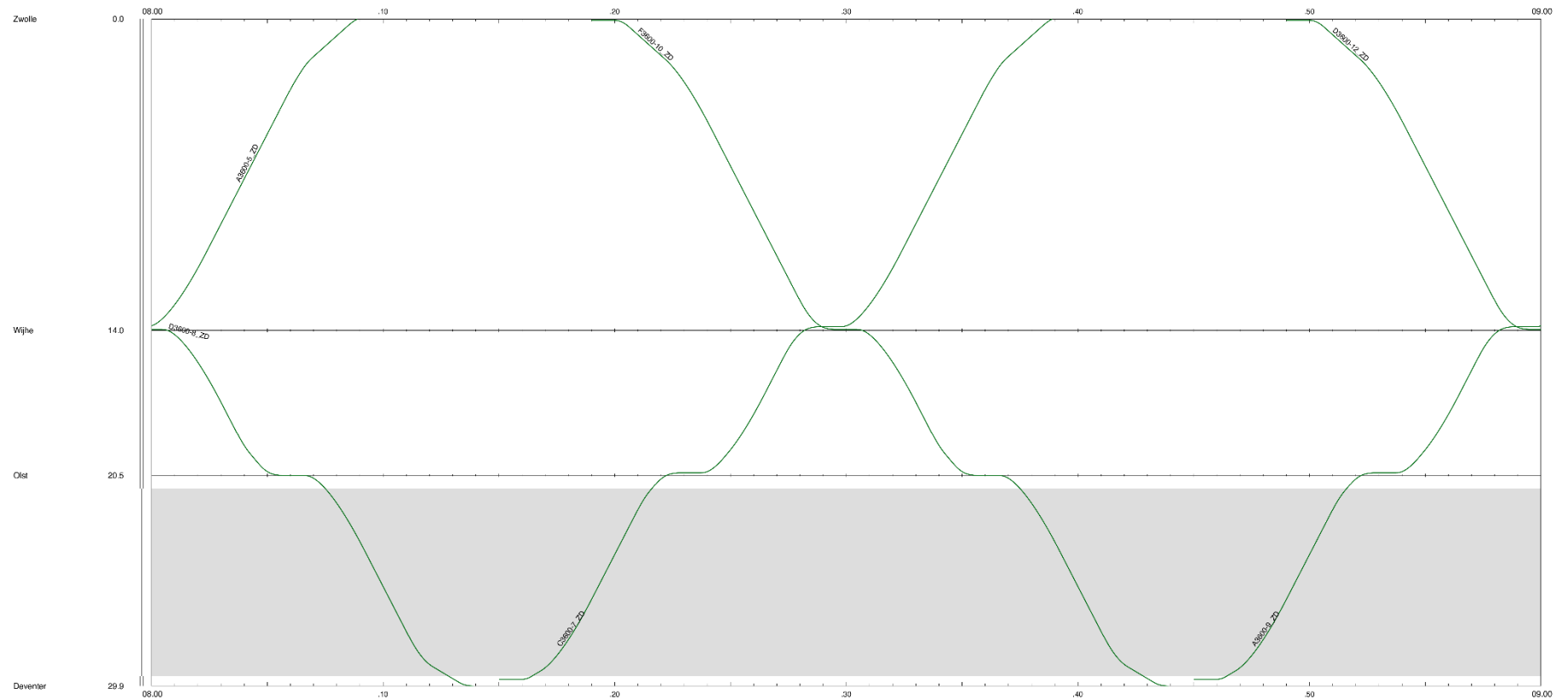
Zwolle - Deventer ERTMS/ETCS Level 2 | Cost-efficient minimum distance strategy



