R. Vergroesen

ERTMS/ETCS Hybrid Level 3 and ATO

A simulation based capacity impact study for the Dutch railway network

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By

R. Vergroesen

Master thesis

This project is proposed is proposed as my master thesis as the final part of the MSc Civil Engineering at the faculty of Civil Engineering and Geosciences, department of Transport and Planning of the Delft University of Technology in cooperation with ProRail.

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Cover image: *SNG Sprinter train used for the ATO tests of NS in December 2019*. Source: R. Vergroesen, 2020

Preface

Before you lies the thesis that completes my time studying at the Delft University of Technology. I have always been interested in transport, especially the railways. Through the MSc Civil Engineering I was able to continue these interests which culminated into this thesis.

While working on this thesis, I had a lot of helpful feedback from my committee. I would like to thank Egidio Quaglietta for being the daily university supervisor. You asked the right questions during discussions to help provide me with new insights into my work. I want to thank professor Rob Goverde for his role as chair of my thesis committee. During the midterm meetings where I had some doubt about portions of my research, your comments and expertise helped me rethink and improve the quality of my work and reassured me I was on the right track. Thirdly I want to thank John Baggen for being my secondary university supervisor. Especially your feedback in the early stages helped me to find the structure I needed in my work.

I want to express my thanks and gratitude to Maarten Bartholomeus and Alwin Pot as my supervisors within ProRail for their guidance, feedback and informative discussions. Special thanks go to Henri Olink for supporting me in the use of the RailSys software. The fun modelling sessions with the four of us in Amersfoort where the expertise of the three of you helped provide me with major insights into the workings of the different signalling and modelling systems. Until the final 2 months of my time working on the thesis, most of my time was spent at ProRails head office, the Inktpot in Utrecht. I want to thank my colleagues from room F2.02-2.06 for the nice conversations, coffee breaks, tips and tricks and the overall pleasant atmosphere in the office.

Finally, I want to thank my family and friends for their support, for keeping me sane in stressful moments and for reminding me to take a step back and relax a bit more during my time at university, especially when the combination of full time work and an active training regime proved to be a bit too much at times.

I hope you enjoy reading this thesis.

Ruben Vergroesen
Delft, May 27th, 2020

Summary

In the 2020 timetable, parts of the Dutch railway network are operating at or near the maximum capacity. The current Dutch signalling (NS'54) and train protection (ATB) systems have been in service for over 50 years. While they have been functioning well, the limits of their capacity are being reached. Before the start of the COVID-19 crisis a large future demand growth for passenger transport by rail for the near future (2030) had been predicted. While it will likely take some years for the demand to recover, improvements will need to be made to for when it does and the demand growth resumes. Current capacity limits on the rail network would not be enough for these future situations.

The ERTMS/ETCS system has been designed with the goal of standardising signalling and safety systems on the railways across Europe, improving interoperability and provide safety improvements over the various national legacy systems. In order to support the predicted demand growth and further connect the Dutch rail network to the rest of Europe, the Dutch government approved the plan to implement ERTMS/ETCS Level 2 on several key corridors on the network.

ERTMS/ETCS Level 2 provides in cab signalling and full braking supervision through the use of train specific braking curves. Radio connection via GSM-R with the radio block centre (RBC) is used to provide trains with a movement authority (MA) on a stretch of track. The system uses physical block section that are released by trackside train detection equipment. In order to maximise the capacity of ERTMS/ETCS, the concept of the Level 3 system was developed. The Level 3 system removes the physical block sections and train detection and allows to follow each other with a short headway based on their braking distance. In order to operate such a system, all trains need a constant connection with the RBC and need to be proven to be integer/complete. As there is no sufficient back-up for when trains are not integer or lose connection with the RBC, this system can currently not be safely implemented.

To get around the issues of the Level 3 system, the Hybrid Level 3 concept was developed. The ERTMS/ETCS Hybrid Level 3 system splits the physical block sections and train detection equipment of the Level 2 system into smaller virtual block sections. Trains equipped with a train integrity monitor (TIM) and a radio connection to the RBC can fully utilise these virtual sections, allowing for very short headways similar to Level 3 operations. The trackside train detection equipment is used as a back-up and for trains that cannot be proven to be integer (e.g. freight trains).

Another system that is considered to be beneficial for capacity is Automatic Train Operation (ATO). With ATO, trains can be operated by automated computer systems, replacing several functions normally performed by the human driver. The grade of automation (GoA) can vary from manual driving with an automatic train protection system for safety (GoA1) to full automatic operation such as seen in metro systems (GoA4). A GoA2 system where the train movements are fully automated with a driver present for oversight and some smaller tasks shows the most potential for main line operations. When ATO is mentioned in the rest of this report, a GoA2 system is meant, unless otherwise specified.

The government plans for ERTMS/ETCS were focussed on the implementation of the ERTMS/ETCS Level 2 system, but also contained an opening for future developments such as Hybrid Level 3 and ATO to possibly be implemented. This thesis is a follow-up study on the Hybrid Level 3 system, focussing on the capacity effects of ATO on top of the ERTMS/ETCS systems. The objective of this study is to quantify the capacity benefits of ATO separate and combined with ERTMS/ETCS Hybrid Level 3 and provide a solution for the capacity problems on the busiest parts of the Dutch rail network. The following research question is chosen to achieve this objective:

What is the contribution of ERTMS/ETCS Hybrid Level 3 combined with Automatic Train Operation over the current systems to the Dutch railway network in terms of capacity?

The research question is answered through a modelling case study on the SAAL corridor (Schiphol, Amsterdam, Almere, Lelystad). This corridor is currently one of the busiest in the Dutch railway network, with a high number of trains and complicated service patterns containing a variety of different train types. Therefore, it is considered a relevant case for this type of research.

Driving behaviour

One of the main benefits of ATO is considered to be the that the train driving behaviour can be optimised to the specifications of the operators. In the case of this thesis it is optimised to provide more capacity. In order to fully visualise the effects that ATO could have on the capacity of a railway network, it is important to know the driving behaviour of human train drivers. The focus is put on the braking behaviour the human drivers, as this is where the ERTMS/ETCS and ATO systems could provide the biggest improvements over the current ATB/NS'54 systems. With the ATB/NS'54 signalling system a constant braking rate of roughly 0,5 m/s^2 is observed in the driver behaviour. This constant braking rate is used by ProRail to simulate the driver behaviour in modelling studies. The ERTMS/ETCS systems do not actively support this type of braking behaviour. An adaptation in braking behaviour closer to the ERTMS/ETCS braking curves is expected. Based on comments from drivers and the specifications of the ERTMS/ETCS systems, a braking behaviour based on a set speed (roughly 5 km/h) below the permitted braking curve was determined. Due to model constraints this was translated to a behaviour where the trains brake according to a curve 2s before the permitted ERTMS/ETCS braking curve.

ATO

The ATO system itself should never be allowed to be safety critical. This means it should always function under an automatic train protection system with full braking supervision. According to the specification from the ERA Subset-125, when ATO functions under ERTMS/ETCS it is allowed to ignore all non-safety critical braking curves. This means that the system could brake later than the human drivers are allowed to under the ERTMS/ETCS systems. Using a margin for system reaction times, a braking curve for the ATO system has been estimated and placed 2s before the EBI (Emergency Brake Indication) curve of the ERTMS/ETCS system for an optimal utilisation of capacity.

The Dutch timetable planning norms contain an additional 60s time buffer between trains. These buffer times are partly used to prevent variations between train runs from causing conflicts and delays. The homogenisation of driving behaviour brought by the ATO system could allow for a reduction in these buffer times. On the smaller local lines, the additional time buffer is reduced to 30s. The assumption is made that ATO could provide the same reduction in buffer time to main line operations.

Case study

In the case study, the ATB/NS'54, ERTMS/ETCS Level 2 and Hybrid Level 3 systems and ATO have been analysed using a variant of the 2030 timetable for the SAAL corridor. The infrastructure containing the ATB/NS'54 system has been used as the base for the case study. The Level 2 system uses the same block formation as the ATB/NS'54 system. In the Hybrid Level 3 variant, the physical blocks and train detection from the Level 2 variant are used and split into virtual sections with a length of 100m. An ATO variant for both the Level 2 and Hybrid Level 3 systems has been modelled.

Timetable compressions are performed to determine the occupation rate for the infrastructure. The SAAL corridor has been split up into 4 sections that are tested in both directions of traffic (including a 4-track section), coming to a total of 10 timetable compressions for each system configuration. Two variations of timetable compressions have been performed, one according to the methods described by the International Union of Railways (UIC) in the UIC 406 Leaflet (i.e. without the use of buffer times) and one with the time buffers from the Dutch planning norms included to show the full capacity benefits of the ATO system.

Figure A provides an overview of the timetable compression results, showing both the driver behaviours (P-2s) and (Permitted). The figure contains a graph showing the occupation rates (i.e. percentage of capacity used) for the different system configurations on the tested sections of the SAAL corridor. The section between Asra and Hfd contains 4 tracks, with the outer 2 being marked as (IC) and the inner 2 being marked as (S) based on the train type most present on those tracks. Through step by step comparison of these results, the capacity benefits of the Hybrid Level 3 and ATO system have been determined.

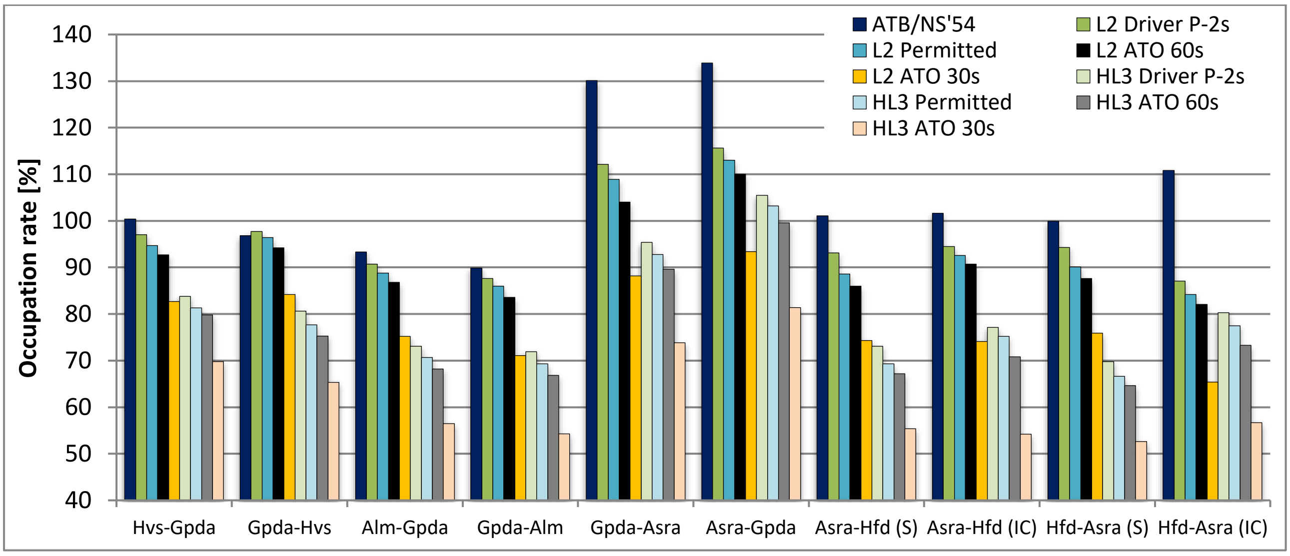


Figure A | Timetable compression results with buffer times included.

Within the case study, the Hybrid Level 3 system combined with ATO provided an average reduction in occupation rate of 43,8 percent point over the ATB/NS'54 system. This reduction consists of the following parts:

- Use of ERTMS/ETCS braking curves vs the stepwise progressive braking of the ATB/NS’54 system (8,8 percent point)
- Shorter virtual block sections provided by the Hybrid Level 3 system (16,0 percent point)
- Optimised driving style with further delayed braking provided by the ATO (5,5 percent point)
- Buffer time reduction assumed possible with ATO (13,5 percent point)

The performance of the different systems in disrupted scenarios has been tested by adding a perturbation in the form of a set departure delay to a selected train, causing several trains to queue up behind the selected train. The time it takes for the effects of the perturbation to be fully dissolved, the secondary delay caused by the perturbation and the number of affected trains were measured. In the first test the same timetable was used across the different systems. Both the ERTMS/ETCS systems and ATO showed a lower amount of delays and affected trains. In a second test the timetable was optimised to fully utile the capacity of each system, by shortening the headways between trains. The shorter headways between trains negatively affected the robustness of the systems, showing larger delays than with the original timetable. With the reduced headways, the Hybrid Level 3 system combined with ATO still showed a similar result compared with the ATB/NS’54 system while the timetable contained roughly 50% more trains. This supports the assumption that a buffer time reduction with ATO could be possible.

It should be noted that the effectiveness of these systems in terms of creating capacity varies per case. Differences in service patterns and infrastructure showed to influence these results. For example, in the locations with a more homogenous service pattern, the use of shorter blocks had a larger effect on the capacity. This indicates that the result for one case will not necessarily be applicable to another case.

Conclusion

Using the current ATB/NS’54 system, the timetables that are expected to be necessary to handle future growths in rail transport are not feasible. The main problem is that trains need a lot of space to run unhindered through the network, making it difficult to achieve high service frequencies without having to expand the infrastructure. The ability to shorten the block reservation through the use of ERTMS/ETCS systems and the use very short virtual blocks provided by the Hybrid Level 3 system specifically allows for shorter headways. The homogenisation and optimisation of driving styles provided by the ATO system allows for even shorter headways between trains through a buffer reduction and therefore a higher service frequency. These benefits allow the Hybrid Level 3 system combined with ATO to become a possible alternative for infrastructure expansion to increase capacity on the Dutch railway network.

Samenvatting

Met de dienstregeling van 2020 zitten delen van het Nederlandse spoorwegnet tegen de maximale capaciteit aan. Het huidige Nederlandse seinstelsel (NS'54) en treinbeveiliging systeem (ATB) zijn al meer dan 50 jaar in gebruik op het spoorwegnet. De systemen functioneren goed, maar lopen tegen hun capaciteitslimieten aan. Voor de start van de COVID-19 crisis was een grote reizigersgroei voorspeld voor de nabije toekomst (2030). De huidige capaciteit van het spoorwegnet is niet voldoende om die voorspelde groei te faciliteren. Ondanks dat het tijd zal kosten voordat de reizigersaantallen zich volledig zullen herstellen, kunnen verbeteringen aan het spoor niet uitblijven voor wanneer de groei weer aanzet.