Zwolle - Deventer ERTMS/ETCS Level 2 I Harmonic

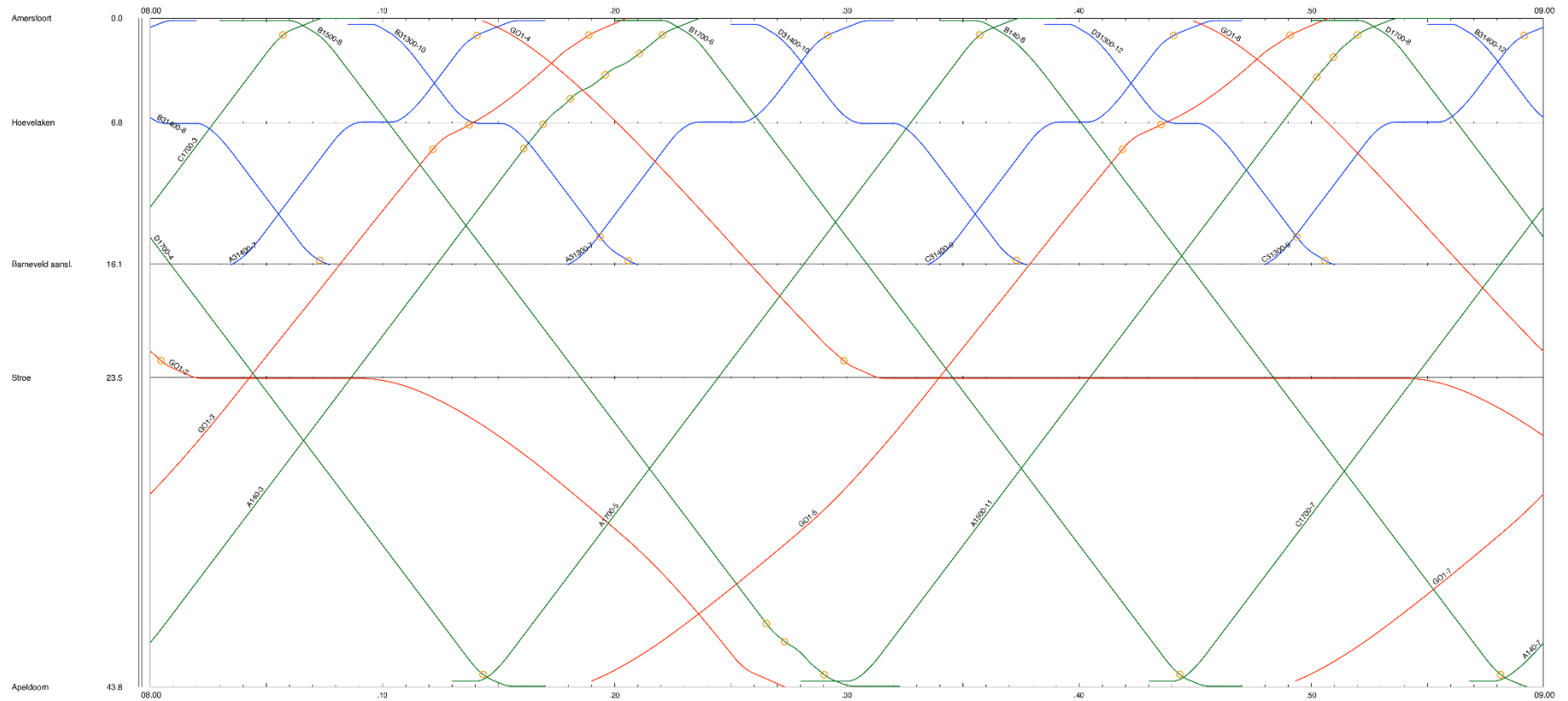


Zwolle - Deventer ERTMS/ETCS Level 2 I Design manual

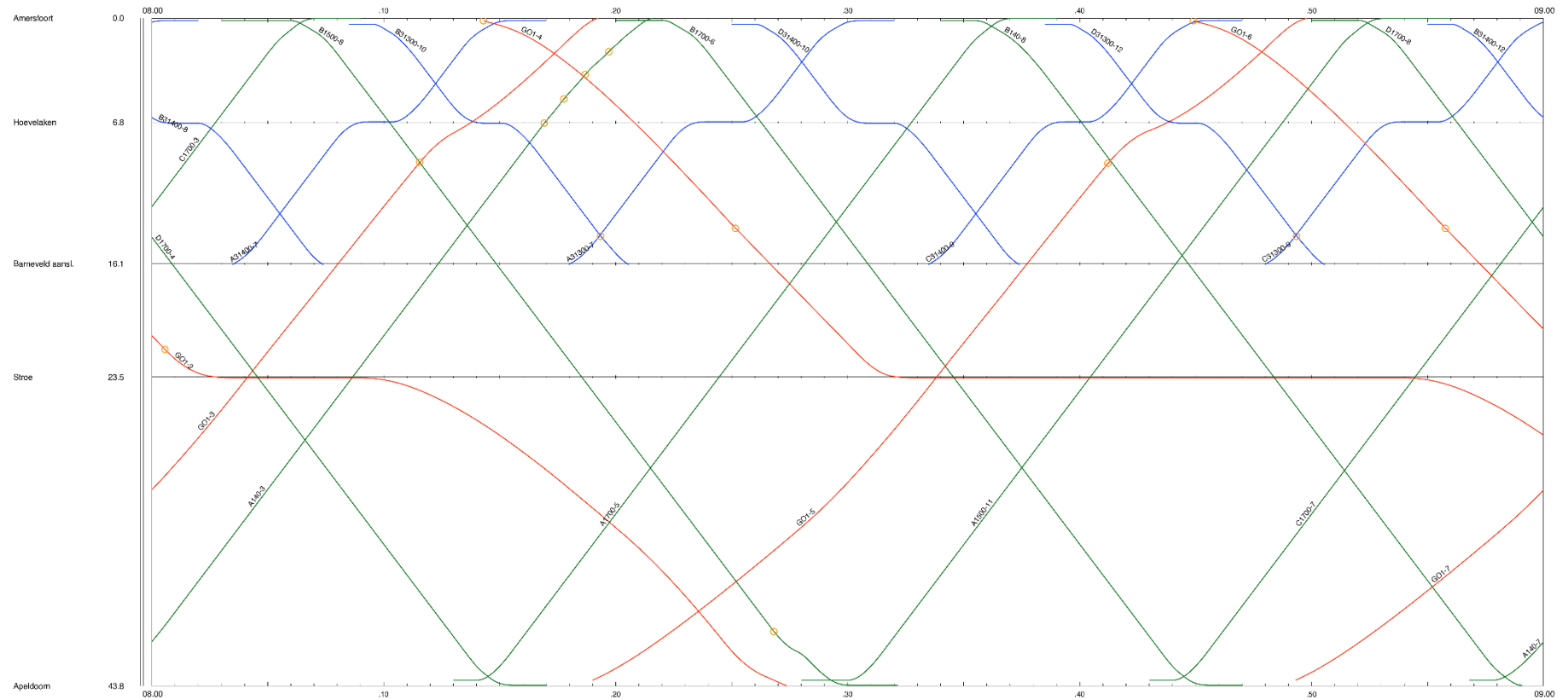


B.2. Amersfoort Centraal – Apeldoorn

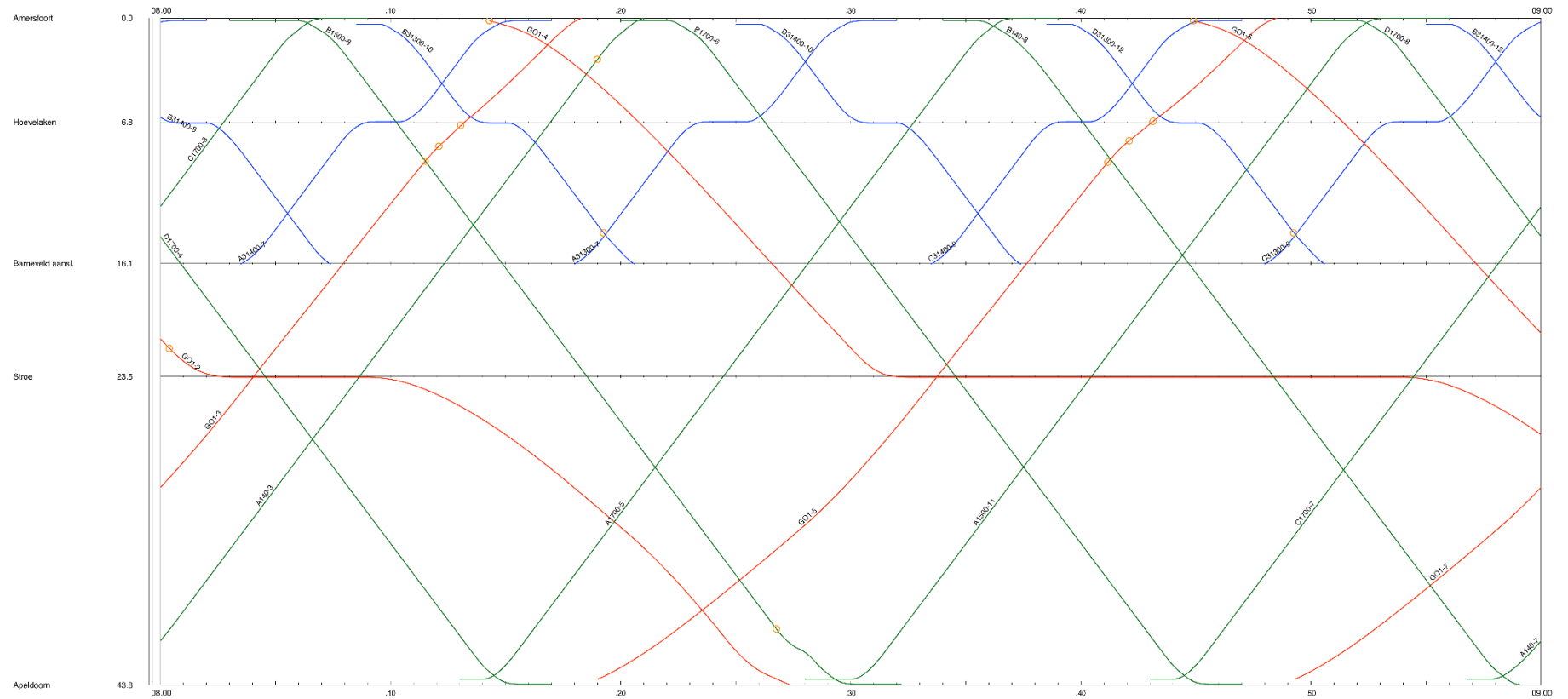
Amersfoort Centraal - Apeldoorn NS'54/ATB-EG I Current block section design



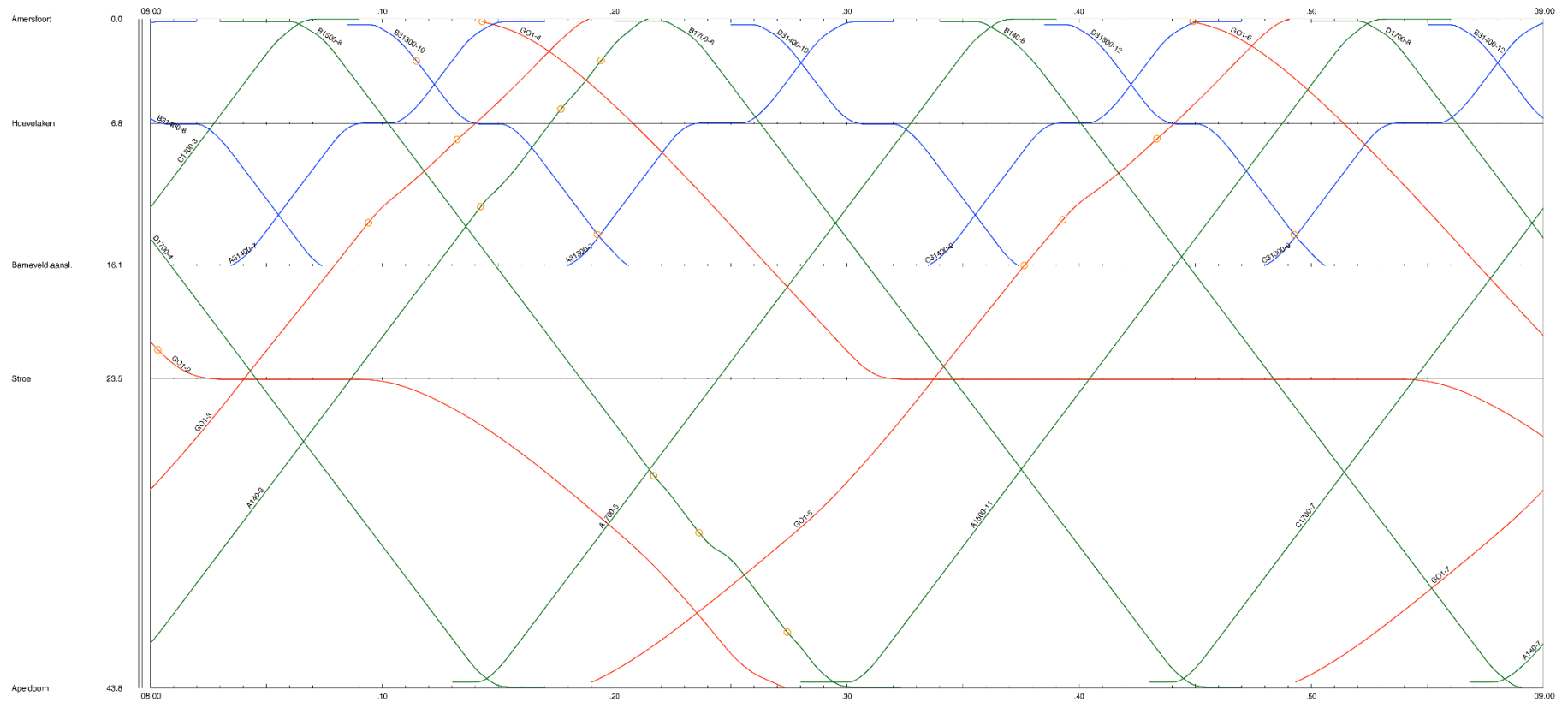
Amersfoort Centraal - Apeldoorn ERTMS/ETCS Level 2 I Current block section design



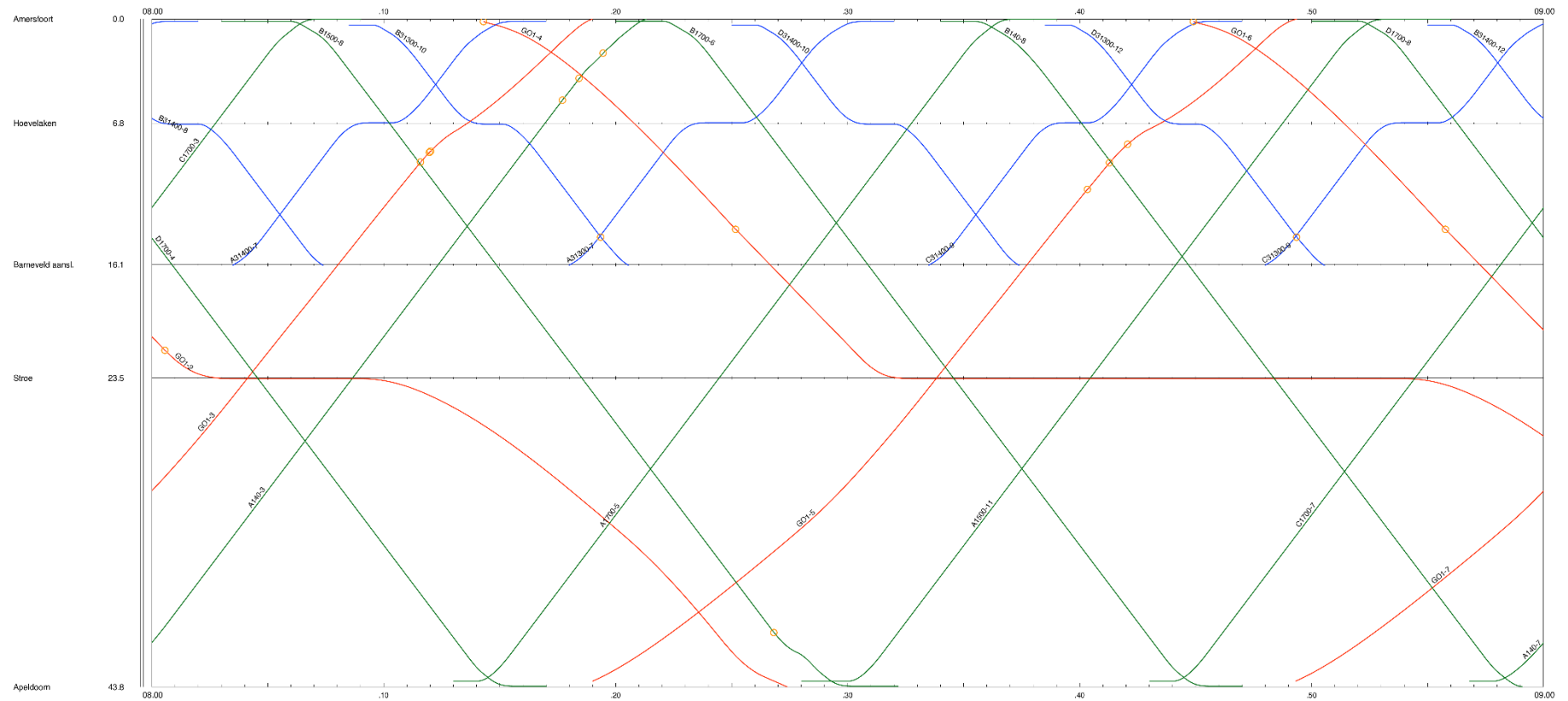
Amersfoort Centraal - Apeldoorn ERTMS/ETCS Level 2 | Minimum distance block section design