ERTMS/ETCS is ontwikkeld met het doel om de beveiliging systemen in het spoor in Europa te standaardiseren, interoperabiliteit en internationaal verkeer te verbeteren en om een verbeterslag in veiligheid ten opzichte van de nationale systemen te maken. De Nederlandse overheid heeft ingestemd met een implementatieplan voor ERTMS/ETCS Level 2 op een aantal belangrijke Europese corridors op het spoorwegnet. De uitrol van ERTMS/ETCS moet de capaciteit verhogen en betere aansluiting op het Europese spoornet bieden.

ERTMS/ETCS Level 2 vervangt de conventionele seinen met een display in de cabine van de machinist. Het system geeft een volledige rembewaking met gebruik van trein specifieke rem curves. Radioverbinding via GSM-R met het radio block center (RBC) wordt gebruikt om treinen te voorzien van een moovement autority (MA). Het system gebruikt fysieke bloksecties die worden vrijgegeven door treindetectie in de baan. Het ERTMS/ETCS Level 3 systeem is ontwikkeld deels met het doel van capaciteitsvergroting. Het Level 3 systeem gebruikt geen fysieke bloksecties en detectiesystemen meer, wat het mogelijk maakt om met zeer korte opvolgtijden te rijden. Hier is een constante radioverbinding met het RBC voor nodig om trein posities te verifiëren en moet de trein constant kunnen bewijzen compleet te zijn. Omdat dit systeem geen goede back-up bevat voor wanneer treinen de verbinding met het RBC verliezen of niet kunnen bewijzen compleet te zijn, is het tot op heden nog niet toegepast.

Het Hybrid Level 3 concept is ontwikkeld om de zwakheden van het Level 3 systeem te overbruggen. Het ERTMS/ETCS Hybrid Level 3 systeem gebruikt de fysieke bloksecties en treindetectie aanwezig in het Level 2 systeem. De fysieke bloksecties worden opgesplitst in kleinere virtuele bloksecties. Treinen die een train integrety monitor (TIM) bevatten (i.e. treinen die kunnen bewijzen compleet te zijn) en verbonden zijn met het RBC, kunnen deze virtuele bloksecties volledig benutten. Dit maakt kortere opvolging vergelijkbaar met het Level 3 system mogelijk. De fysieke bloksecties en treindetectie vormen de back-up voor het systeem en maken het mogelijk om ook treinen zonder TIM (e.g. goederentreinen) toe te laten.

Automatic Train Operation (ATO) is een ander systeem wat mogelijk extra capaciteit kan bieden. Met ATO worden de treinen bestuurd door een geautomatiseerd computersysteem dat een aantal functies van de machinist over neemt. De grade of automation (GoA) van het systeem kan variëren van normale bediening door een machinist met een automatische beveiliging (GoA1) tot volledig automatisch rijdende treinen zoals te zien bij metrosystemen (GoA4). Een GoA2 systeem waarbij de treinen automatisch rijden, met de machinist in de

cabine als back-up heeft het meeste potentie voor het hoofdrailnet. In de rest van dit rapport wordt met ATO een GoA2 systeem bedoeld, tenzij iets anders wordt aangegeven.

De plannen van de overheid voor de uitrol van ERTMS/ETCS zijn gefocust op het Level 2 systeem, maar bevatten een mogelijkheid voor toekomstige ontwikkelingen zoal Hybrid Level 3 en ATO. Deze thesis is een vervolgstudie voor het Hybrid Level 3 systeem met de focus op de combinatie van ERTMS/ETCS en ATO. Het doel van de thesis is om inzicht te krijgen in hoe deze systemen de capaciteit zouden kunnen uitbreiden en een mogelijke oplossing kunnen bieden voor de drukste delen van het Nederlandse spoorwegnet. Om dit doel te bereiken is de volgende onderzoeksvraag gekozen:

Wat kan ERTMS/ETCS Hybrid Level 3 gecombineerd met Automatic Train Operation bijdragen op gebied van capaciteit ten opzichte van de huidige systemen op het Nederlandse spoorwegnet?

Deze vraag wordt beantwoord door middel van een model casestudie voor de SAAL-corridor (Schiphol, Amsterdam, Almere, Lelystad). Deze corridor is een van de drukste op het spoorwegnet met een groot aantal treinen en complexe dienstregeling met een grote variatie aan trein types. Dit maakt de SAAL-corridor een interessante casus voor onderzoek in deze systemen.

Machinistengedrag

Een van de grootste voordelen van ATO is dat het rijgedrag kan worden gehomogeniseerd en geoptimaliseerd op basis van de specificaties van de vervoerders. In dit onderzoek is het rijgedrag geoptimaliseerd voor het creëren van capaciteit. Om het volledige effect van de ATO op de capaciteit te kunnen beoordelen, moet het rijgedrag van machinisten bekend zijn. De focus is hierbij gelegd op het remgedrag, gezien de ERTMS/ETCS en ATO-systemen hier de grootste bijdrage in kunnen leveren ten opzichte van de huidige ATB/NS’54 systemen. Onder de ATB/NS’54 systemen is een remgedrag geobserveerd overeenkomstig met een constante remvertraging van ongeveer 0,5 m/s^2. Deze constante remvertraging wordt door ProRail ook gebruikt om machinistengedrag te simuleren. De ERTMS/ETCS-systemen geven geen actieve ondersteuning voor dit soort remgedrag. Een aanpassing in het remgedrag van machinisten meer richting de remcurves van het systeem wordt daarom verwacht. Gebaseerd op commentaar van machinisten en de specificaties van de ERTMS/ETCS-systemen is een remgedrag gebaseerd op een constante snelheid (ongeveer 5 km/h) onder de permitted remcurve bepaald. In de modelleersoftware is dit vertaald naar een remcurve 2 seconden voor de permitted ERTMS/ETCS-remcurve.

ATO

Het ATO-systeem zelf mag nooit de kritieke schakel zijn in de veiligheidsketen. Dit betekent dat het altijd moet functioneren in dienst van een overkoepelend treinbeveiligingssysteem met volledige rembewaking. Volgens de specificaties in de ERA Subset-125 mag ATO onder ERTMS/ETCS alle niet veiligheidskritieke remcurves negeren. Dit betekent dat ATO een trein later kan laten remmen dan toegestaan voor machinisten onder ERTMS/ETCS. Met gebruik van een marge voor systeem reactietijden is een remcurve voor ATO bepaald die 2 seconden voor de EBI (Emergency Brake Indication) curve is geplaats voor een optimale capaciteit.
Volgens de huidige planningsnormen voor de Nederlandse dienstregeling worden reizigerstreinen ingepland met een kielzog van 60 seconden tussen de treinen. Deze buffer is

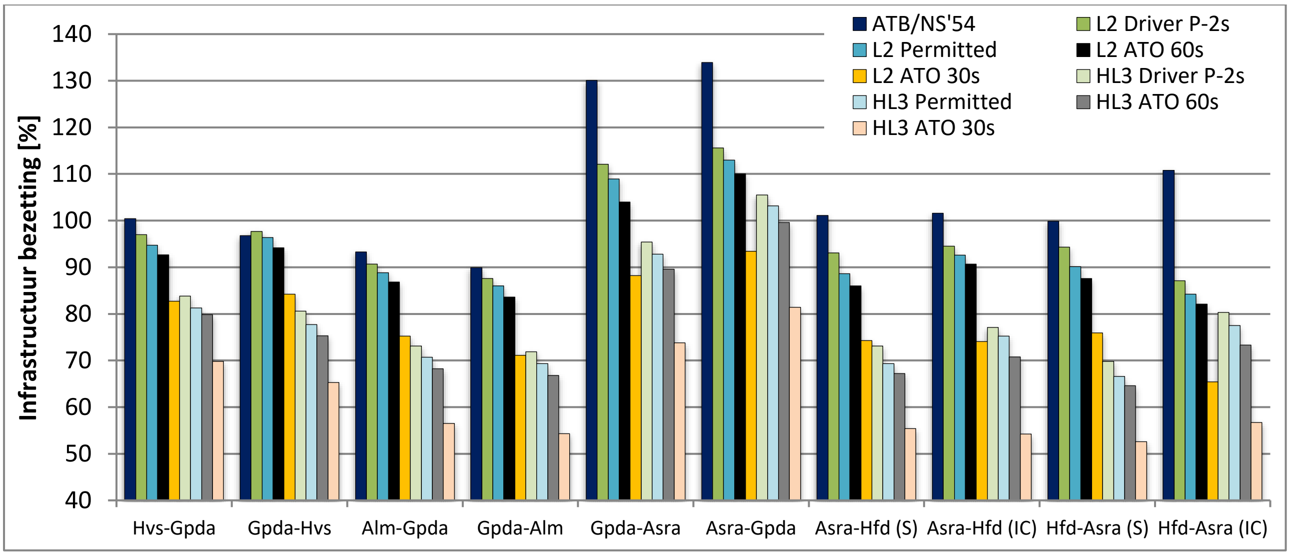
toegepast om de verschillen tussen opvolgende treinbewegingen op te vangen en conflicten en vertragingen te voorkomen. De homogenisering van het rijgedrag die ATO kan brengen zou een reductie in de kielzogbuffer mogelijk kunnen maken. Op de lokale spoorlijnen in het noorden en oosten van het land is deze buffer al verkleind naar 30 seconden. Er wordt aangenomen dat ATO eenzelfde buffer reductie mogelijk kan maken voor het hoofdrailnet.

Casestudie

In de casestudie worden de ATB/NS’54, ERTMS/ETCS Level 2 en Hybrid Level 3 systemen en ATO getest op de SAAL-corridor met een variant van de dienstregeling van 2030. De infrastructuur met ATB/NS’54 is gebruikt als de basis voor de casestudie. Het Level 2 systeem gebruikt dezelfde blok configuratie. Voor het Hybride Level 3 system zijn de blokken opgedeeld in virtuele blok secties van 100 meter. Een aparte variant voor ATO is toegevoegd in de modellen voor de Level 2 en Hybrid Level 3 systemen.

Compressies van de dienstregeling zijn gemaakt om de bezettingsgraad voor de verschillende systemen te bepalen. Hiervoor is de SAAL-corridor opgesplitst in 4 kortere trajecten (waaronder een 4-sporig traject rond Schiphol). Deze trajecten zijn in beide rijrichtingen getest, resulterend in 10 compressies per systeemvariant. De dienstregelingcompressie is uitgevoerd in 2 variaties: een zonder het gebruik van buffers volgens de methode van de UIC (International Union of Railways) 406 voorschriften en een met de buffer uit de Nederlandse planningnormen. Het gebruik van de buffers in de compressie maakt het mogelijk om het volledige effect van ATO op de capaciteit te laten zien.

Figuur A geeft een overzicht van de resultaten van de dienstregeling compressie. Voor de ERTMS/ETCS-systemen zijn zowel het geschatte machinisten gedrag (P-2s) als rijden volgens de permitted curve meegenomen. De grafiek toont de bezetting van de infrastructuur voor de geteste trajecten. Het traject tussen Asra en Hfd is 4-sporig. De buitenste 2 sporen zijn hier gemarkeerd met (IC) en de binnenste 2 sporen zijn gemarkeerd met (S) naar het meest voorkomende trein type op deze sporen. Met deze resultaten zijn de capaciteitsvoordelen van de Hybrid Level 3 en ATO-systemen bepaald.



Figuur A | Dienstregeling compressie resultaten inclusief buffers

Het Hybrid Level 3 systeem gecombineerd met ATO resulteerde in een gemiddelde reductie in infrastructuur bezetting van 43,8 procentpunt ten opzichte van het ATB/NS'54 systeem. Deze reductie bestaat uit de volgende delen:

- Gebruik van ERTMS/ETCS-remcurves ten opzichte van de stapsgewijze remming van de ATB/NS'54 systemen (8,8 procentpunt)
- Kortere virtuele blok secties van het Hybrid Level 3 systeem (16,0 procentpunt)
- Optimalisatie van het rijgedrag met ATO (5,5 procentpunt)
- Aangenomen bufferreductie met ATO (13,5 procentpunt)

De prestaties van de verschillende systemen in verstoorde situaties zijn getest door een vertrekvertraging toe te voegen in het model voor een specifieke trein. Dit resulteert in een ophoping van vertraagde treinen. De benodigde tijd om de verstoring te verwerken, de totale secundaire vertraging en de hoeveelheid verstoorde treinen zijn gemeten en vergeleken om de systeemprestaties te beoordelen. In de eerste test is een constante dienstregeling gebruikt over voor alle systeemconfiguraties. De ERTMS/ETCS-systemen en ATO resulteerde in significant betere prestaties dan het ATB/NS'54 systeem met een reductie in vertraging en aantal verstoorde treinen. Een tweede test is uitgevoerd waarbij de dienstregeling is aangepast om de maximale capaciteit te gebruiken (zelfde patroon, met minimale opvolging tussen treinen). De kortere opvolging resulteerde in een minder robuuste dienstregeling. Ondanks de reductie in robuustheid ten opzichte van de originele dienstregeling voor de Hybrid Level 3 en ATO combinatie, de prestaties van deze combinatie met minimale opvolgtijden was nog steeds vergelijkbaar met die van de ATB/NS'54 terwijl een frequentie verhoging van ongeveer 50% werd gerealiseerd. Dit ondersteunt de aanname van een mogelijke reductie in kielzogbuffer met ATO.

Het moet wel worden benoemd dat de effectiviteit van deze systemen wisselt per case. Verschillen in het dienstregelingpatroon en de infrastructuurconfiguratie resulteerde in verschillende resultaten binnen de casestudie. Bijvoorbeeld op locaties met een meer homogeen dienstregelingpatroon, resulteerde de kortere blokken van het Hybrid Level 3 systeem in een grotere toename in capaciteit. Dit laat zien dat resultaten voor één case niet direct toepasbaar zijn voor een andere case.

Conclusie

De capaciteit van de infrastructuur met het ATB/NS'54 systeem is onvoldoende om de benodigde dienstregeling voor de verwachte toekomstige reizigersgroei te verwerken. Het grootste probleem is dat treinen een lang gereserveerd pad nodig hebben met ATB/NS'54 om ongehinderd over het spoorwegnet te rijden. Dit maakt hogere treinfrequenties moeilijk te implementeren. De kortere blokreservering mogelijk door het gebruik van de ERTMS/ETCS-systemen en de kortere blocksecties specifiek van het Hybrid Level 3 systeem maakte kortere opvolgingen zonder een bufferreductie mogelijk. De homogenisering en optimalisering van het rijgedrag door ATO maakt reductie in opvolgtijden mogelijk door een verkleining van de buffers. Deze resultaten laten zien dat de Hybrid Level 3 en ATO combinatie een mogelijk alternatief kan vormen voor infrastructuur uitbreiding om capaciteitsvergroting te realiseren voor het Nederlandse spoorwegnet.

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1. Introduction

The Dutch rail network is one of the busiest in the world. In the 2020 timetable, parts of the Dutch railway network are operating at or near the maximum capacity of the current signalling and traffic management systems. Before the start of the COVID-19 crisis a large future demand growth for passenger transport by rail for the near future (2030) had been predicted While it will likely take some years for the demand to recover, improvements will need to be made to for when it does and the demand growth resumes. Current capacity limits on the rail network would not be enough for these future situations.

Increasing capacity can be done in several ways, adapting/expanding the infrastructure and adapting the signalling systems. Expanding the infrastructure is a very costly option and is preferably not done when not absolutely necessary. Looking at the signalling systems would therefore be the preferred way of increasing the capacity.

1.1. Signalling systems

The current Dutch signalling (NS’54) and automatic train protection (ATB-EG) systems are over 60 years old. They have functioned well over this period but do have their drawbacks and limitations. The main limitations of the ATB-EG system are that it only provides 5 different speed authorities and only provides limited brake supervision. The limitations allow for signals to be passed at danger below a speed of 40 km/h, without the ATP system interfering.

In May 2019, the Dutch government approved a plan for ERTMS/ETCS implementation on the network. ERTMS is the European Rail Traffic Management System, developed for promoting interoperability of different counties rail networks. One of the benefits of ERTMS/ETCS is that it can provide a capacity increase depending on the level and configuration. The plans of the Dutch government are for the implementation of ERTMS/ETCS Level 2 on several key corridors on the network. However, the limitation to level 2 is not mentioned in the letter to parliament from May 2019. This letter does mention ERTMS/ETCS Level 3 options.

A master thesis project on the capacity benefits of ERTMS/ETCS Hybrid Level 3 (HL3) on the Utrecht-Den Bosch corridor has been done (Jansen, 2019) in cooperation with ProRail. This study showed that the ERTMS/ETCS HL3 systems (ERTMS/ETCS combined with existing trackside detection systems) can provide a considerable capacity increase over the current (NS’54/ATB-EG) systems.

1.2. Problem description

One of busiest corridors on the Dutch rail network is the OV-SAAL (Schiphol, Amsterdam, Almere, Lelystad) corridor. This corridor is currently already congested and in need of extra capacity. The OV-SAAL corridor is part of the ERTMS/ETCS implementation plan of the Dutch government. By the year 2030 ERTMS/ETCS Level 2 should be operational on the OV-SAAL corridor. ProRail states that the capacity increase provided by Level 2 alone would not be sufficient for the desired 2030 timetable.

One of the knowledge gaps mentioned in the HL3 study is the effect of Automatic Train Operation (ATO) on the capacity of the network. ATO is used combined with ERTMSETCS Level 2 on the Thameslink route in the centre of London to allow operations with a frequency of 24 trains per hour (C. Götz, 2014). The ATO on the Thameslink route is active on a relatively simple stretch operated at speeds of roughly 50 km/h. Little is known on what the capacity benefits are exactly when ATO is applied to a larger and more complex network with higher speed operation and mixed (HST, IC, Sprinter and freight train) traffic.

1.3. Objective

This project is a follow-up study to the capacity study on HL3, focussing on the effects of ATO on top off ERTMS/ETCS on the capacity of the Dutch rail network. The objective of this study is to quantify the capacity benefits of ATO separate and combined with ERTMS/ETCS Hybrid Level 3 and provide a solution for the capacity problems on the busiest part of the Dutch rail network.

This study is meant to provide a deeper insight into the workings of developing technology in the railway sector and the possibilities to optimise the use of the rail infrastructure capacity through these technologies.

1.4. Research questions

The main research question for the thesis is the following:

What is the contribution of ERTMS/ETCS Hybrid Level 3 combined with Automatic Train Operation over the current systems to the Dutch railway network in terms of capacity?

To reach the objective of this thesis and answer the main question, the following sub questions are proposed.
- *What kind of braking behaviour do drivers apply under ERTMS/ETCS operations and how can this braking behaviour realistically be modelled?*
- *How can the effects of ATO on the capacity realistically be modelled?*
- *What is the effect in terms of capacity of adding ATO over the use of ERTMS/ETCS L2 and HL3?*
- *How do the infrastructure configuration and service patterns influence the effect of the ERTMS/ETCS and ATO systems on the capacity?*

1.5. Methodology

The thesis will analyse the developing technologies and concepts of ATO and ERTMS/ETCS HL3 to find the possible benefits for the implementation of these technologies on the Dutch railway network. One of the objectives of the thesis is to develop a technique to reliably model the effects of the use of ATO combined with ERTMS/ETCS on the capacity of a railway network. In order to do this the human driving behaviour under the ERTMS/ETCS systems also needs to be known to be able to make a proper comparison.

The possible benefits of ATO over ERTMS/ETCS HL3 on the capacity will be investigated through a literature study that will focus on how ATO could create an increase of capacity over the use of ERTMS/ETCS. Modelling techniques and parameters will be determined through the literature review. These techniques and parameters will be used in simulations in a case study on the OV-SAAL corridor to determine if these can create enough capacity for the desired 2030 timetable.

Different capacity modelling tools will be analysed to determine which is best suited for simulating the capacity effects of the proposed systems. Special attention is given to the simulation of the effects of the ATO system.

Simulations will be made of different scenarios containing combinations and different alternative configurations of ATO and ERTMS/ETCS to demonstrate the capacity benefits of each and quantify these benefits. These scenarios will be compared to each other and used to create a design that theoretically should optimise capacity given realistic infrastructure constrains.

1.6. Project scope and limitations

In order to demonstrate the possible capacity benefits of ATO combined with ERTMS/ETCS, simulations will be used. It is very time consuming to simulate the entire Dutch railway network at once. Therefore, a smaller part of the network is chosen for the capacity simulations. As mentioned in the methodology description, the OV-SAAL corridor has been chosen due to the need for a large capacity increase on this route over the coming years.

A number of different scenarios haven been proposed for the thesis to be able to study the effect each system has on the capacity. The following have been proposed in order to be able to better compare results with other studies to determine how network characteristics influence the effect the proposed systems have on the capacity.

- ATB/NS'54 (base scenario for comparison)
- ERTMS/ETCS Level 2 (several versions containing different driver behaviours)
- ERTMS/ETCS Level 2 + ATO
- ERTMS/ETCS Hybrid Level 3 (several versions containing different driving behaviours)
- ERTMS/ETCS Hybrid Level 3 + ATO

Limitations
The following combinations of systems and changes will not be considered in this thesis.

ATO over ATB. This will not be considered for numerous reasons. The first being that the concept (ATO over ATB-EG) currently does not exist yet, making it very difficult to do more than speculate on how this combination (ATO with trackside signals) would work. This would be too time consuming. The second reason is that ATB is very conservative in its braking, i.e. brakes need to be applied very early compared to other systems, meaning the ATO would probably not be able to be effectively utilised in terms of creating more capacity. Lastly the planned migration from ATB to ERTMS/ETCS on the Dutch network over the coming years would mean that further developing ATB would not be logical.

3kV. One thing that is mentioned often as a possible capacity increasing measure for the Dutch network is upgrading the catenary from 1500V to 3000V. The choice has been made to limit the thesis to capacity creating measures through the signalling systems due to the time constraints.

1.7. Report structure

Chapter 2 will contain a literature review on the current and developing systems of railway signalling, forming the background information for the thesis. The current systems that are active on the Dutch railway network will be explained to provide a base to compare the developing systems with. The developments of ERTMS/ETCS and ATO will be researched to determine the benefits in terms of capacity.

Chapter 3 describes the methods used for capacity assessment. The capacity assessment methods described in the UIC 406 leaflet will be explained. The ERTMS/ETCS braking curve theory is translated to blocking time theory used in the UIC 406 leaflet. A similar translation will be done for ATO.

Chapter 4 introduces the modelling software. It contains a comparison of the available modelling tools and will go further into tool the chosen for this study. The parameters and constraints that are present inside the modelling tool are explained here. Parameters controlling the driving behaviour for the trains and parameters for the infrastructure are explained separately.

Chapter 5 researches the human driver behaviour, going into the different braking behaviours for the ATB/NS’54 and ERTMS/ETCS systems. Using the model parameters and constraints, a realistic driving/braking behaviour for ERTMS/ETCS that can be used in the model is chosen. This chapter answers the first sub-question on human driver behaviour.

Chapter 6 explains how the ATO could affect the capacity of the Dutch rail network. It goes into functions of the ATO system to determine what the effects of the ATO system could be on operations. Some important safety aspects regarding the ATO will be explained here. The driver behaviour covered in chapter 5 is compared it to the possible driving style of the ATO system to show what benefits the ATO system could provide. This ends with a summary of how the effects of ATO will be modelled that will provide an answer to the second sub-question.

Chapter 7 continues where chapter 4 stopped with a further description of the model used for the research. The model setup is explained. The infrastructure and timetable are explained and important remarks on these are provided. The human driver behaviour and ATO explained in chapters 5 and 6 will be translated into the model scenarios, further describing the modelling process.

Chapter 8 contains a capacity assessment through the results of the model case study. Timetable compressions for a number of sections on the SAAL corridor are provided and the results are compared between the different systems and driving behaviours. In this chapter the effects of the ATO on the capacity will become visible. The use of different methods (UIC 406 vs national planning norms) provides a more complete overview of what is necessary to create sufficient capacity for the future timetables. The chapter ends with a short analysis of system performance in perturbed scenarios that will provide some insight into the effects of shorter headways on system robustness.

Chapter 9 provides a further analysis of the results shown in chapter 8 to study the link between infrastructure, service patters and the capacity benefits of the ERTMS/ETCS and ATO systems. This chapter aims to answer the last sub-question.

Chapter 10 summarises the answers to all the research questions and provides an overall conclusion of this thesis. Recommendations will be given on further research topics and developments.

2. Background information

A literature study has been done to provide the necessary background information of the signalling systems to be able to find a solution for the capacity problems on the SAAL corridor. The literature study starts with the current safety systems, detection and ATP systems like the Dutch system (ATB). The ERTMS/ETCS systems that are planned to be implemented on a number of corridors on the network will be discussed afterwards and compared to the current ATB system. The current and future developments of ATO systems will be discussed and the type of ATO system(s) to apply in the study will be determined. The SAAL corridor itself will be explained further in the end to give a full overview of the scope and boundaries of the study in terms of systems and location.

2.1. Safety systems

A number of safety systems are developed for the railways to ensure safe operations. The systems that are important for the research of this thesis are explained below. These systems provide trains with protected conflict free routes and ensure safe movements along these routes.

2.1.1. Interlocking

An interlocking (IXL) is a system that prevents trains from conflicting movements. The IXL is provided with a route request for a specific train. The system uses train detection to check whether a route is clear. The route is then set, by changing and locking points to the right setting. Only if the route is fully set and no other conflicting trains are detected along the route, can the signal be given to the train to proceed.

Early interlocking systems consisted of a number of mechanical levers and cables that were directly connected to switches and signals, that were all controlled from signal boxes on the side of the tracks. Route relay interlocking (RRI) was developed to replace the mechanical systems to allow for remote control over a larger area through a control panel. Since the 1980s, the relay interlockings are being replaced by computer based interlockings (CBI). In this system the switches and signals are controlled and locked by software from a centralised control system.

2.1.2. Trackside train detection

The interlocking systems use train detection apparatus to determine whether a route or track section is occupied. When a section is occupied, the interlocking will keep it locked so that no other train can enter the section. When the detection systems indicate the train to have left the section, it can be released for use by other trains. Two types of trackside train detection systems are commonly used, track circuits and axle counters.

Track circuits
Track circuits are a very common method of train detection. A section of track is divided into blocks with insulated joints. The blocks have signals at each end that control the train movements. An electrical circuit is formed by connecting the rails at the ends of the block. At one end of the block, a power source is connected to the circuit. At the other end a relay is

placed that detects the current from the power source. When the block is unoccupied, the sensor will detect the current. If a train enters the block section the wheelsets will provide a shortcut for the circuit, stopping the current from reaching the relay.

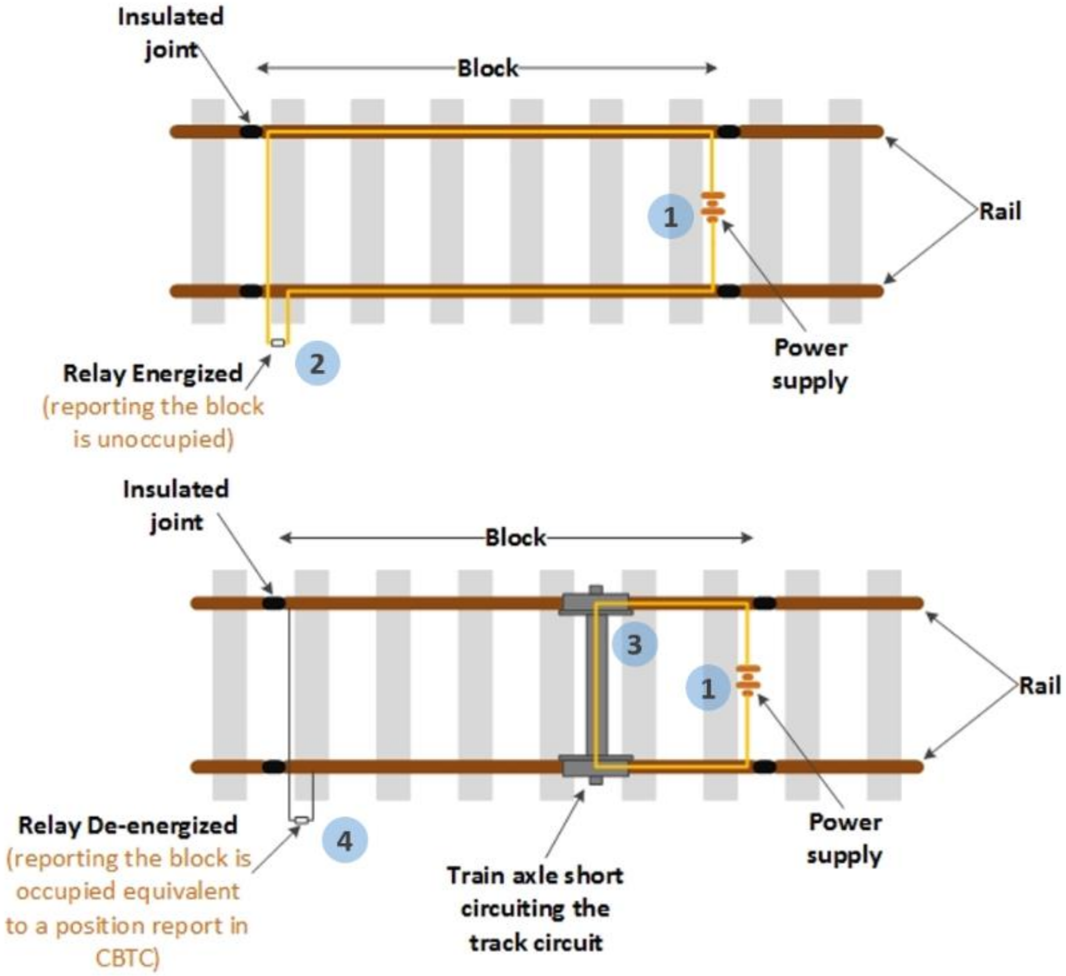


Figure 1 | Track circuit. Source: (RailSystem.net, 2019b)

Figure 1 shows a diagram of a track circuit in unoccupied and occupied state. The relay in the track circuit is coupled to the signalling system, causing the signal to be set to danger when the relay loses power.