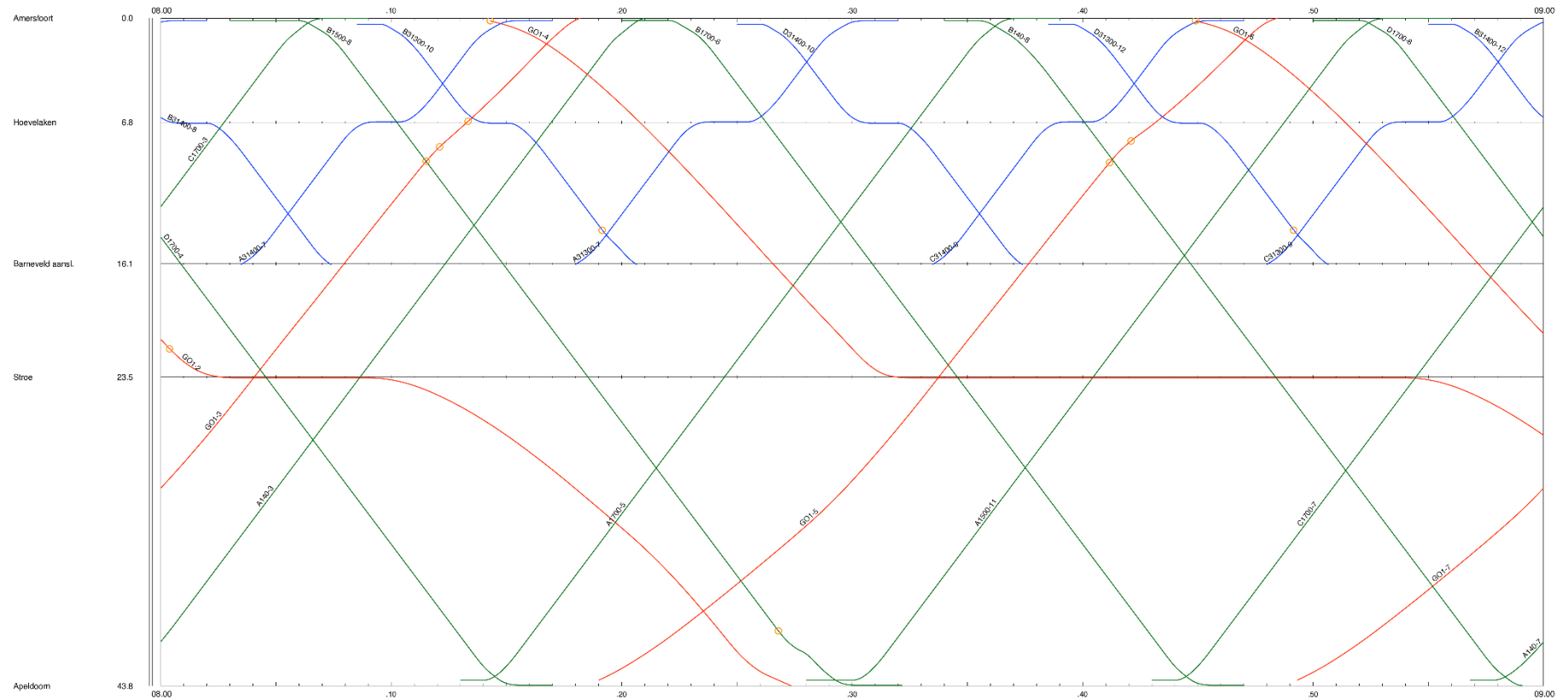
Amersfoort Centraal - Apeldoorn ERTMS/ETCS Level 2 | Cost-efficient minimum distance strategy