Axle counters

An axle counter is a trackside train detection device that counts the number of wheelsets or axles that have passed to determine if a track section is occupied. The axle counter consists of 2 independent sensors that are placed next to each other that form the detection point. The sensors measure the changes in the electromagnetic fields generated by the system. The wheel flanges cause a slight change in these fields. Every change is detected as one axle having passed.

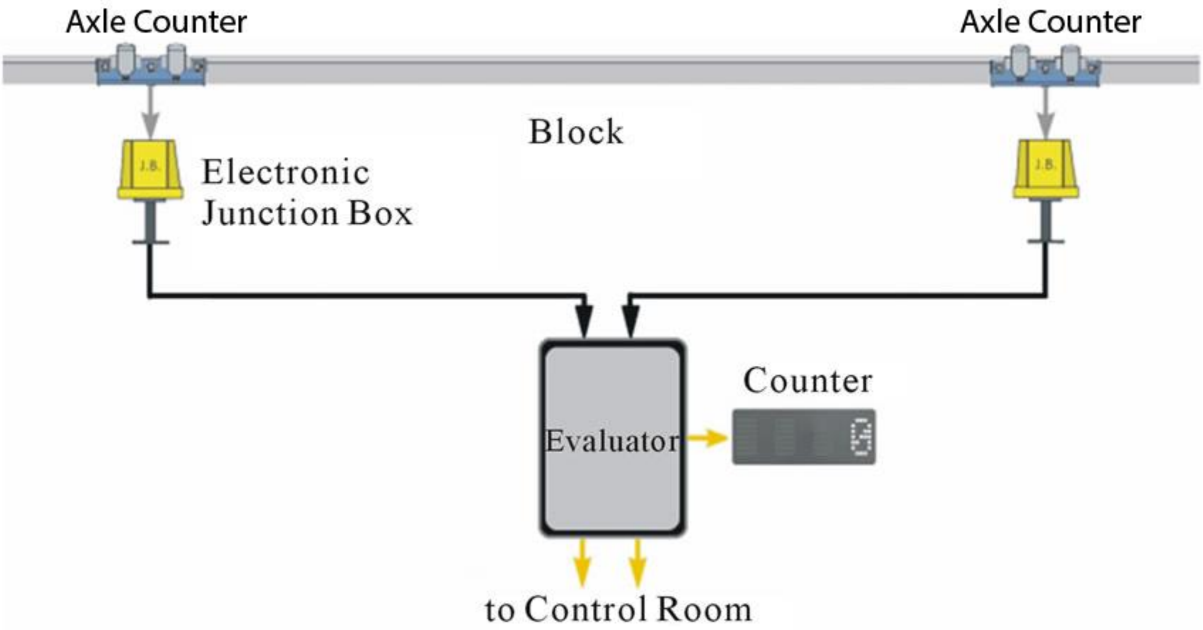


Figure 2 | Diagram of an axle counter. Source: (RailSystem.net, 2019a)

The use of 2 sensors allows the axle counter to determine the speed and direction of the passing train based on order and time between the detections. The sensors are placed at edges of block sections. The axle counter counts the number of axles that have passed it. The sensors are connected to a computer called an evaluator that compares the count to the previous and next counters and registers the differences between the sensor counts. If consecutive axle counters give the same count, the system indicates the track section in between as being cleared with the count of 0 as shown in Figure 2. If the consecutive axle counters indicate different counts (counter is not 0), the track section is considered occupied.

2.1.3. Automatic block signalling

Block signalling is a form of automatic interlocking where trains are separated by physical block sections. The signals provide the train drivers with an indication of the occupancy in the coming blocks. Train detection systems are used to determine whether a block section is occupied by a train.

In the Netherlands a three aspect signalling systems is used. In the three-aspect signalling system, the signals provide the following information, based on the information from the train detection systems.

- Red signal (Danger, next block is occupied, no authority to enter)
- Yellow signal (Slow down and prepare to stop at next signal, block after next signal is occupied)
- Green signal (Proceed, next two blocks are not occupied)

The Dutch signalling system, NS54’ with ATB operates in a similar way as the three-aspect block signalling system. NS’54 is progressive speed signalling with various reducing speed targets allowing braking over multiple blocks. In order to guarantee safe operations, the length of the blocks needs to be larger than the braking distance needed to achieve the speed targets.

2.1.4. Automatic Train Protection

Automatic Train Protection (ATP) systems use the movement authority (MA) provided by the interlocking and signalling systems to safeguard a trains operation. An ATP system monitors a trains speed and or movement authority and will intervene when the train comes outside the limits of its authority. Effectively the system is a guard against driver errors that result in a train movement related accident (Connor & Schmid, 2019). ATP systems provide the driver with in-cab assistance to keep to the authorised speed and location.

ATP systems can have a range of different functions in the categories of cab signalling, supervision and intervention functions. Cab signalling functions can include warning signals indicating necessary driver action, in cab repetition of trackside signs and s display of speed information. Supervision functions include driver alertness and attentiveness checks, train stop function and speed and braking supervision of various degrees. The intervention functions are focussed on safeguarding the train after a driver mistake is made by stopping traction power and applying the brakes to slow or fully stop the train

The systems are informed through data transmission between a control centre and the train. This can be done intermittent, through beacons or cable loops or continuous through coded track circuits, radio or other types of wireless data transmission.

ATP systems are classified based on their functions and the type of data transmission they use. There are 6 different classification for ATP systems. The classifications are shown in Table 1 combined with examples of ATP systems that belong to these classifications. The functionalities of the different classifications are provided below.

Table 1 | Classification of ATP systems. Source: (Goverde, 2018)

Data transmission	**Functions**		
	No braking supervision	Braking supervision	Dynamic speed profile
Intermittent	1	3	5
	AWS (UK), Crocodile (BE/FR), Signum (CH)	ASFA (ES), Indusi/PZB (DE), TPWS (UK)	ATB-NG (NL), TBL (BE), ZUB (CH/DK), ETCS L1
Continuous	2	4	6
	ALSN (RU), ATB-EG (NL), EVM (HU)	BACC (IT), TVM 300 (FR)	LZB (DE/AT/ES), TVM 430 (FR), ETCS L2/L3

1. Attentiveness checks, train stop function.
2. Attentiveness checks, train stop function, check of brake application (through coded track circuits).
3. Attentiveness checks, train stop function and simple (low data volumes) braking supervision.
4. Attentiveness checks, train stop function and simple (low data volumes) braking supervision (through coded track circuits).
5. Dynamic speed profile through static beacons and balises.
6. Dynamic speed profile provided by coded track circuits, cable loops or continuous radio communication.

2.2. Signalling and ATP systems

In this section the current and proposed signalling and ATP systems for the Dutch railway network will be explained to provide background information for the research.

2.2.1. ATB

First it is important to look at the systems that are currently in place on the Dutch network. ATB is the Dutch rail signalling/safety system, it stands for Automatische Treinbeinvloeding (roughly translated: Automatic Train Control) and is a type of ATP system. The ATB works in combination with a block signalling system (NS'54 legacy signalling). The ATB system consists of trackside and on-board equipment. The trackside equipment used to support the ATB system consist of the following:

- Signals (part of the block signalling system, not the ATB itself)
- Track circuits (train detection, data transmission (EG))
- Axle counters (train detection)
- Beacons (data transmission (NG))
- ATB cable loops (data transmission (NG))

Next to this equipment, a number of different trackside signs are in place to inform the drivers under the ATB system. A number of these signs can be seen in Figure 3. The signs indicate track speed (white square or green triangle signs), (temporary) speed changes (yellow triangle) and ATB boarders (yellow diamond).

Figure 3 | Trackside signs for ATB. Source: (Split, 2018)

ATB has two main variants, the first generation (ATB-EG) and the new generation (ATB-NG). Both of these variants are active on the Dutch railway network. The basics of ATB remain the same in both versions. A dispatcher or automatic block signalling system must set a route for every movement. Signals are connected to the control centre through cable connections. An ATB code is sent to the train through the trackside equipment. The train detects the code and displays the signal in the cab indication an action a driver will have comply with. The system uses fixed block sections and visual trackside signals to safeguard the train operations. Based on the information from the ATB systems design regulations (ProRail, 2018a), the differences in the variants of the ATB systems are explained below.

2.2.1.1. ATB-EG

The first-generation ATB systems can provide the train with five different speed limit authorisations (40, 60, 80, 130, 140). The authorisations are given to the train through the system codes transmitted from the trackside equipment. Track circuits are used for the transmission of the ATB code. The train detects the code and translates it to the corresponding maximum speed authorisation. If this maximum speed is exceeded, the train warns the driver with a brake-order. If no reaction to this brake-order is given within a certain time, the train will automatically apply the brakes to come to a complete stop. The ATB-EG system only checks if brake application is applied, not to what level this is done.

The downside of this system is that it can only guard if the brake application is performed, but not whether the brake application is sufficient. Guarding against signal passage at danger is therefore not guaranteed. This means that the system does not guard against the passing of the signal. The ATB-EG does not support the driver with brake application supervision at speeds below 40 km/h.

2.2.1.2. ATB-NG

This version of ATB works with beacons instead of the track circuits, with the possible addition of loops for a continuous data transmission. The beacons transmit the data to the train when the train passes it. The transmitted data is comparable to the data in the ATB-EG system, but slightly more expanded. A more complete speed profile is transmitted to the train with steps of 10 km/h.

ATBNG has the function to guard brake curves based on the individual brake characteristics of the rollingstock. The system calculates the latest possible braking curve for the specific train to reach the lower speed limit. The braking curve than counts as a sort of maximum speed limit. The driver needs to slow the train down to below this braking curve. The system will warn the driver with visual and audible warnings to slow the train when it comes too close to the calculated braking curve. If the braking curve is passed, the train will automatically apply the brakes to fully stop the train. The ATB-NG system does contain a train-stop function, stopping trains automatically if a signal at danger is passed at any speed. It is meant to intervene when a train passes a signal at danger below the release speed, mitigating the problem found in ATB-EG.

The braking curve provides a new problem, since it prevents the passing of the red signal, even after the signal has turned to green, because the new information cannot be received without passing a new beacon.

The release speed prevents this problem from occurring. The release speed is a set speed (usually 15 of 30 km/h depending on locations of beacons) at which the braking curve will be cancelled. The train can reach the next beacon or loop when driving slower than the set release speed. If the train passes a red signal below the release speed, the next beacon will tell the train to automatically stop. If the train is allowed to move again afterward, a low speed has to be held until the next block beacon is passed.

2.2.2. ERTMS/ETCS

Passenger and freight traffic has become increasingly internationally important with the fading boarders within Europe. International rail ravel has been troubled by differences between the national networks like currents, signalling and safety systems. An example of this mentioned in a promotional video of ProRail (VirtualValley, 2006) is the Thalys trains running between Amsterdam and Paris being equipped with 7 different systems. To improve the interoperability of the railways across Europe and effectively creating a Trans-European rail network, the ERTMS/ETCS system has been developed.

ERTMS stands for European Rail Traffic Management System. (Stevens, 2008) describes ERTMS/ETCS as a set of specifications to which a train control system has to comply to ensure interoperability of railways throughout Europe. The specifications are put forward by the EU to standardise the railway systems.

ETCS is the European Train Control System and is a part of ERTMS/ETCS. This system runs the train control and signalling. Different manufacturers can produce their own version of the system that should be compatible with other manufacturers systems due to the standardised specifications. The system uses standardised braking curves specific to each model of rolling stock to determine the allowed speed for the trains.

Basics

ERTMS/ETCS is described as an ICT based system that uses either LAN cables and infill loops (ETCS Level 1) or wireless communication (ETCS Level 2 and higher) between train, trackside equipment and a centralised traffic control centre for continuous data transmission (ProRail, NS, Ministerie van Infrastructuur en Waterstaat, 2019). The ERTMS/ETCS specifications contain a number of standard systems:

- Eurobalise (Boxes placed on the track that send information to the train, type of beacons)
- Euroloop (Cable loops for more continuous data transmission between train and track)
- Eurocab (Also known as the European Vital Computer (EVC), standardised train equipment that contains the safety systems. Every safety system the train needs for its operations can be added to this in modules)
- Euroradio (radio interface that transmits and receives data through GSM-R)

ERTMS/ETCS contains cab signalling combined with an ATP system that provides a dynamic speed profile and braking supervision using rolling stock specific braking curves. The communication between track and train is done through balises and via GSM-R (GSM network for railways).

With the ERTMS/ETCS system a train dispatcher requests a train path through the network. The system checks if the path is available and can be safely granted. The interlocking will set and lock the route. If the route is set, a movement authority (MA) will be given to the train and will be shown on the DMI (Driver Machine Interface).

2.2.2.1. ERTMS/ETCS Level 1

ERTMS/ETCS Level 1 is closest to the conventional system used in the Netherlands (ATB-NG). Level 1 provides point to point signalling using conventional train detection, fixed blocks, data transmission through Eurobalises and often (existing) trackside signals. Movement authorities are generated by Lineside Electrical Units (LEU) an are transmitted to the trains through the balises on the track, similar to the beacons used in ATB-NG. Level 1 often uses the conventional lineside signals for directing the train driver, although these are optional. The data sent through the balises to the EVC is used by the system to calculate speed profiles and braking curves. The train will only receive updates to its MA when a balise is passed. Figure 4 shows a diagram of the principles of ERTMS/ETCS Level 1. The figure shows the communications between the different signalling components. The trackside detection equipment communicated with the signalbox to provide the occupancy information input for the signal controls.

The use of an infill loop before the balise can improve the functionality of the Level 1 system. The loop allows the train to receive an update to its MA before the balise is passed. The increased frequency of MA updates allows for more optimised speed profile to be attained. ERTMS/ETCS Level 1 has been implemented in the port of Rotterdam area of the Betuweroute.

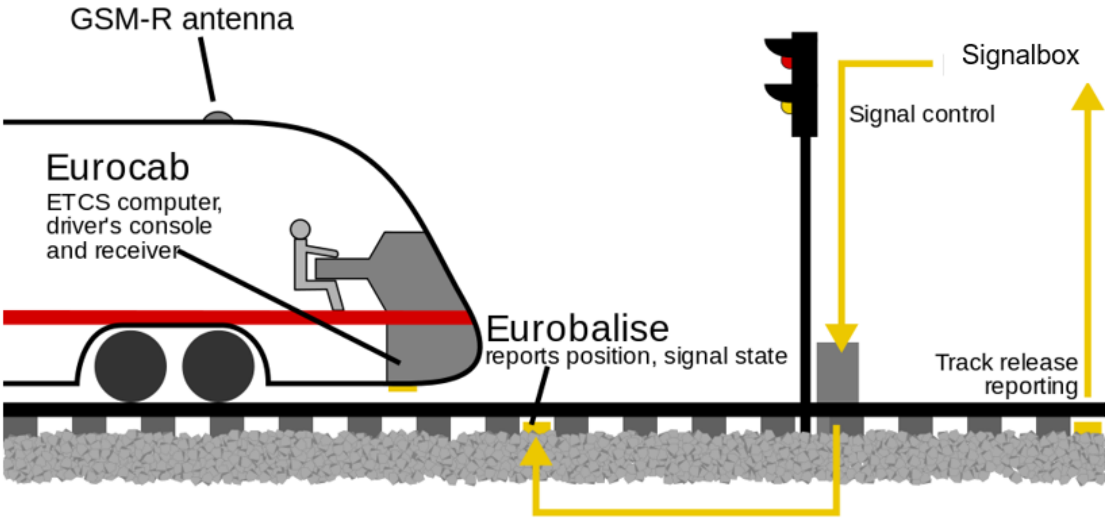


Figure 4 | ERTMS/ETCS L1 principles. Source: (Ministerie van Infrastructuur en Milieu, 2014)

2.2.2.2. ERTMS/ETCS Level 2

ERTMS/ETCS Level 2 provides a more continuous train signalling and control system through a GSM-R radio connection. The MA will be provided by the Radio Block Centre (RBC) through this GSM-R connection. Two-way communication between the train and the RBC provides both the driver and traffic controller with up to date information. ERTMS/ETCS Level 2 uses fixed blocks combined with in-cab signalling. The trackside signals have been replaced by ERTMS/ETCS markerboards indicating the start and end position of block sections. Balises are used to update the information on the tracks ahead of the train and provide a reference point for the trains location. The trains odometer will provide the system with a location between the updates from the balises. Conventional methods of train detection like axle counters and track circuits are used to check the block occupation. A diagram explaining the communication between train and infrastructure can be seen in Figure 5. The figure shows the use of the GSM-R radio for data transmission between train and control centre (‘Signalbox’ in figure).

On the Dutch network, Level 2 has been used on the HSL-Zuid line between Schiphol and the Belgian border and the Betuweroute freight line between Rotterdam and the German border. It has also already been installed on the Amsterdam-Utrecht line and the Hanzelijn between Lelystad and Zwolle. On these two lines, the Dutch ATB system is also still active.

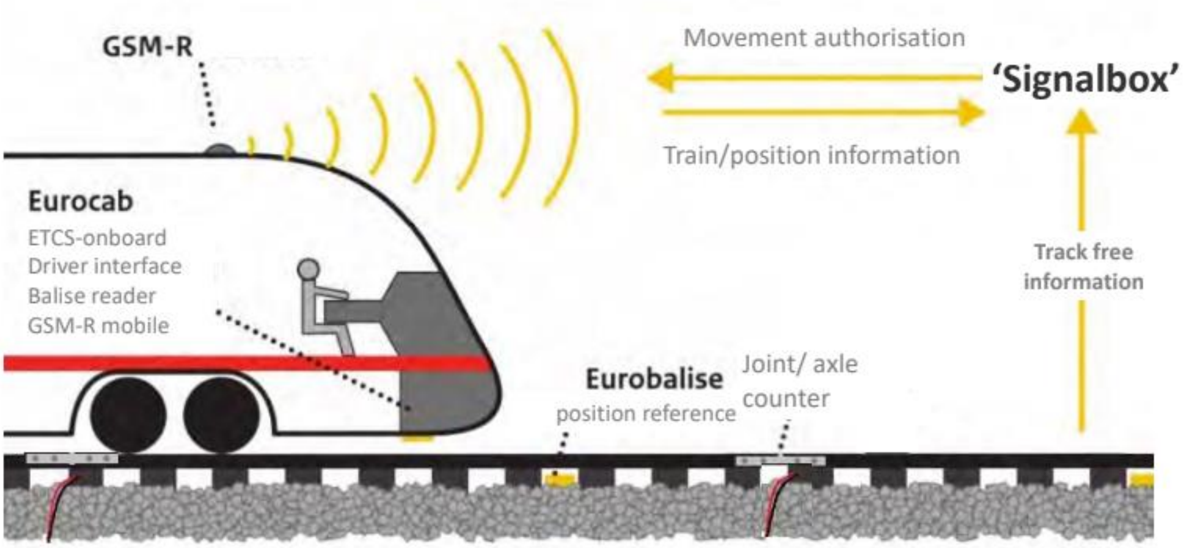


Figure 5 | ERTMS/ETCS L2 principles. Source: (Bartholomeus, 2018)

2.2.2.3. ERTMS/ETCS Level 3

ERTMS/ETCS Level 3 provides in-cab signalling based on radio communication. Similarly to level 2, The data transmission is done through GSM-R and the trackside Eurobalises. The RBC provides the train with its movement authority. The balises are mainly used as a refence point to update the trains location. Level 3 uses a Train Integrity Monitor (TIM) to check if the train is still integer (in one piece). The monitor transmits this information to the RBC using the GSM-R connection. The TIM provides the system with the same data as track circuits and axle counters did in the lower levels. The biggest difference is that the TIM provides this data frequently, instead of only at certain locations or intervals. This allows for the removal of fixed blocks and use of moving blocks where trains keep a minimal set distance from each other based on their individual baking curves. The use of moving blocks would allow for operations with minimal headways between trains. A diagram explaining the principles of Level 3 is provided in Figure 6. The figure shows the importance of the wireless connection between the train and the control centre, since there is no more trackside detection equipment present in the system.

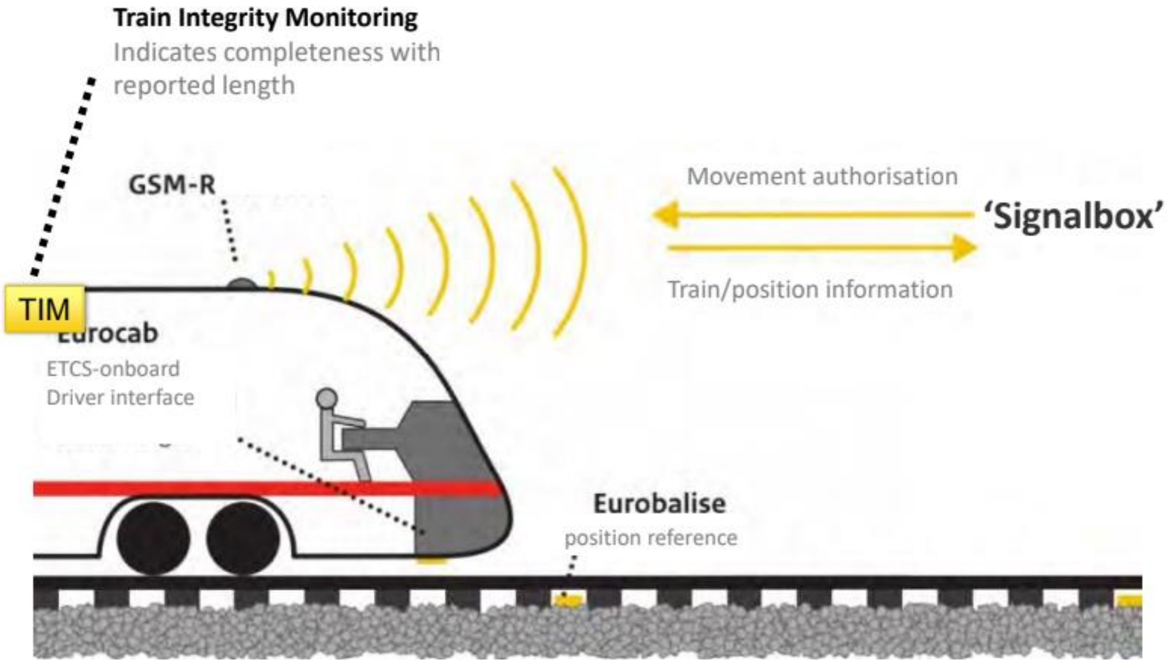


Figure 6 | ERTMS/ETCS L3 principles. Source: (Bartholomeus, 2018)

A pure level 3 system can only be implemented when 100% of the trains contain a TIM unit and are connected to the RBC, otherwise it cannot be guaranteed the track is not occupied, due to the lack of trackside train detection systems. Level 3 can be implemented to save costs on trackside equipment. Since track circuits, axle counters and conventional signals can be removed, this lowers the overall maintenance cost, allowing for low cost operations. The downside is that the GSM-R connection to the RBC and the integrity data from the train are crucial to safeguard the operations. If either one fails at any point, safety cannot be guaranteed.

2.2.2.4. ERTMS/ETCS Hybrid Level 3

The biggest challenges of full Level 3 operation according to (Furness, van Houten, Arenas, & Bartholomeus, 2017) are the necessity of the TIM for all trains and the lack of trackside train detection equipment. In situations where no radio connect is possible for example, the lack of trackside detection equipment means the train will not be viable at all to the RBC. A number of different concepts for implementation of Level 3 systems have been developed. The most mature of which is the Hybrid Level 3 concept.

The Dutch government has stated in a report on the implementation of the Dutch ERTMS-program (Rijksoverheid, 2019b) that they will not include the implementation of Hybrid Level 3 in the current program. The government however did include the preparation of the system for future upgrades into the program. This is also mentioned in a ERTMS-program progress report from the government (Ministerie van Infrastructuur en Waterstaat, 2019). This indicates a future upgrade of the planned Level 2 system to Hybrid Level 3 is likely to happen in a later stage of ERTMS/ETCS implementation on the Dutch railway network.

Hybrid Level 3 is a combination of ERTMS/ETCS Level 3 and conventional trackside train detection equipment. When trains possess a TIM, and other necessary on-board equipment, they can run in a similar way to Level 3 operations, but with fixed (virtual) blocks. The big difference with normal Level 3 is that trains without an integrity monitor can also run on the system due to the presence of the conventional train detection equipment. The trackside detection equipment is used as a backup system to be able to determine if a block section is occupied. This results in a redundant train detection system. The Hybrid Level 3 uses the fastest safe input out of the location information provided by the train and trackside detection. This allows trains without the TIM can run similar to ERTMS/ETCS Level 2 operations. The difference is that the integer train can be followed in level 3 operation and non-integer train (no TIM) can be followed in operation similar to Level 2. This also mitigates delays due to connection loss.

If a train loses connection to the RBC or if a train moves without RBC connection (for example when shunting), the trackside detection equipment will function as a backup to show the physical block that was last known location of the train and all sections the train had authority to enter as occupied until it is certain the block is cleared. Also, if the train position information is delayed either because of communication delays or margins in the train length or position determination (odometry error), the trackside train detection is used to release the section.

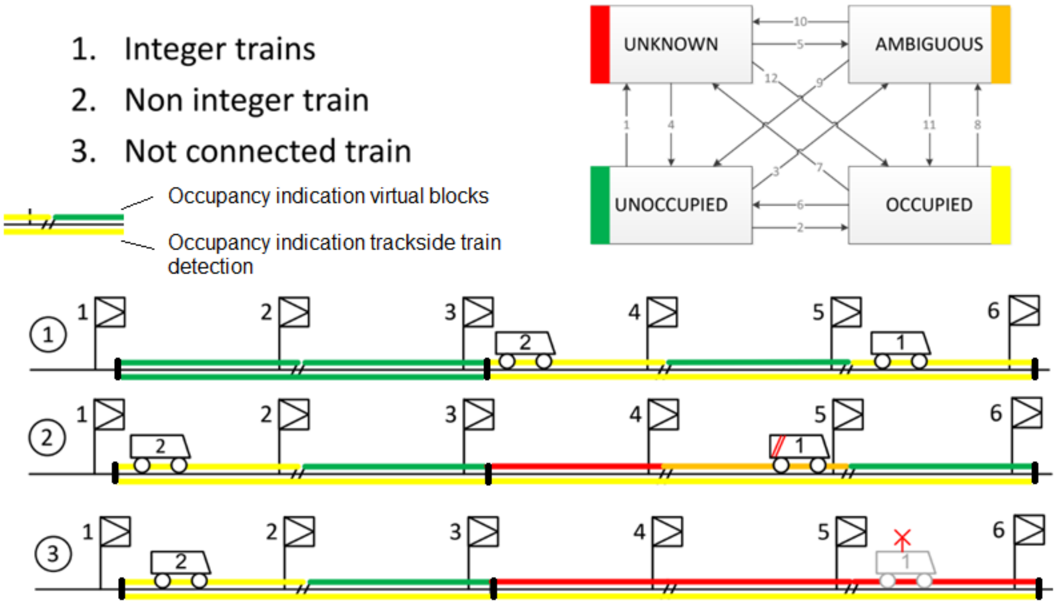


Figure 7 | Hybrid Level 3 signalling. Source: (Bartholomeus, 2018)

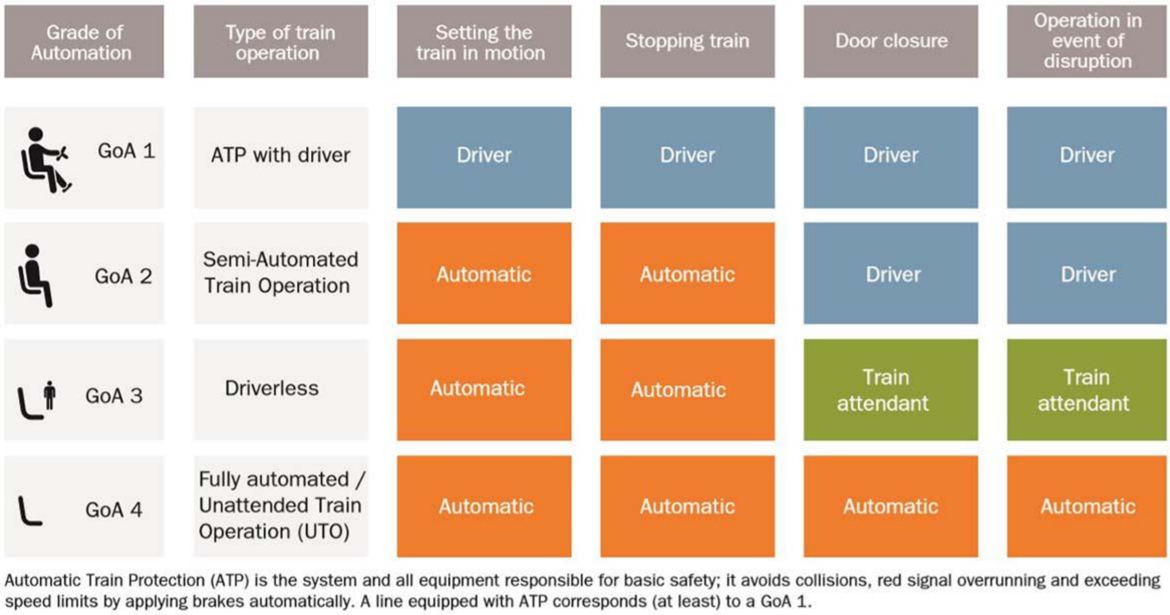
Figure 7 given an overview of how Hybrid Level 3 operation works in three different cases related to the trains TIM and RBC connection. In the figure there is trackside train detection at markers 1, 3 and 6. These form 2 physical block sections, which are divided into a total of 5 virtual block sections. In case 1 both trains have a TIM equipped and are connected with the RBC. The trackside detection shows the entire physical block to be occupied. Due to the TIMs the trains can run in fixed virtual block Level 3 operation, meaning that only the virtual block they are in is shown as “occupied” by the system. This allows the second train to follow close behind and enter the physical block before the first train has left.