Amersfoort Centraal - Apeldoorn ERTMS/ETCS Level 2 I Harmonic

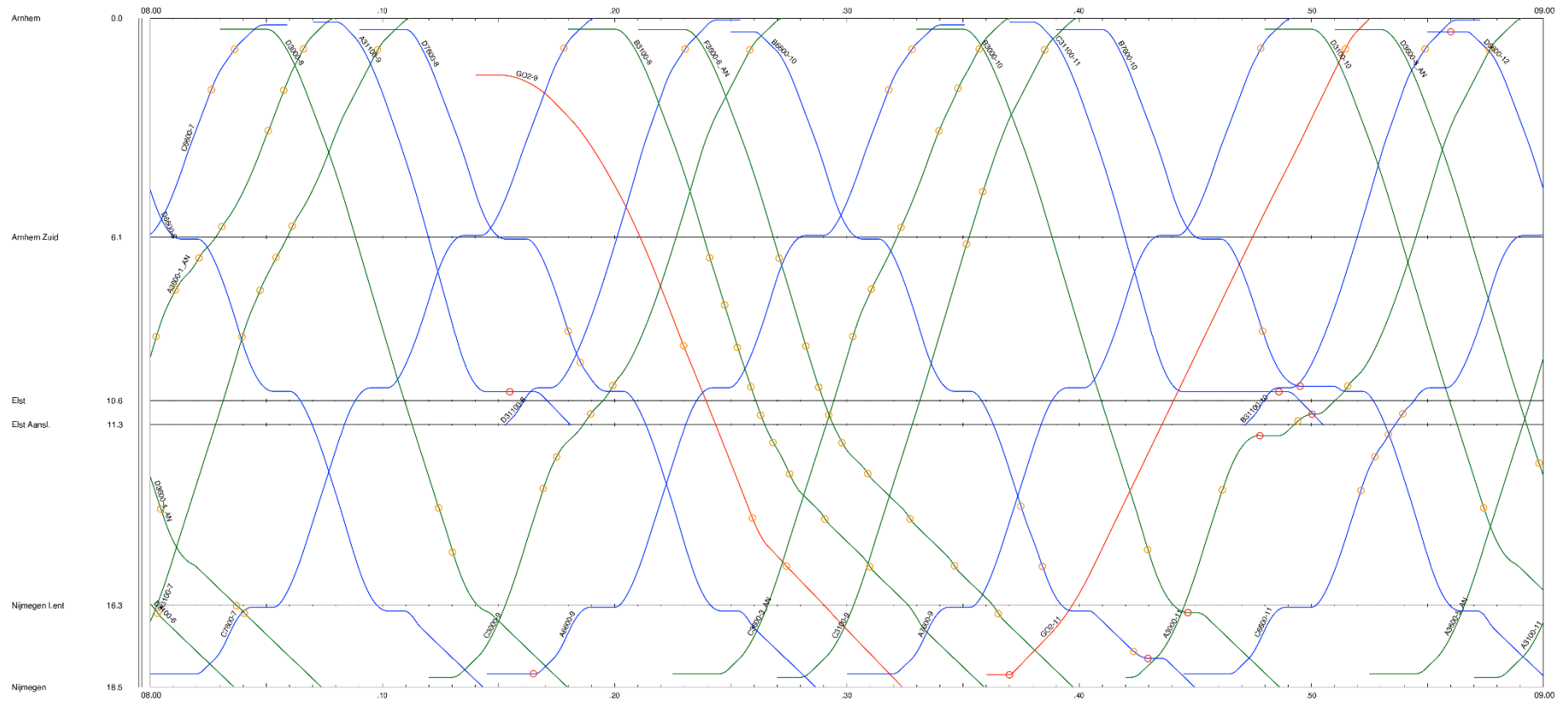


Amersfoort Centraal - Apeldoorn ERTMS/ETCS Level 2 I Design manual

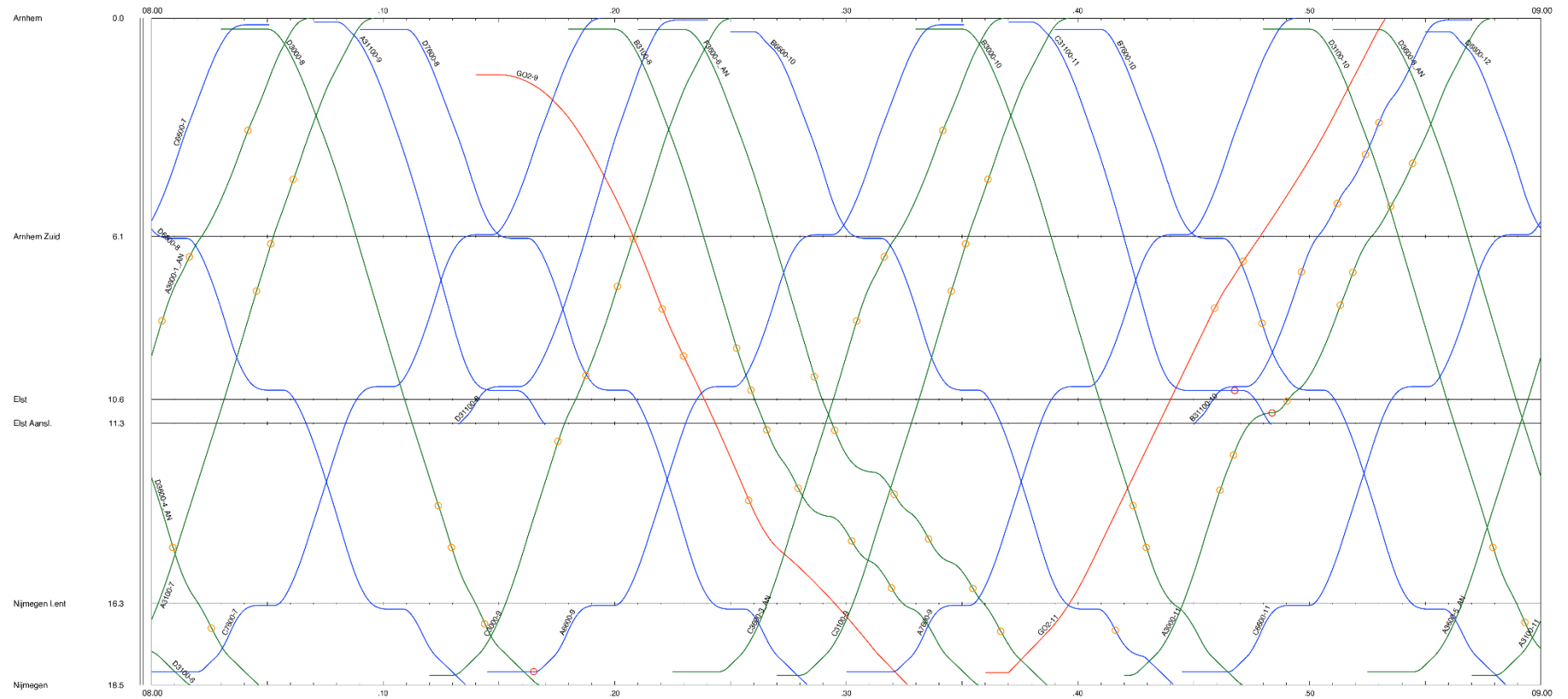


B.3. Arnhem Centraal – Nijmegen

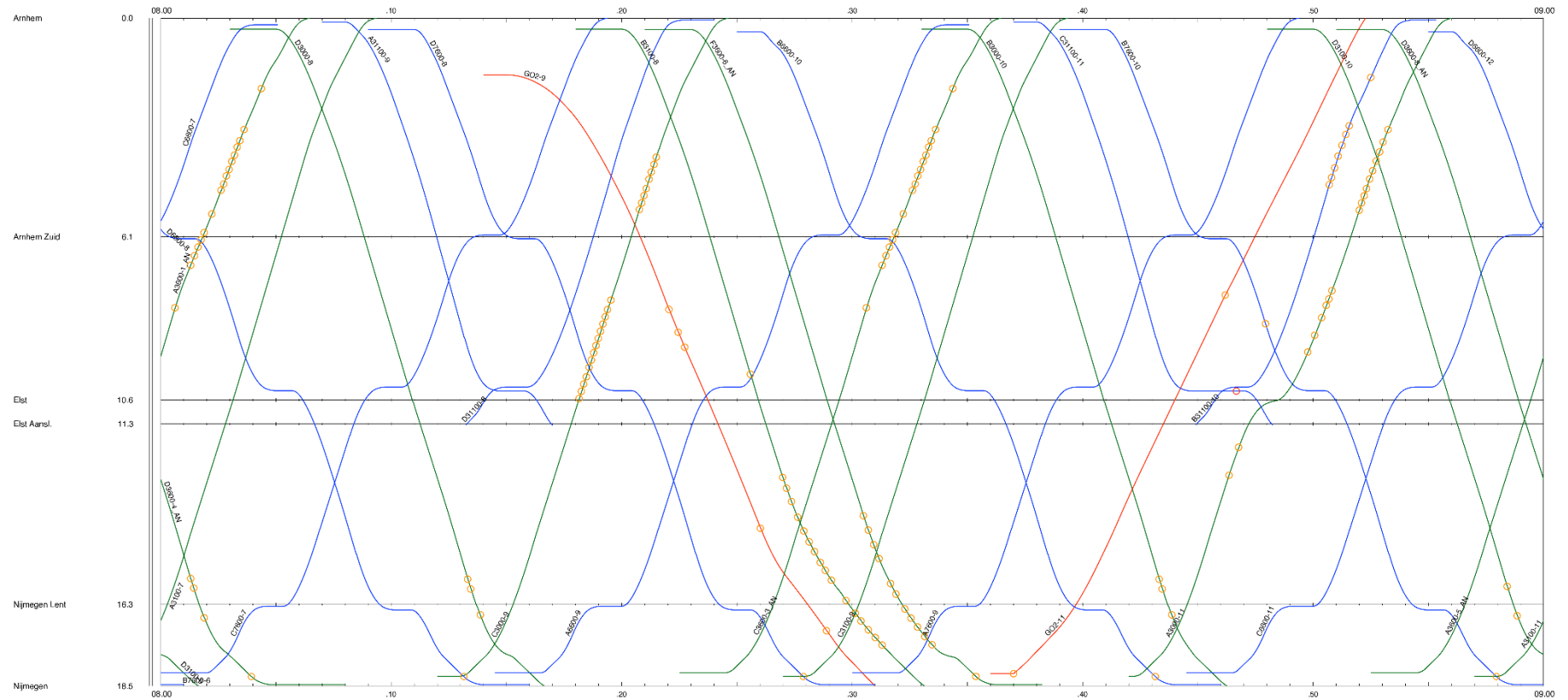
Arnhem Centraal - Nijmegen NS'54/ATB-EG | Current block section design



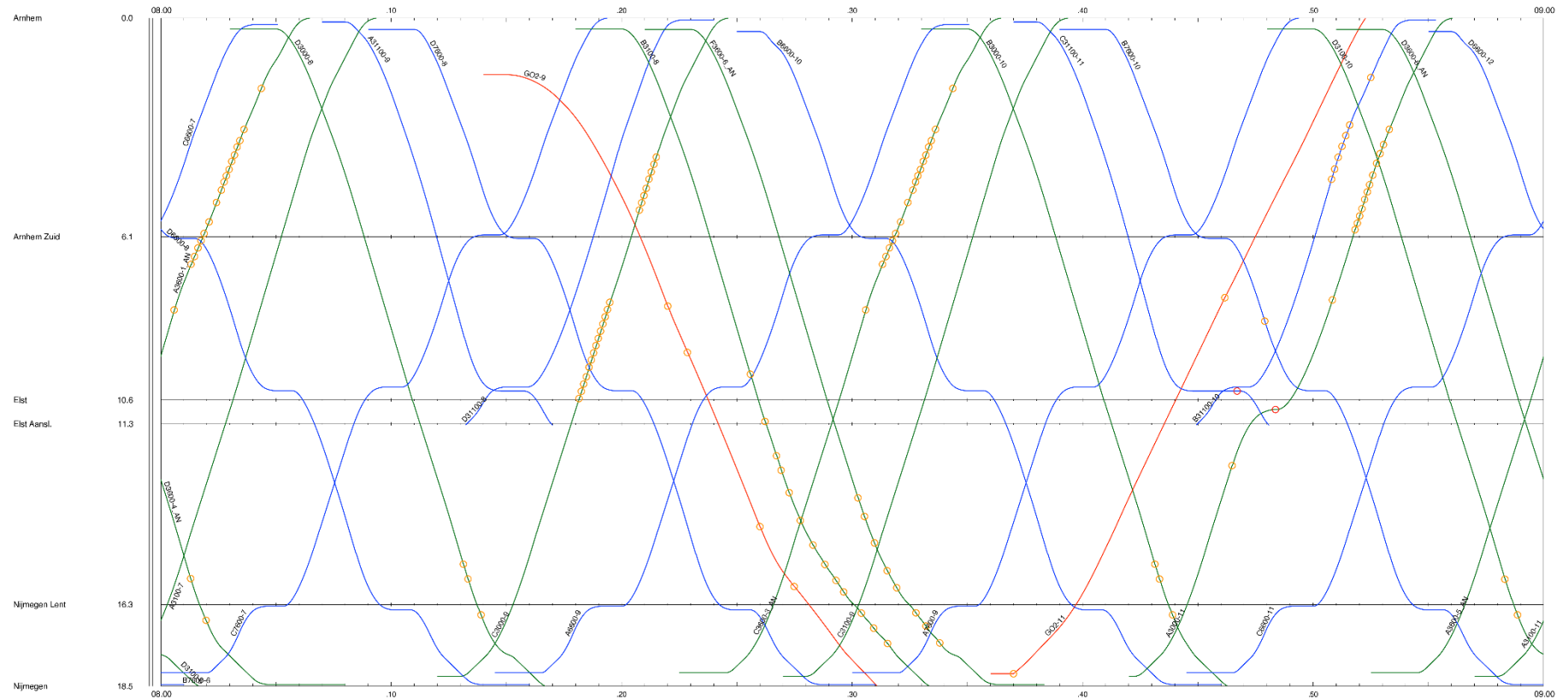
Arnhem Centraal - Nijmegen ERTMS/ETCS Level 2 | Current block section design