In case 2 the first train is not equipped with a TIM. The trackside detection equipment indicates that the train is somewhere inside the physical block section. Through connection with the RBC the position of the front of the train is known, it can be seen that the virtual section between 5 and 6 is indicated by the system as “unoccupied”. The figure shows the virtual section between 4 and 5 to be indicated as “ambiguous”. This means that the system knows that the section is occupied by at least 1 train, but the system does not know if the train is still integer (the train could have split into multiple parts without the system knowing it). The rest of the virtual sections behind the non-integer train that are part of the same physical block section are given the status “unknown” because as long as the trackside detection shows the physical block to be occupied, it cannot be proven that the virtual block section is not occupied. Only when the trackside detection indicates the physical block is no longer occupied, the section can be released.

In case 3 the first train is not connected to the RBC, meaning that it can only operate according to the information provided by the trackside detection equipment. The trackside detection indicates the physical block to be occupied. The virtual block system does not know where the train is within the physical block section, therefore it indicated the state of the entire physical block as unknown. Only when the trackside detection indicates the physical block is no longer occupied, the section can be released.

2.3. ATO

ATO stands for Automatic Train Operation. It means that (a part of) the train operation is computer controlled, instead of controlled by a driver. ATO has been implemented in a number of metro systems worldwide, the earliest since roughly 1970. There are a number of different Grades of Automation (GoA) within the scope of ATO. These have been developed for classifying the automation level in metro systems but are usable for conventional trains also. The grades vary from a driver advisory system or ATP system as a backup to the driver, to a driverless fully automatic operating train. The different GoA can be found in Figure 8, and will also be explained below.



Grade of Automation	Type of train operation	Setting the train in motion	Stopping train	Door closure	Operation in event of disruption
GoA 1	ATP with driver	Driver	Driver	Driver	Driver
GoA 2	Semi-Automated Train Operation	Automatic	Automatic	Driver	Driver
GoA 3	Driverless	Automatic	Automatic	Train attendant	Train attendant
GoA 4	Fully automated / Unattended Train Operation (UTO)	Automatic	Automatic	Automatic	Automatic

Automatic Train Protection (ATP) is the system and all equipment responsible for basic safety; it avoids collisions, red signal overrunning and exceeding speed limits by applying brakes automatically. A line equipped with ATP corresponds (at least) to a GoA 1.

Figure 8 | Grades of Automation explained. Source: (UITP, 2012)

GoA 0
This is when no automation is present in the system. This is on-sight train operations like done in trams.

GoA 1
In GoA 1, the train is operated by a driver in all normal operational situations. The automations that are present lie in the safety systems. An ATP system is present in the operations for when the driver loses control, or an unsafe situation is reached. The automated system will than stop the train. The current manual driving with the ATB automatic train protection on the Dutch network can be considered GoA 1.

GoA 2
GoA 2 is a form of semi-automatic train operation with a driver present in the cab. This entails that a driver or the automatic system starts the train at the beginning of its service. The driver will switch on the automatic systems when operations start. The automatic system drives and stops the train in the right locations. The driver is responsible for closing the doors and making sure it is safe to depart. During disruptions the driver will take over from the automatic system and will operate the train manually.

GoA 3
GoA 3 corresponds to driverless operations (UITP, 2012). This means that the automated system can fully control the train, with no driver present in the cab. An attendant is still on board the train for assisting the system in closing the doors, and possibly taking over operations during disruptions and other situations when the automatic systems cannot reliably operate the train. In normal operations, the attendant does not have to dive the train.

GoA 4
Unattended Train Operation (UTO) is what is classified as GoA 4. This means that the trains are operated fully automatically with no driver or attendant on board the train. This form of operation is so far only implemented in metro systems. Disruptions are also handled by the automatic system. Due to the higher speeds and more complex operations, this form of automatic operation has not been implemented in regular train services.

2.3.1. Benefits of automation

According to a report by (Poulus, van Kempen, & van Meijeren, 2018) ATO has the potential to offer a variety of benefits depending on the grade of automation. The ATO systems can optimise the driving style for specific goals, time savings, creating optimal capacity, or saving energy. The biggest benefit of the ATO system in terms of capacity and reliability is that it removes the effect of human factors from the train operation, creating a more homogenous driving style throughout the operating fleet. Train drivers all have their own driving style, partially depending on how and by whom they were taught. Due to these differences between drivers, a certain size buffer is needed between trains. The ATO systems could be able to limit of even eliminate the need for this buffer due to their ability to create a homogenous driving stile.

The ATO systems have the ability to brake more sharply and replicate the ERTMS/ETCS braking curves more closely, minimising the occupation time of sections of track. The ATO system can be programmed to drive as efficiently as possible to save energy when the energy capacity of the network is (too) small.

2.3.2. Trials and implementations

Implementations

The first heavy rail application of ATO can be seen on the Czech railway network. The Czech ATO system AVV, has been in service for over 25 years already (Kampík, 2016). The AVV system currently used is a GoA 2 type system that is focussed on improving efficiency and reducing the driver workload. ADZ Praha are currently looking into combining the AVV system with ERTMS/ETCS. (Kampík, 2016) mentions this would be the ideal combination for the Czech network.

In 2018 an ATO system produced by Siemens has been put in service on the core section (through the centre of London) of the Thameslink route. The ATO system operates in combination with ERTMS/ETCS Level 2 to provide enough capacity to operate 24 trains per hour per direction through the core of the network (Allgöwer, 2014). The ATO system installed on the Thameslink route is a GoA 2 system. The ATO system drives the train according to the calculated speed profile to keep to its timetable. The system automatically opens the doors and signals the driver when it is time to leave to close them and check the platform is safe. The driver will then initiate the departure procedure.

Trials

ATO trials have been held in several countries over the past few years. As part of their smartrail4.0 program the SBB has been testing the use of ATO over ERTMS/ETCS Level 1 and 2. The goal of the smartrail program is to digitise the railways in Switzerland and create more capacity with the use of ATO. The program targets to implement a GoA 2 system by 2021-22 (Smith, 2018).

The Deutsche Bahn has tested ATO GoA-2 on a line of the Hamburg S-Bahn network. The goal is that by 2021 the line will be in service with a combination of ERTMS/ETCS Level 2 and ATO GoA 2, similar to the Thameslink line in London. DB also tested ATO for main line operations on a 30km stretch of track in Saxony in 2017 using diesel trails.

2.3.3. ATO in the Netherlands

A test with ATO was done on the Betuweroute done by ProRail, Alstom and Rotterdam Rail Feeding (rail freight operator) in 2018. During the test a locomotive travelled over a stretch of track of 100 km in both directions with a GoA 2 system driving the train. An article from SpoorPro (van Gompel, 2018) stated that the test simulated a timetable with stops and also a disruption to where the system had to anticipate how to react to the new situation.

Arriva has also held tests with their trains operating under a GoA 2 system combined with ATB-NG on a line in Groningen. The tests were performed with DMUs produced by Stadler Rail owned by Arriva. During these tests, the effect of ATO on the punctuality and energy efficiency of the trains were studied.

NS announced in 2019 it wants to start doing tests with ATO to find out what the effects would be on regular operations on the Dutch network. An article in the International Railway Journal (Vosman, 2019) stated that NS plans on testing a GoA 2 system on one of their new SNG trains. The first of these tests has been performed in December 2019 on the Hanzelijn between

Lelystad and Zwolle. During the test the ATO system was used to have the trains operate along a pre-programmed timetable to test the accuracy of stopping locations and punctuality of the automatic operations. NS indicated to be interested in further test with ATO GoA 2 over the coming years.

The number of tests with ATO over the last few years make it clear that multiple railway undertakings and ProRail are interested in the development of ATO for the Dutch network.

2.4. OV-SAAL

As part of the thesis a case study will be done on the OV-SAAL corridor. In this section some background information on the OV-SAAL corridor will be provided. SAAL stands for Schiphol, Amsterdam, Almere, Lelystad. Figure 9 shows a map indicating the location of the OV-SAAL corridor. The corridor starts at Schiphol airport, runs through the south axis of Amsterdam and splits off towards Almere an Lelystad after Weesp. In the current situation the entire corridor is equipped with the ATB-EG system.

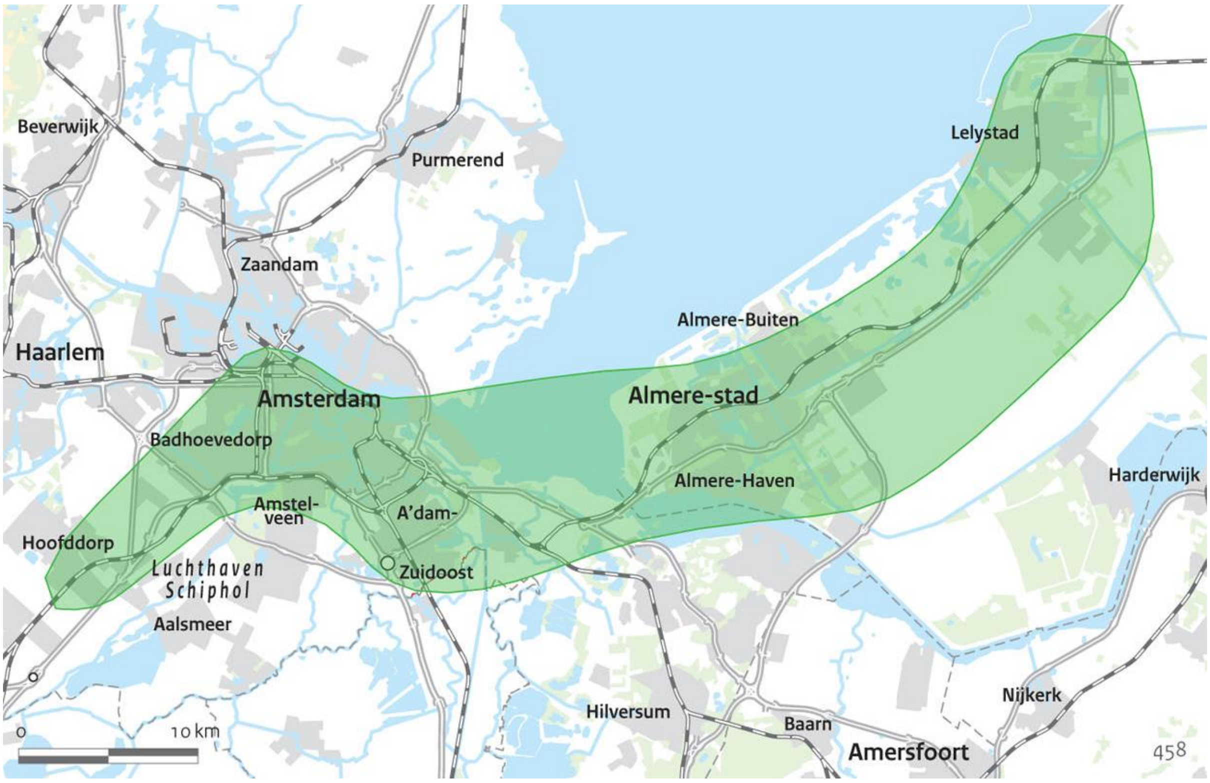


Figure 9 | Map of the OV-SAAL corridor. Source: (Rijksoverheid, 2019a)

Planned projects

Along the OV-SAAL corridor a number of projects are planned that will affect the capacity of the corridor. The Amsterdam Zuid station will be expanded over the coming years. Two platform tracks will be added to the station by 2030 to increase the capacity for train movements along the southern rail axis of Amsterdam.

The station of Weesp is also planned to be expanded. In order to improve the capacity and prepare the corridor for an increasing number of trains, two passing tracks are planned to be added to the station allowing the intercity trains to pass the local trains with increased frequencies. These plans are not fully complete and will depend on whether the planned timetable can be fit into the current track layout of the station.

From 2027 onwards, ERTMS/ETCS Level 2 has been planned to be installed on the entire corridor to allow shorter headway times between trains and improve the capacity. The end goal for the corridor is to implement what the Dutch call “spoorboekloos rijden”, driving without a timetable. What is meant by this is that trains depart every 10 minutes (or even less), basically metro style operations on the main lines.

3. Capacity assessment

In order to determine and compare effects of systems on the capacity of a stretch of track or route, a clear calculation has to be done that can be repeated and applied to all different systems you want to compare. This chapter will describe how capacity can be assessed and what methods will be used during this thesis to assess the effect different signalling and operating systems have on the capacity.

3.1. Standard methods

Two of the most used methods to calculate and compare capacities are calculating the minimum technical headway times and calculating the blocking times for the stretch of track or route of interest. The latter method is often used in combination with the capacity consumption/occupation determining method of the UIC 406 leaflet. The designed timetable build-up of the calculated blocking times is compressed to determine the infrastructure occupation rate.