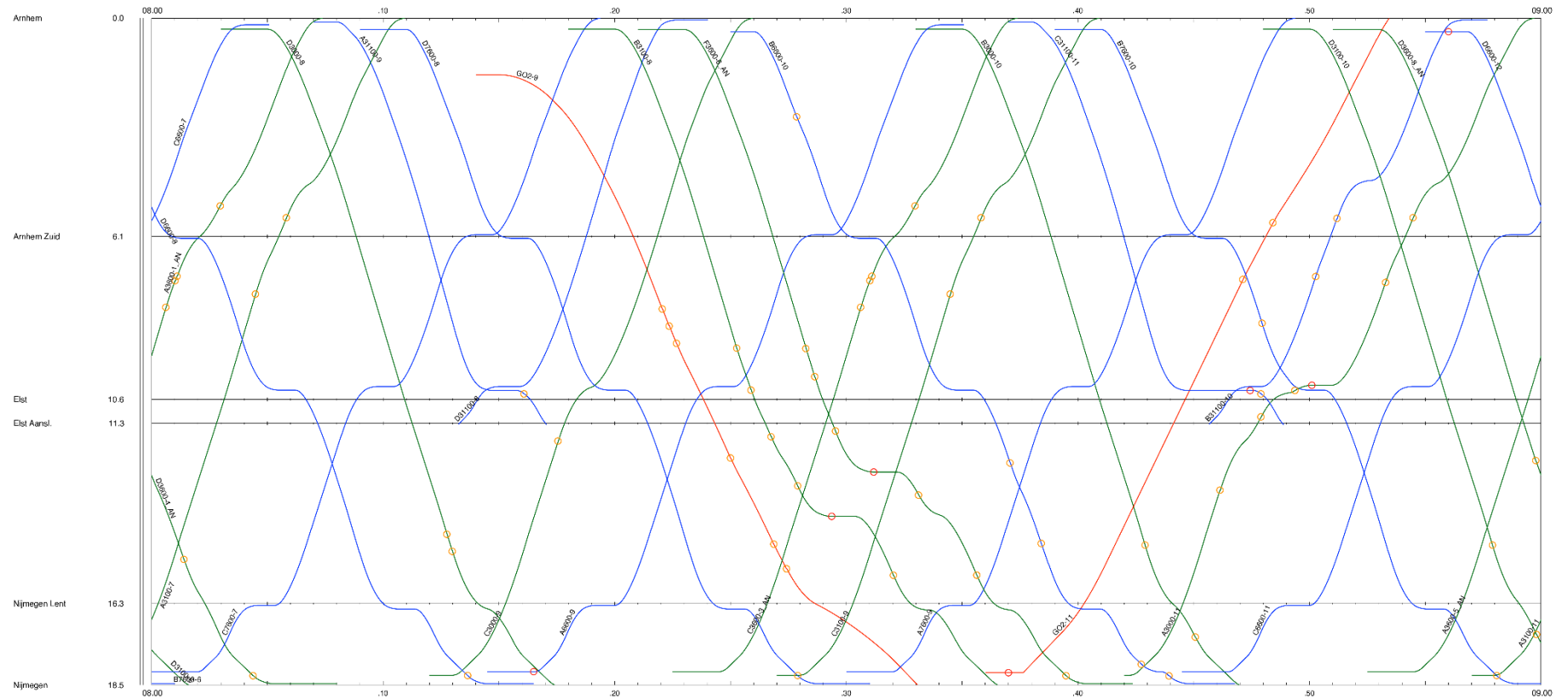
Arnhem Centraal - Nijmegen ERTMS/ETCS Level 2 | Minimum distance block section design



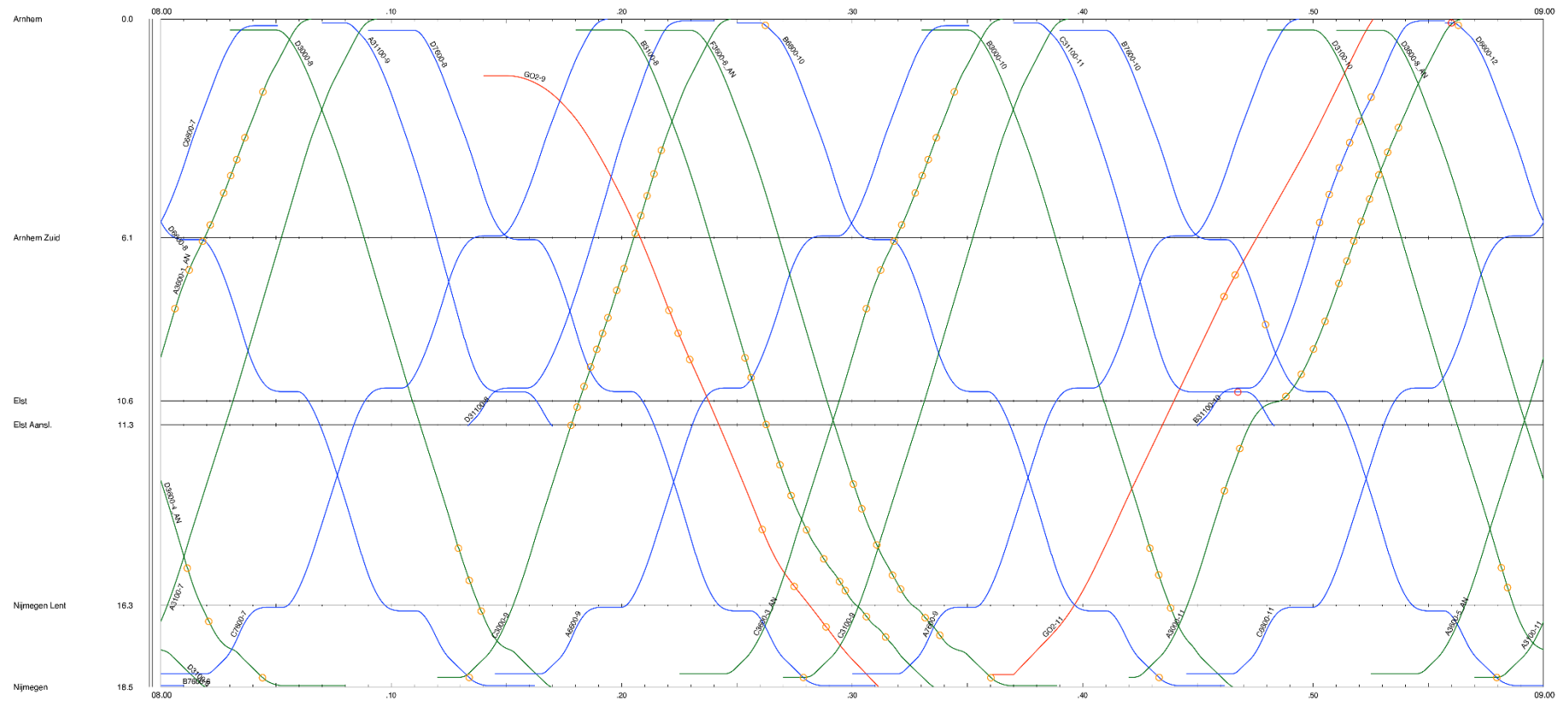
Arnhem Centraal - Nijmegen ERTMS/ETCS Level 2 | Cost-efficient minimum distance strategy



Arnhem Centraal - Nijmegen ERTMS/ETCS Level 2 I Harmonic



Arnhem Centraal - Nijmegen ERTMS/ETCS Level 2 I Design manual



Appendix C: Results non-disruptive conditions

C.1. Travel time – total mean travel time per strategy

The time-route diagrams show that hindrance occurs in this study area in the NS'54/ATB-EG situation (see Appendix B.3. Arnhem Centraal – Nijmegen). With any ETCS strategy, this hindrance is reduced. Especially the ETCS minimum distance, cost and design manual strategies perform well here. In contrast, the harmonica strategy shows the smallest improvement, which can be explained by the design approach where only two equal trains were simulated at the same time. As a result, mixed combinations such as freight train followed by an intercity train was simulated as possible combination in order to determine the design.

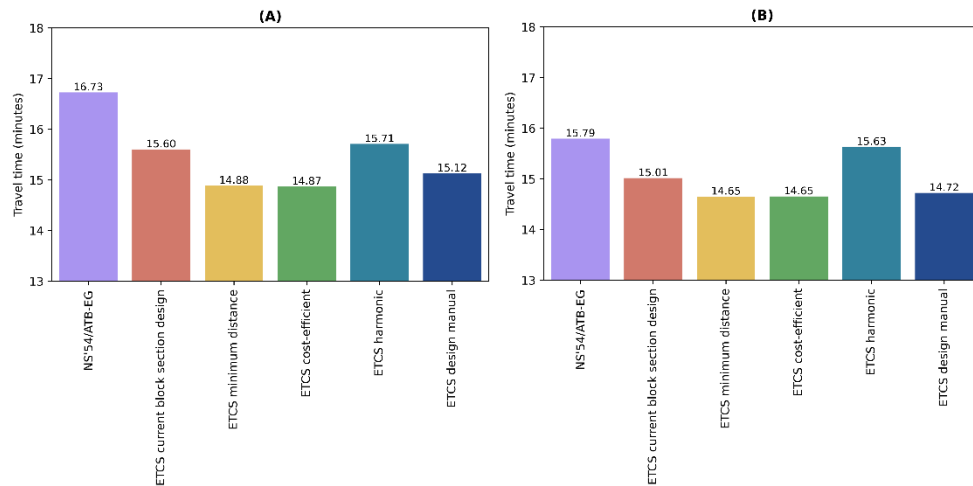


Figure 31: Mean travel time per strategy (8:00-9:00) (A) Arnhem Centraal – Nijmegen (B) Nijmegen – Arnhem Centraal

C.2. Travel time – mean travel time per strategy and train type

The results of the mean travel time per strategy and train type for the Zwolle – Deventer study area can be seen in Figure 32. As this figure shows, the results are the same as for Figure 16 as only one type of train operates here.

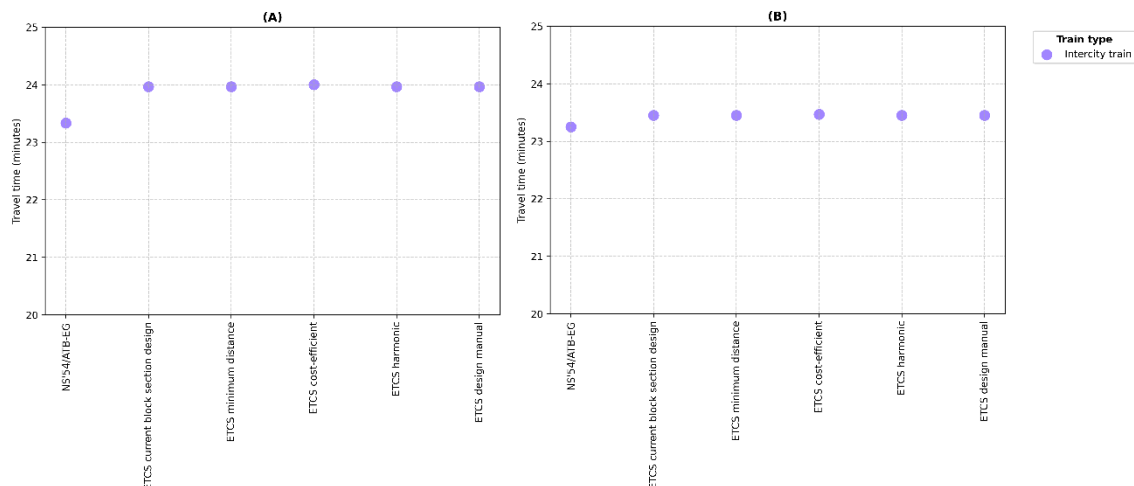


Figure 32: Mean travel time per strategy and train type (8:00-9:00) (A) Zwolle – Deventer (B) Deventer – Zwolle

For Amersfoort Centraal – Apeldoorn corridor, the differences in travel time between the NS'54/ATB-EG and the various ETCS strategies are minimal, as seen in Figure 33. No specific combination of train type and block section design strategy show a clear performance benefit

from implementing ERTMS/ETCS Level 2 on this route. This observation aligns with the overall average travel time results shown in Figure 17A.

In contrast, the reverse direction exhibits more variation across strategies and train types. Train experience more operational hindrances in that direction, which creates more potential for improvement to the baseline scenario. This pattern was also identified from Figure 17B.

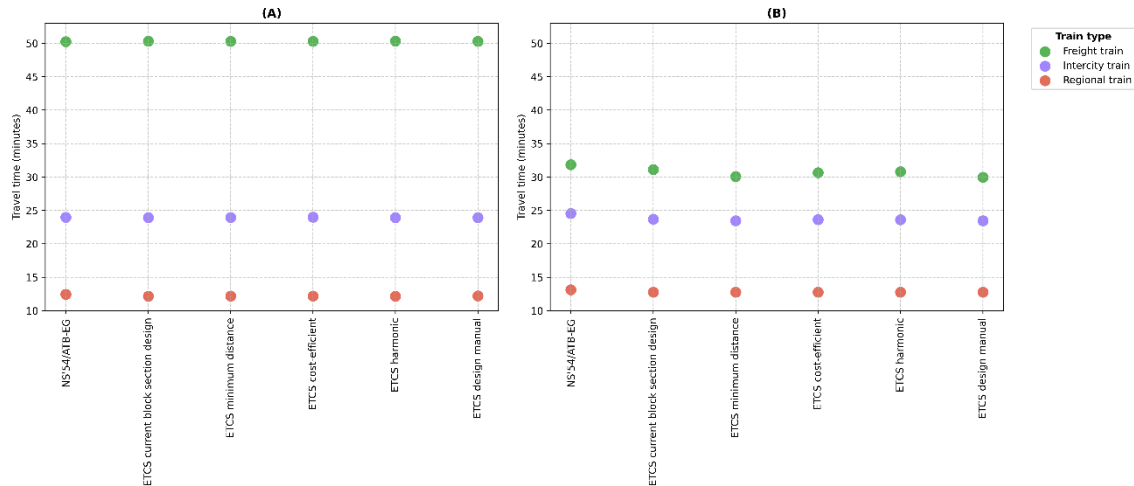


Figure 33: Mean travel time per strategy and train type (8:00-9:00) (A) Amersfoort Centraal – Apeldoorn (B) Apeldoorn – Amersfoort Centraal

C.3. Travel time deviation compared to NS'54/ATB-EG

The deviation in travel time per strategy compared to NS'54/ATB-EG for Zwolle – Deventer and vice versa can be seen in Figure 34. This figure shows the same trend as the average travel time (per train type): the Zwolle – Deventer section has a noticeably larger increase in travel time than the Deventer – Zwolle section. This result confirms the previously mentioned braking curve effect and shows that the impact of ERTMS/ETCS Level 2 is not equal in both directions. Although the differences per strategy are minimal, they are structural: all ETCS strategies lead to an increase in travel time compared to the NS'54/ATB-EG situation.

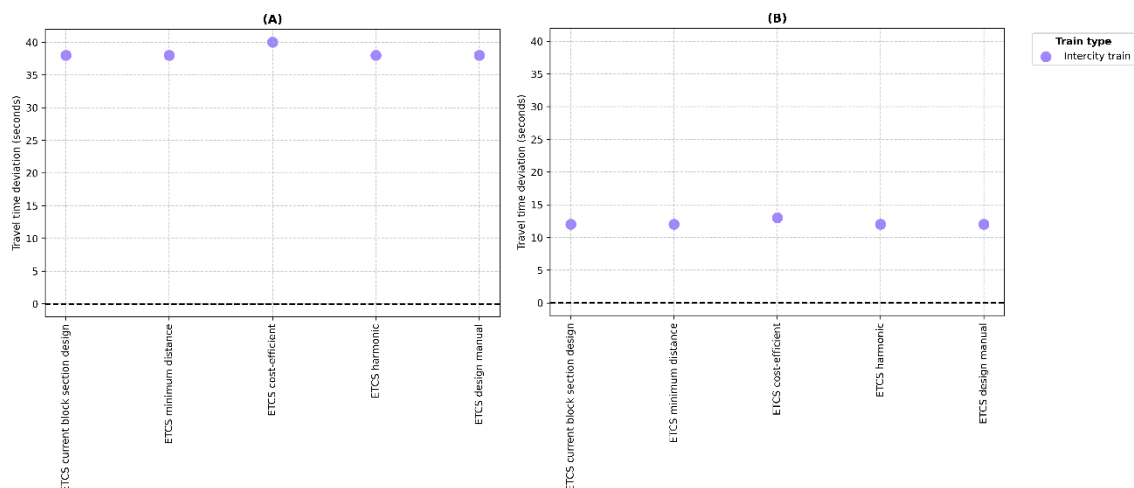


Figure 34: Travel time deviation (8:00-9:00) (A) Zwolle – Deventer (B) Deventer – Zwolle

The results of the travel time deviation for both directions between Arnhem Centraal and Nijmegen are shown in Figure 35. Notably, the freight train shows quite some fluctuations under the ETCS current block section design and harmonic strategies for both directions. This variation is primarily caused by earlier braking compared to the other strategies, which in turn is influenced by the behaviour of the preceding train and the used block lengths. These effects also impact the

regional and intercity trains running directly behind the freight train, resulting in reduced travel time improvements for these trains as well.

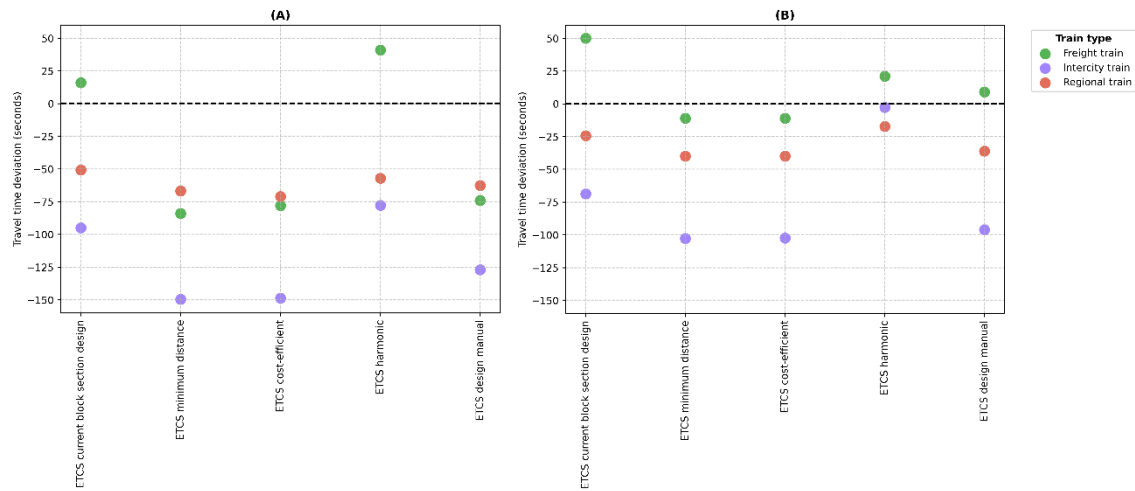


Figure 35: Travel time deviation (8:00-9:00) (A) Arnhem Centraal – Nijmegen (B) Nijmegen – Arnhem Centraal

Appendix D: Results disruptive conditions – train failure

D.1. Resilience – recovery period

As shown in Table 15, the ETCS minimum distance and design manual strategies achieve the shortest recovery periods. The recovery times of these strategies are about 33 and 25 minutes at a recovery threshold of 3 or 5 minutes, respectively.

In contrast, NS'54/ATB-EG, ETCS current block section design, and particularly the ETCS cost-efficient strategy show longer recovery times. NS'54/ATB-EG and ETCS current block section design show similar results, and take about 43 minutes to recover with a 3-minute threshold, and about 34-36 minutes with a 5-minute threshold. The ETCS cost-efficient strategy show the longest recovery time for the 5-minute threshold, with around 49 minutes. This is due to the longer block sections that were used in this strategy.

Table 15: Recovery period for the train failure of Apeldoorn – Amersfoort Centraal

Strategy Recovery threshold	NS'54/ ATB-EG	ETCS – current block section design	ETCS – minimum distance	ETCS – cost- efficient	ETCS – harmonic	ETCS – design manual
3 min	00:43:21 (100%)	00:43:07 (-0.54%)	00:33:21 (-23.07%)	00:48:53 (+12.76%)	00:34:26 (-20.57%)	00:33:21 (-23.07%)
5 min	00:35:53 (100%)	00:34:24 (-4.13%)	00:25:36 (-28.66%)	00:35:19 (-1.58%)	00:31:24 (-12.49%)	00:25:01 (-30.28%)

D.2. Weighted Travel Time Extension (WTTE)

The results for the Weighted Travel Time Extension largely align with the previously discussed resilience results. Since the same trains operate on this route, the seat capacity remains consistent across all strategies with the WTTE calculation. On the Deventer – Zwolle section, the ETCS minimum distance strategy not only achieves the shortest recovery period but also records the lowest WTTE score (171.28%) (see Figure 36).