One observation from tests done within the Swiss smartrail4.0 program is that the characteristics (track layout, topology, etc) of the track section can have large effects on the effectiveness of the systems in terms of capacity creation (Eichenberger, Graffagnino, Hirt, & Scherrer, 2019). This means that results of tests and studies on one route might not be representable for other routes or entire national railway networks. It therefore is important to analyse the methods used when comparing the results of different capacity studies.

3.1.1. Minimum headway times

Calculating the minimal technical headway times gives an indication of the capacity of a stretch of track. The capacity studies done in the smartrail4.0 program of the Swiss national railways SBB all use the minimum headways as the capacity indication. The use of the minimum headways for capacity indication allows for a more easy adaptability of the calculations when new technology and systems such as ERTMS/ETCS and ATO is concerned.

(Eichenberger, Graffagnino, Hirt, & Scherrer, 2019) offer a new concept for the smartrail program to increase capacity. The report on the concepts of smartrail mentions that in Switzerland, blocking sections are not yet widely developed and that the concept of headway times is applied instead. Here the journeys of consecutive trains are observed at each signal through their headways.

A headway model for use on ERTMS/ETCS equipped lines is described where the technical headway time is calculated given a number of train and signalling parameters. The model is described using the following parameters:

- Technical headway time:	tZfZ
- Speed (train speed):	v
- Train length:	s_{Zug}
- Overlap:	s_{DW}
- Signal section length:	s_{SA}
- Braking distance:	s_B
- Response time:	t_E (= 10s, standard in Switzerland)

- Resolution time: t_A (= 2s, standard in Switzerland)

$$tZfZ = \frac{s_B + s_{SA} + s_{DW} + s_{Zug}}{v} + t_E + t_A$$

The equation is a simplified version using a constant homogenous train speed. The braking distance used by the model (s_B) is comprised of de driver reaction time (4s, standard), the technical reaction time (time for the brakes to build up) and the safe monitoring of the braking distance (example: ERTMS/ETCS braking curve supervision).

The headway model can be converted to a blocking time model to be able to compare the different signalling systems. Figure 10 gives an indication of how the headways can be translated to blocking distance.

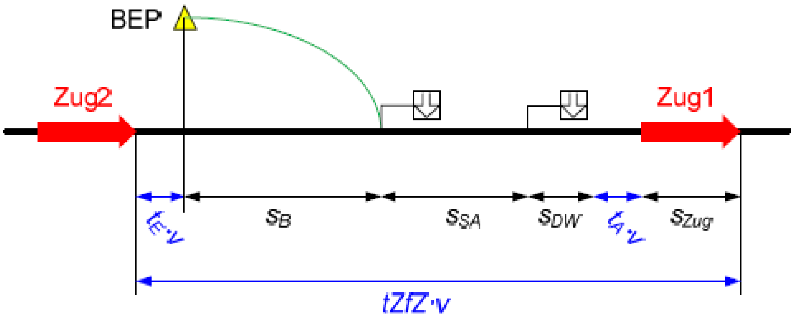


Figure 10 | Technical minimal headway model. Source: (Eichenberger, Graffagnino, Hirt, & Scherrer, 2019)

3.1.2. Blocking time theory

Blocking time is the time a block section is reserved for use by a specific train. Figure 11 gives an overview of what the blocking time consists of. It represents the amount of capacity necessary for that specific train. Blocking times are more focussed on the infrastructure. Using blocking times instead of the minimal headway times allows to create a full timetable based on the capacity of the infrastructure. The standard blocking time model is depicted in Figure 11 below. The figure contains a visual representation of the block time for the ATB/NS'54 signalling. It contains the following elements:

- Setup time (i.e. route formation/interlocking)
- Sight/reaction time
- Approach time
- Physical block occupation (i.e. 1 block length/running distance)
- Clearance time
- Route release

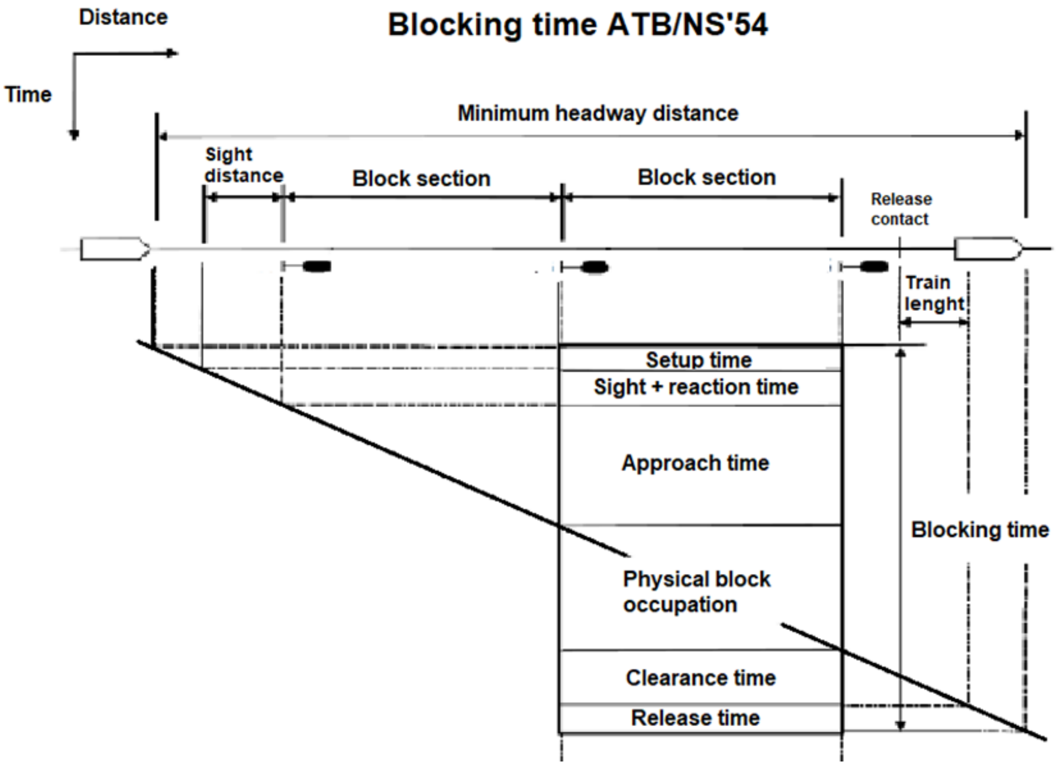


Figure 11 | Standard blocking time model. Source: (Hansen & Pachl, 2014)

The standard blocking time model is designed for visual trackside signalling systems similar to the Dutch ATB and NS54 system. In this model the approach distance/time is usually the length of one block, unless approach signals are used. The running distance also equals the length of one block. The clearance time is the time needed to travel the distance from the end of the block (used for running time) to the point where the entire train has cleared the detection point clearing the block. The clearing distance basically equals the train length plus the distance between the signal and release contact. The route release is the time the interlocking takes to release the block after the entire train has past the release contact.

The standard blocking time model is used within the capacity consumption method from the UIC leaflet 406 (International Union of Railways, 2013). This method will be explained further in the next section. The standard blocking time model can be adapted for the use on cab signalling systems. This adaptation will be explained in section 3.3 using the ERTMS/ETCS braking curves explained in section 3.2.

3.1.3. UIC Code 406 for railway capacity assessment

According to the UIC leaflet 406, capacity occupation time rate can be used as an indicator for the overall capacity on a track section with a given timetable. The leaflet describes a timetable compression method that is used to calculate this capacity occupation rate. The capacity occupation rate represents the utilisation of the infrastructure, displaying the occupancy time of the infrastructure over a selected time period.

$$Occupation\ time\ rate\ [\%] = \frac{Occupancy\ Time}{Defined\ Time\ Period} \times 100$$

The occupation time itself is determined through a blocking time model. The occupation rate is determined by compressing the timetable. This is illustrated in Figure 12. The occupation time rate is calculated over a defined time period, usually 1 or 2 hours to include the time table patterns. When an entire corridor or network is concerned a larger time period, equal to the operation time should be used. The timetable for a day/period representing the timetable characteristics should be used in the calculations of the occupation time rate.

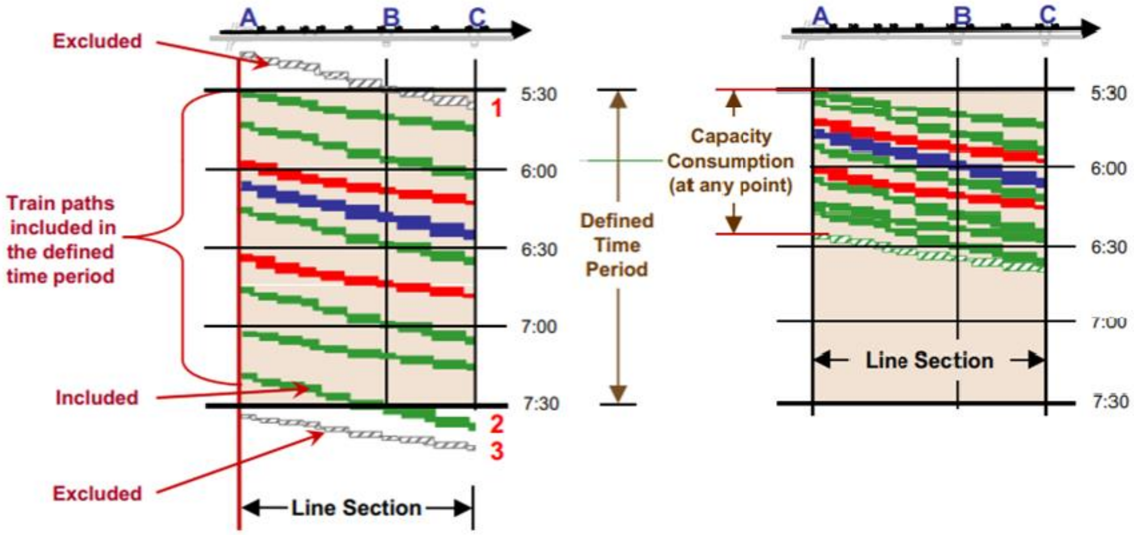


Figure 12 | Timetable compression method explained. Source: (International Union of Railways, 2013)

Figure 12 shows the application of the timetable compression method. Only train paths that start inside the defined time period are included in the calculation. In order to determine the occupation time, the first train path within the defined time period can be copied and inserted into the timetable after the final train path. The start of this copied train path denotes the capacity consumption (right figure of Figure 12).

Within this thesis, a capacity study will be done for the OV-SAAL corridor. The corridor contains a number of stops and crossing traffic that needs to be taken into account when looking into the capacity occupation of a timetable. The UIC 406 leaflet describes ways to take this into account. If the train stop occurs in a place with no overtaking possibilities it will be included in the occupancy time within the compression method because the main line will be occupied. When a train is stopped on a side track off the main line and passing is possible, the stopping time will not be taken into account in the timetable compression method as shown in Figure 13. Crossing traffic also has to be taken into account in the compression method because the main line is temporarily occupied by this traffic.

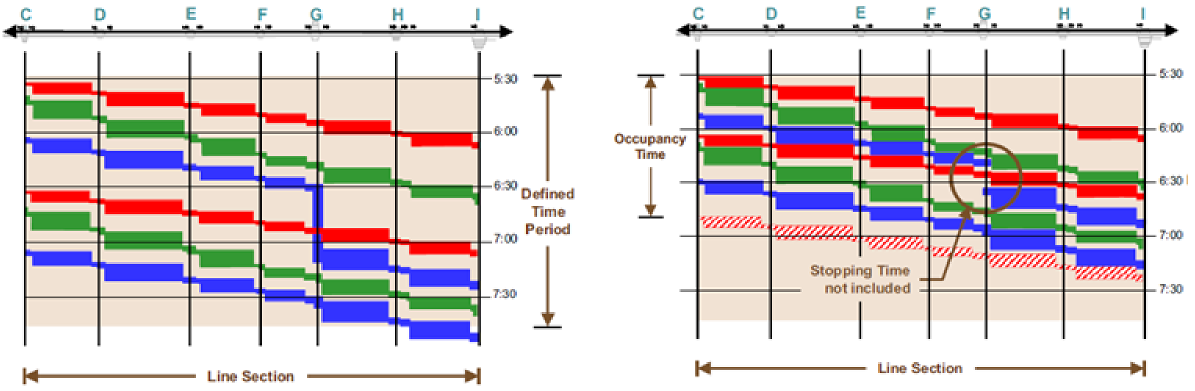


Figure 13 | Stopping time in compression method. Source: (International Union of Railways, 2013)

The UIC specified a norm for the occupancy rates depending on the types of lines. The infrastructure managers have the choice whether or not to use the proposed occupancy time rates. The occupancy time rates shown in Table 2 give an indication of what portion of the capacity can be used to provide a stable timetable.

Table 2 | Occupancy time rates proposed by the UIC. Source: (International Union of Railways, 2013)

Type of line	**Peak period**	**Daily period**
Dedicated suburban passenger traffic	85 %	70 %
Dedicated high-speed line	75 %	60 %
Mixed-traffic (passenger + freight) line	75 %	60 %

The occupancy time rate depends on the composition and characteristics of the time table. The more homogenous the timetable is, the lower the occupancy time rate will be compared to mixed traffic (regional train, IC, freight) lines. The service pattern of the timetable however, does not always allow for a homogenous time table.

When looking at the occupancy time rate of a longer line, the line can be split into sections to simplify the process. These sections should start and end at a point where trains can pass each other. The line sections will be looked into individually and the occupancy time rate of the entire line is determined by looking at the critical occupancy time rate of the individual line sections. The critical occupancy time rate is the highest rate of the individual line sections. This critical rate will than count as the occupancy time rate for the entire line.

3.2. ERTMS/ETCS braking curves

In order to be able to apply the blocking time model for cab signalling systems (ERTMS/ETCS Level 2 and Hybrid Level 3) the basic model has to adapted to include the ETRMS/ETCS braking curves used in the systems. The braking curves and theory behind them will be explained in this section.

ERTMS/ETCS supervises a trains speed and location to ensure that it is not outside the permitted bounds (speed limit and MA). The ERTMS/ETCS will command the intervention of the braking system of the train to avoid the risk of the train exceeding the limits of its authority. Based on the track and train characteristics, the on board EVC (European Vital Computer) calculates braking curves over distance using a mathematical model. The braking curves all lead to the same point in distance, the Supervised Location (SvL). Depending on national values, the SvL could be the same location as the End of Authority (EoA). In the Netherlands this is the case.