While the differences in WTTE scores between most strategies are relatively small, the ETCS cost-efficient strategy stands out. It shows the highest WTTE (177.66%) and also one of the slower recovery and disruption times. This suggests that under this strategy, trains are affected by the disruption for a longer period, leading to greater overall delay in travel time.

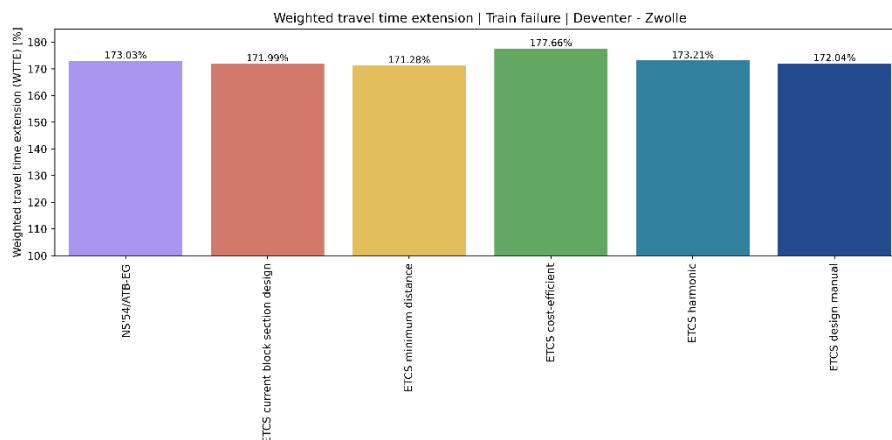


Figure 36: WTTE values of train failure | Deventer – Zwolle

On the Zwolle – Deventer section, where the impact of the disruption is more indirect (since the blockage occurs in the opposite direction), the WTTE values are generally lower, and the results

between strategies is smaller, as can be seen in Figure 37. Still, the ETCS minimum distance strategy once again performs best, with the lowest WTTE score (146.04%), consistent with its shorter recovery time in this direction as well.

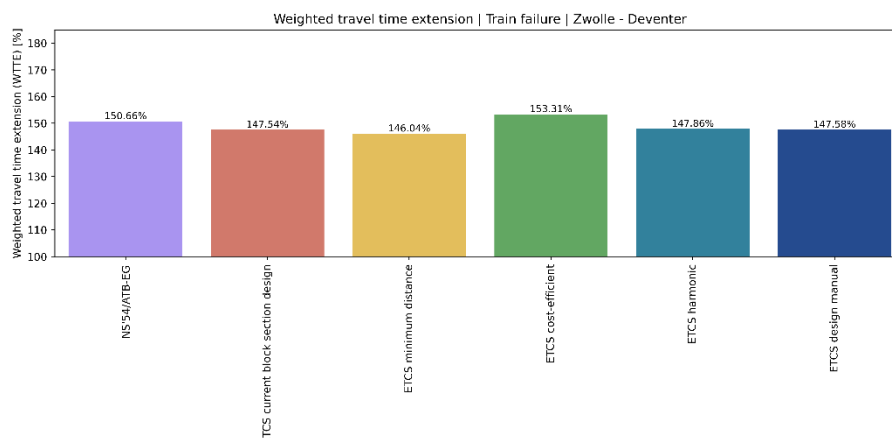


Figure 37: WTTE values of train failure | Zwolle – Deventer

The WTTE results in Figure 38 fit the above resilience pattern. The ETCS minimum distance and cost-efficient strategies show the lowest WTTE values. NS'54/ATB-EG shows the highest WTTE, which is in line with the relatively long recovery and disruption time. The other ETCS strategies score around 110-111%, outperforming NS'54, but showing little variation among themselves. The ETCS cost-efficient still includes a lot of blocks in this study area, just as the ETCS minimum distance strategy. The reason it performs slightly better here is due to a small difference in travel time near Nijmegen between the two strategies. However, since this difference is less than 10 seconds, it is considered marginal.

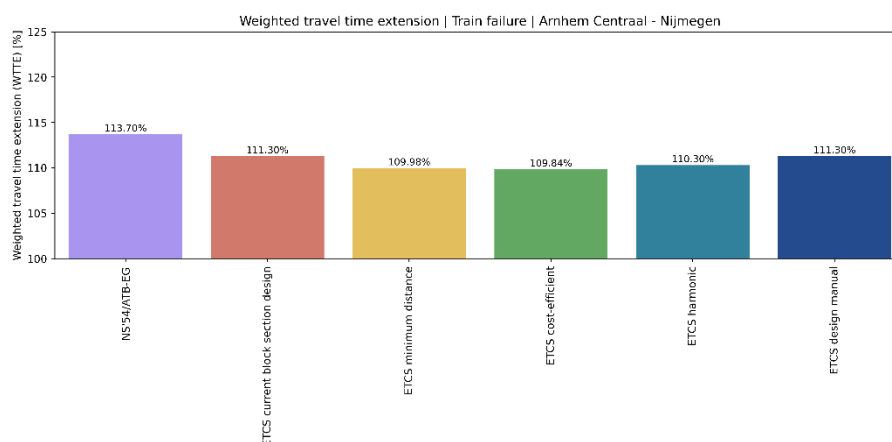


Figure 38: WTTE values of train failure | Arnhem Centraal – Nijmegen

Appendix E: Results disruptive conditions – communication failure with SMBs

E.1. Resilience – recovery period

The recovery times shown in Table 16 indicate that the strategies NS'54/ATB-EG, ETCS current block section design, ETCS minimum distance, and ETCS design manual all perform comparably. All with recovery periods just under 30 minutes. Of these, NS'54/ATB-EG shows a slightly longer recovery time than the three strategies mentioned.

This difference can be explained by braking behaviour near the disruption location. In the NS'54/ATB-EG situation, the approaching train reaches the disruptive location slightly earlier than the ERTMS/ETCS Level 2 trains. However, ERTMS/ETCS Level 2 trains brake more gradually over the final stretch, resulting in a slightly later arrival at the same location when running without hindrance. Despite these timing differences, the first train to pass the disruption location according to the timetable is the same across all four strategies, as these trains do not have to brake yet on this part of the route. Since the train in the NS'54/ATB-EG situation arrives slightly earlier and the trains resume normal operations at the same time, its disruption period is slightly longer. This explains why the recovery times of these strategies are almost identical, with NS'54/ATB-EG recovering just marginally slower.

In contrast, the strategies ETCS cost-efficient and ETCS harmonic show much longer recovery periods (over 50 minutes). This deviation is due to an operational bottleneck at the station of Zwolle. The train affected by the communication failure arrives in Zwolle at the same time as another train is scheduled to depart towards Deventer. Because both trains use the same platform and short single-track section, a conflict arises, causing delays to both services. As a result, it takes longer for the system to return to normal operation with these strategies. This does not happen in the other situations. In these situations, the delayed train arrives later in Zwolle, which means that the train from Zwolle to Deventer has already left.

Table 16: Recovery period for the communication failure with SMBs of Deventer – Zwolle

Strategy Recovery threshold	NS'54/ ATB-EG	ETCS – current block section design	ETCS – minimum distance	ETCS – cost- efficient	ETCS – harmonic	ETCS – design manual
3 & 5 min	00:29:24 (100%)	00:29:09 (-0.85%)	00:29:09 (-0.85%)	00:51:24 (+74.83%)	00:52:40 (+79.14%)	00:29:09 (-0.85%)

Table 17 presents the recovery period for a communication failure involving SMBs on the Apeldoorn – Amersfoort Centraal route. The data shows that NS'54/ATB-EG, ETCS current block section design, and ETCS harmonic achieve the shortest recovery times, each under 14 minutes. This indicates that these strategies are able to return to normal operations relatively quickly after the failure is resolved.

The ETCS cost-efficient strategy performs moderately, with a slightly longer recovery time of around 15 or 19 minutes, depending on the recovery threshold. This can be explained by the fact that longer block sections are used in this strategy. As a result, the headway between trains is increased and therefore less flexibility to resolve the disruption.

The ETCS minimum distance and design manual show longer recovery times. The reason for these larger recovery periods is because of the operational response to the communication failure. With these strategies, the train must stop before each SMB and request a new movement

authority from the dispatcher (European Instruction). This is quite time consuming and creates hindrance for other trains.

Table 17: Recovery period for the communication failure with SMBs of Apeldoorn – Amersfoort Centraal

Strategy Recovery threshold	NS'54/ ATB-EG	ETCS – current block section design	ETCS – minimum distance	ETCS – cost- efficient	ETCS – harmonic	ETCS – design manual
3 min	00:13:22 (100%)	00:13:08 (-1.75%)	00:52:41 (+294.14%)	00:19:29 (+45.76%)	00:13:07 (-1.87%)	00:33:32 (+150.87%)
5 min	00:13:22 (100%)	00:13:08 (-1.75%)	00:48:56 (+266.08%)	00:15:01 (+12.34%)	00:13:07 (-1.87%)	00:33:32 (+150.87%)

E.2. Weighted Travel Time Extension (WTTE)

Figure 39 presents the WTTE for the communication failure scenario with SMBs of the Deventer – Zwolle route. The lowest WTTE values are observed for NS'54/ATB-EG (106.92%) and ETCS current block section design (107.52%), which is in line with their relatively short recovery and disruption periods. The ETCS cost-efficient (111.09%) and ETCS harmonic (110.89%) strategies, despite showing longer disruption periods, do not perform poorly on WTTE. This can be explained by the nature of their delay pattern: these strategies cause relatively minor delays for multiple trains, rather than large delays for a few. Since the delay factor used in WTTE penalises longer delays more heavily, these smaller delays per train contribute less to the overall WTTE score.

In contrast, ETCS minimum distance (123.73%) and ETCS design manual (124.38%) provide the highest values for WTTE. While these strategies recover quickly and show short disruption periods, the affected trains experience greater delays individually, leading to higher delay factors. This highlights the following: a quick recovery and a short disruption period do not necessarily imply a lower passenger impact.

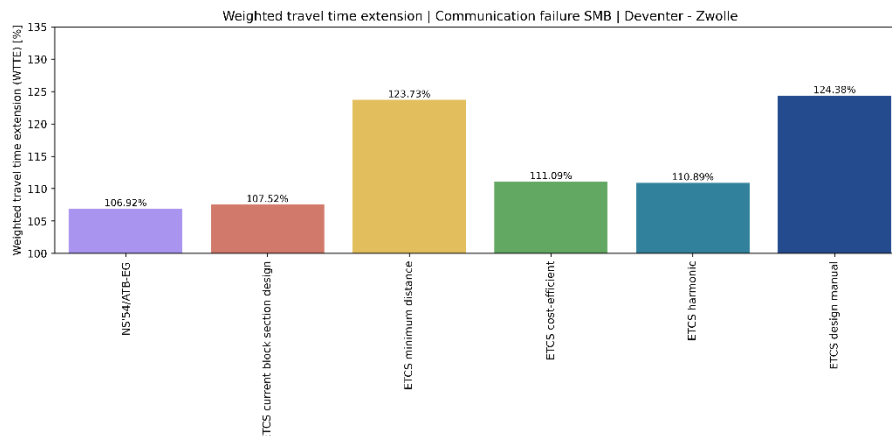


Figure 39: WTTE values of communication failure with SMBs | Deventer – Zwolle

The WTTE results in Figure 39 largely mirror the earlier findings regarding the resilience. The NS'54/ATB-EG, ETCS current block section design, and ETCS harmonic strategies all score equally low (101.44%), indicating that passengers on these route experience only a minimal increase in travel time during the communication failure.

The ETCS cost-efficient strategy also shows a relative low WTTE (102.39%), even though its disruption period is longer than the three best-performing strategies. This can be explained by the

fact that the disruption lasts longer, but it causes only minor delays per train. These small delays, distributed over multiple trains, results in a limited impact regarding the WTTE.

In contrast, the ETCS minimum distance strategy shows a very high WTTE of 138.99% – the highest of all strategies. This is consistent with its poor performance in both recovery and disruption periods. Since the disruptive train must stop for dispatcher instructions after each SMB, the trains behind the disruptive train experience a lot of hindrance and delay. When multiplied by the seat capacity and relative delay, this results in a high WTTE score.

The ETCS design manual also scores relatively higher (111.14%). This is due to a larger number of trains experiencing delay compared to NS'54/ATB-EG, ETCS current block section design, ETCS cost-efficient, and ETCS harmonic. However, the WTTE remains lower than that of ETCS minimum distance, as the number of required stops is reduced due to the use of fewer SMBs. As a result, trains are still able to return to their scheduled timetable more quickly than under the minimum distance strategy.

In summary, the WTTE results confirm that strategies with frequent, severe stops (such as minimum distance and design manual) have a higher overall impact on passengers, while strategies that spread out minor delays across several trains (like cost-efficient) can still score well on WTTE, despite a longer disruption window.

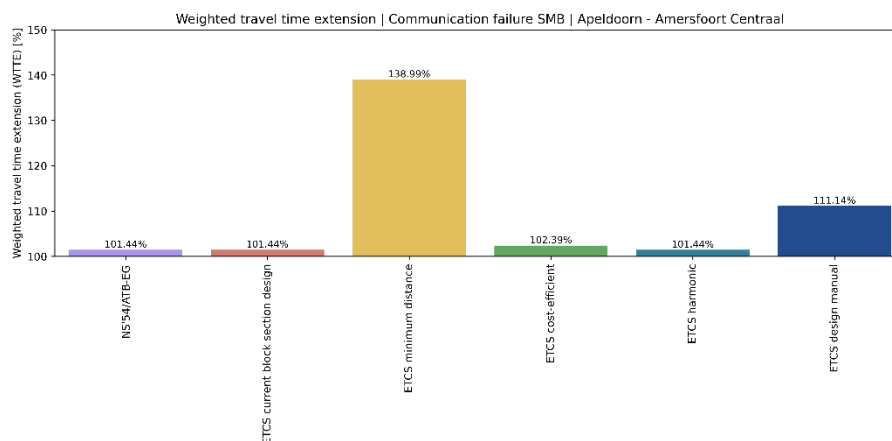


Figure 40: WTTE values of communication failure with SMBs | Apeldoorn – Amersfoort Centraal

Appendix F: Results disruptive conditions – communication failure with LMBs

F.1. Resilience – recovery period

As shown in Table 18, there is no difference in the recovery period between the use of SMBs and LMBs for a communication disruption on the Deventer – Zwolle section. This can be explained by the fact that the disruptive train does not cause any interference with the train running in the opposite direction (Zwolle – Deventer) with these strategies. As a result, the system's recovery period remains unchanged regardless of whether LMBs or SMBs are used.

Table 18: Comparison between recovery periods for the communication failure with SMBs and LMBs of Deventer – Zwolle

Strategy Recovery threshold	Use of SMBs		Use of LMBs	
	ETCS – minimum distance	ETCS – design manual	ETCS – minimum distance	ETCS – design manual
3 & 5 min	00:29:09 (-0.85%)	00:29:09 (-0.85%)	00:29:09 (-0.85%)	00:29:09 (-0.85%)

Table 19 presents the recovery periods for the communication failure between Apeldoorn and Amersfoort Centraal, comparing the use of SMBs and LMBs. The results show improvements when LMBs are implemented. For both the ETCS minimum and design manual strategies, the recovery period is reduced, both just over 13 minutes. This closely matches the recovery periods of NS'54/ATB-EG, ETCS current block section design, and ETCS harmonic.

Table 19: Comparison between recovery periods for the communication failure with SMBs and LMBs of Apeldoorn – Amersfoort Centraal

Strategy Recovery threshold	Use of SMBs		Use of LMBs	
	ETCS – minimum distance	ETCS – design manual	ETCS – minimum distance	ETCS – design manual
3 min	00:52:41 (+294.14%)	00:33:32 (+150.87%)	00:13:07 (-1.87%)	00:13:07 (-1.87%)
5 min	00:48:56 (+266.08%)	00:33:32 (+150.87%)	00:13:07 (-1.87%)	00:13:07 (-1.87%)

F.2. Weighted Travel Time Extension (WTTE)

Figure 41 illustrates the WTTE values for the communication failure with LMBs on the Deventer – Zwolle section. When comparing these results to those with SMBs (see Figure 39), a noticeable difference can be observed for the ETCS minimum distance and design manual strategies.

Both strategies show a clear reduction in WTTE values, even though no differences were observed in either the recovery or disruption periods. The lower WTTE values indicate that train arrive in Zwolle much earlier than in the scenarios with SMBs. This improvement can be attributed to the operational advantage of using LMBs and the block section design. For the ETCS minimum distance and ETCS design manual, the length of the section where the train must operate at 40 km/h is shorter compared to the other scenarios, which results in a lower WTTE value.

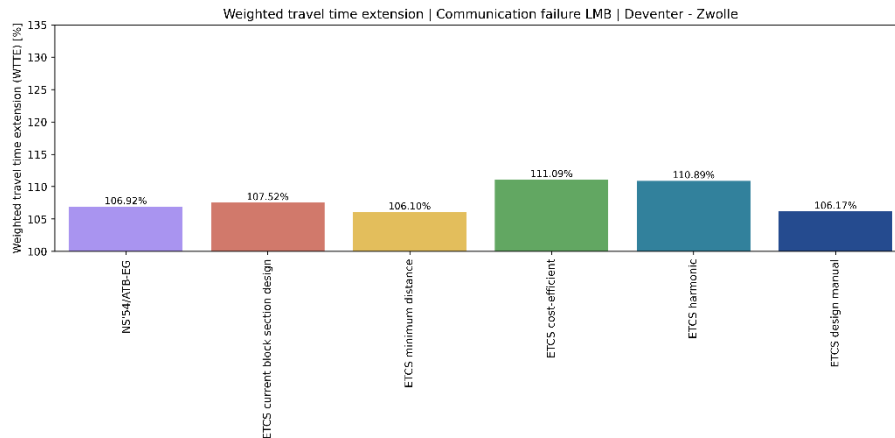


Figure 41: WTTE values of communication failure with LMBs | Deventer – Zwolle

Finally, Figure 42 illustrates the WTTE values for the communication failure using LMBs. Again, the impact of implementing LMBs is clearly visible. The WTTE for ETCS minimum distance drops from 138.99% (with SMBs) to just 102.28%, while ETCS design manual sees a reduction from 111.14% to 101.76%. these improvements reflect the fact that fewer trains experience delays, and those that do are delayed for a shorter duration, leading to a much lower overall WTTE score.

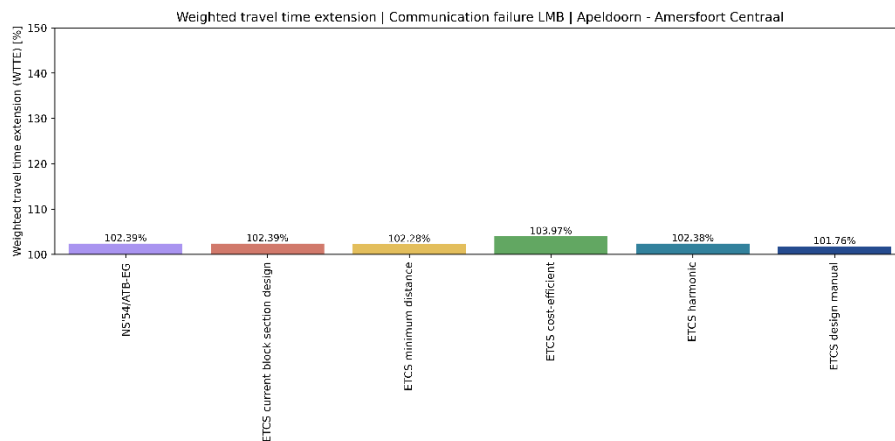


Figure 42: WTTE values of communication failure with LMBs | Apeldoorn – Amersfoort Centraal