There are two kinds of braking curves, safety braking curves and guidance curves. The safety braking curves are designed to provide what the ERA called a parachute function (European Railway Agency, 2016a). This shall be understood as the preventive reaction of the control systems against a train exceeding its authority limits. In addition to this functionality, the guidance braking curves provide an advising function to the train driver.

The guidance curves: Indication (I), Permitted speed (P) and Warning (W) curves, are calculated in real time by the on board ERTMS/ETCS system based on the trains speed location and MA. The safety curves (EBI, EBD, SBI, SBD) are used for commanding the brakes in case the drivers' reactions are insufficient.

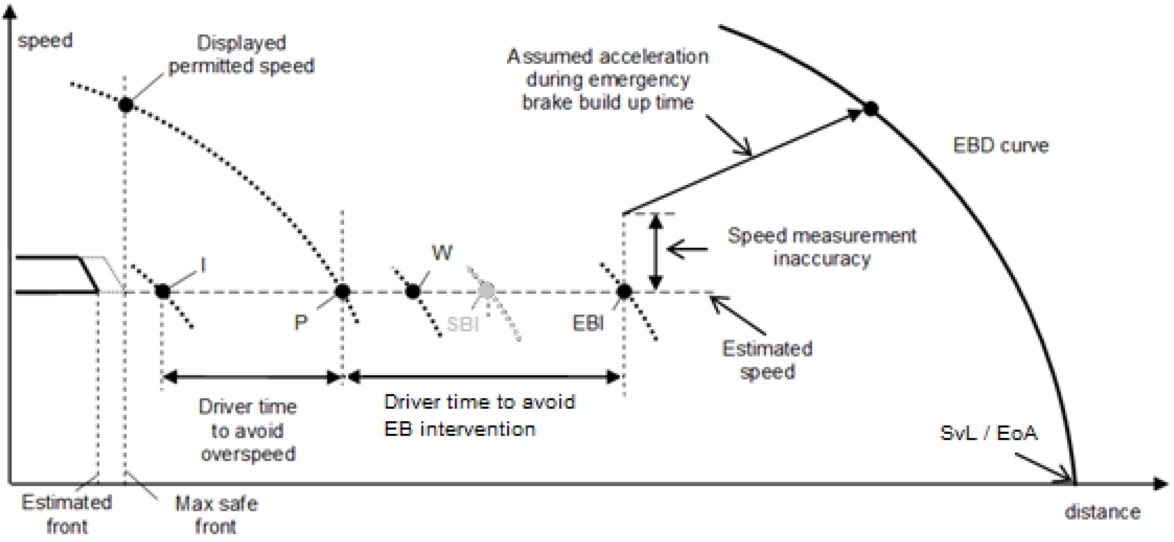


Figure 14 | Overview of EBD curve and related supervision limits. Source: (European Railway Agency, 2016a).

The ERTMS/ETCS has the option to command the service brake of the train to prevent excessive wear of braking disks and track on the emergency brakes. If this option is selected 2 facultative curves will be calculated, the Service Brake Deployment (SBD) and the Service Brake Indication (SBI) curves. If the driver does not apply the brakes in time or enough and the SBI is passed, the service brake is deployed, and the train will brake according to the SBD curve. In the Netherlands this option is not selected, and only the EBI and EBD will be used as intervention curves.

The final "parachute" of the system is the emergency brake application function. This is guarded with the Emergency Brake Indication (EBI) curve. Similarly as explained above with the SBI curve, the ERTMS/ETCS system commands the application of the brakes when the EBI curve is passed. After the brakes build-up and become effective, the train will brake according to the Emergency Brake Deployment (EBD) curve. Based on the location of the EDB curve, the locations of the other braking curves are determined. Figure 14 gives an overview of the braking curves and their relations.

3.2.1. Braking curve parameters

The braking curves are calculated by an algorithm in the on board EVC requiring numerous input parameters based on the following:

- Physical parameters measured by the on-board unit (speed, position, acceleration)
- Fixed values defined in the ERTMS/ETCS baseline
- Trackside data, transmitted through the balises (target speeds, slopes, etc)
- On-board data relating to the rolling stock

The trackside and on-board data are the most important relating to the EBD curve. The system must predict with a certain confidence level that the trains will be able to stop according to the EBD curve to fulfil the level of safety required for operations.

Using a number of factors, the guaranteed deceleration is determined based on the train and trackside conditions to provide a EBD curve that a train is guaranteed to be able to follow. An introduction document to braking curves from the ERA (European Railway Agency, 2016a) describes the method used to model the EBD curve. It is modelled as a set of interconnecting curves between target locations based on the guaranteed deceleration form the emergency brake (A_safe_brake) between certain speeds and the acceleration/deceleration due to gradients (A_gradient) in the tracks. Figure 15 shows the influence of these two parameters on the EBD curve.

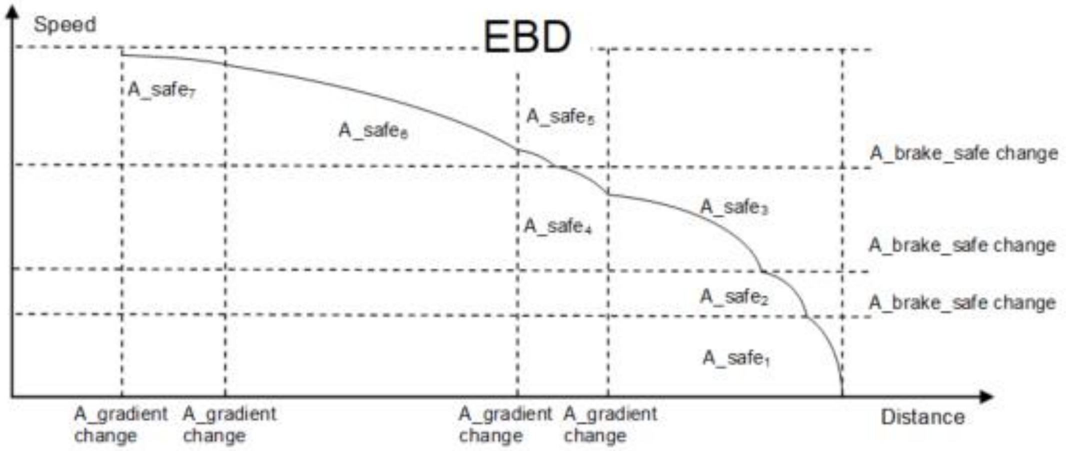


Figure 15 | Construction of the EBD curve. Source: (European Railway Agency, 2016a).

Due to the safety braking curves being safety critical, it is crucial that the braking curves must be guaranteed to be achieved by the rollingstock with a certain confidence level. The nominal brake performance (A_brake_emergency) is captured in a step function of deceleration against speed. A guaranteed brake performance is quantified by using a number of correction factors related to the characteristics and conditions of the track and rolling stock. Reference conditions are determined under which the nominal braking performance must be established. These conditions include: environmental conditions, friction elements, wheel and rail profile wear and more. Two districts correction factors have been created to get the guaranteed deceleration.

Kdry_rst is used to quantify the performance of the emergency brakes on dry rails. The value for this factor is determined through a Monte Carlo analysis combined with a confidence level

(N_NVEBCL) determined at national level by the IM. The thesis by (Jansen, 2019) denotes the typical vales for Dutch rolling stock to be in the range of 0,70-0,88.

Kwet_rst quantifies the loss of emergency braking performance on a reduced wheel/rail adhesion, compared to dry rails. This value can be quantified through field tests as per the EN15595 standard. Dutch law prescribes the safe braking deceleration is to be based on braking performance in dry conditions, therefore the Kwet_rst factor is not used. The factor is mitigated through via a weighting factor M_NVAVADH

3.2.2. Gamma and Lambda trains

The ERA describes Gamma trains as trains with a fixed composition or a finite number of predefined compositions. For these trains it is possible to preconfigure deceleration profiles, correction factors and brake build-up times. The EBD curve is determined through the following factors and formulas. Figure 16 depicts the relations between variables and factors to determine the EBD curve (A_{safe}).

$$A_{brake\_dry} = A_{brake\_emergency} \times K_{dry\_rst}(M\_NVEBCL)$$
$$A_{brake\_safe} = A_{brake\_dry} \times \{K_{wet\_rst} + M\_NVAVADH \times (1 - K_{wet\_rst})\}$$
$$A_{safe}(v,d) = A_{brake\_safe}(v) + A_{gradient}(d)$$

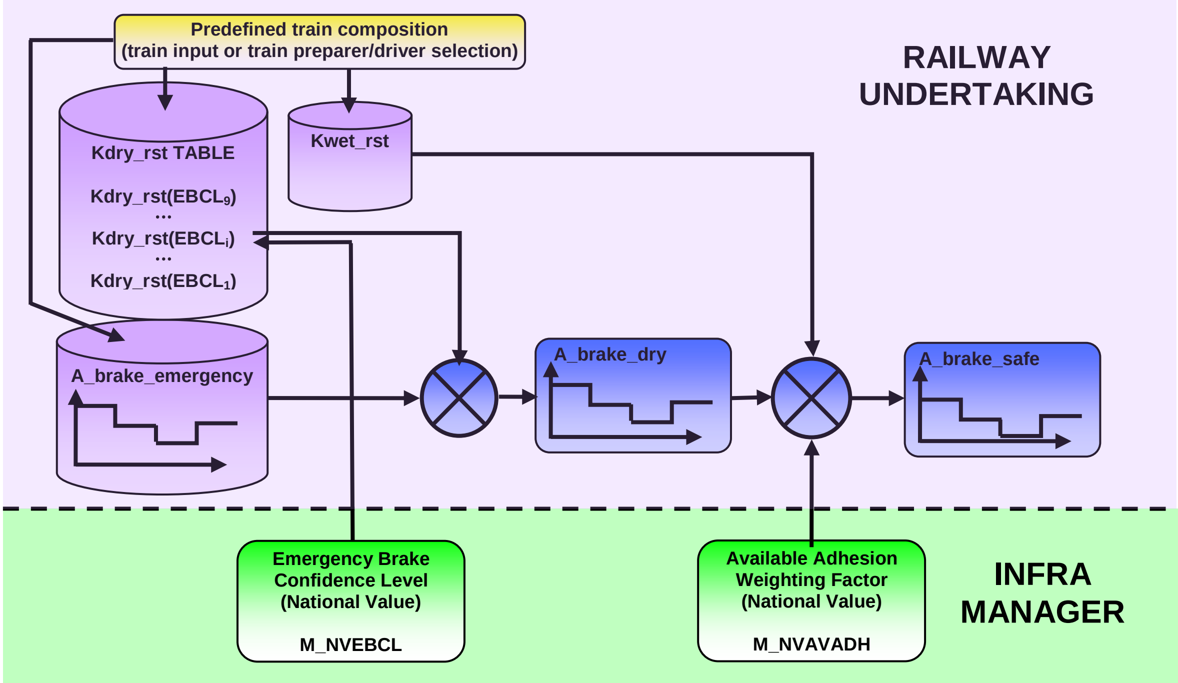


Figure 16 | Correction factors for Gamma train in EBD calculation. Source: (European Railway Agency, 2016a)

In the case of variable composition trains, it is not possible to predefine the parameters and correction factors needed for EBD calculation. In this case the braked weight percentage needs to be entered by the driver or preparer of the train to calculate the trains braking power. The on-board ERTMS/ETCS unit converts this into the EBD curve and a brake build-up time. These trains are called Lambda trains.

The IM defines a number of correction factors that will be sent to the train through the trackside ERTMS/ETCS equipment. These factors are dependent on the train type, and train length and are provided in form of a step function of the trains speed or length. Figure 17 shows how the trains braking parameters are determined using the pre-defined factors.

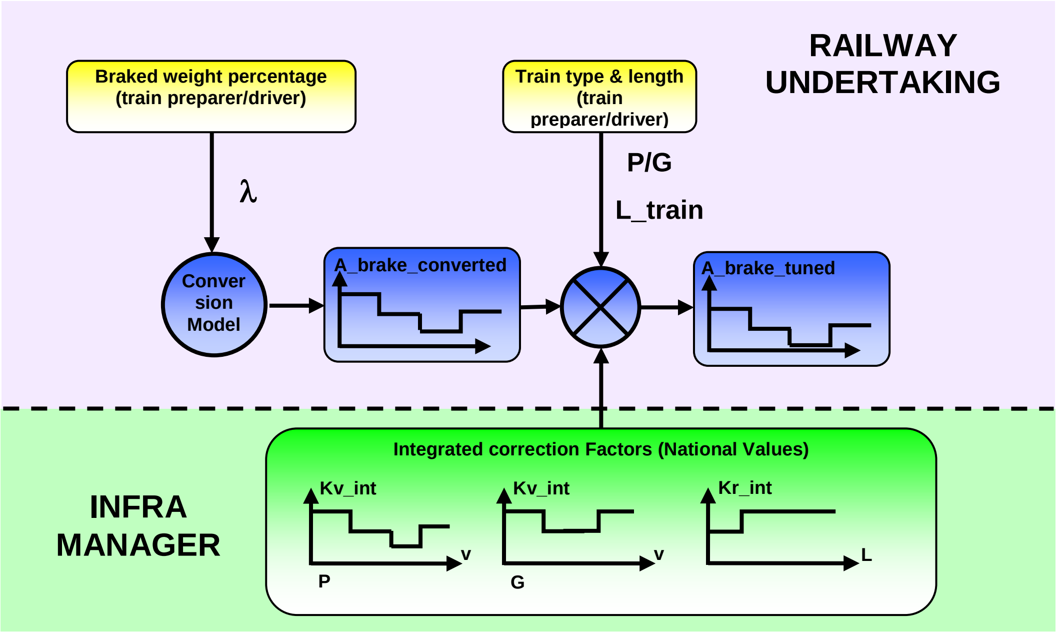


Figure 17 | Correction factors for Lambda trains. Source: (European Railway Agency, 2016a)

The parameter A_{brake_tuned} is the equivalent of A_{brake_safe} for Lambda trains. In order to compute the EBD curve, the following formulas are used.

$$A_{brake\_tuned} = A_{brake\_converted}(\lambda) \times K_{v\_int}(Train\ type) \times K_{r\_int}(L\_train)$$
$$A_{safe}(v,d) = A_{brake\_tuned}(v) + A_{gradient}(d)$$

3.3. Translating braking curves into blocking times

As mentioned in section 3.1.2, the standard blocking time model corresponds to trackside signalling systems and fixed block operations. The standard model can be transformed to be able to be used for in cab signalling systems such as ERTMS/ETCS Level 2 and Hybrid Level 3. A paper on the enhancement of blocking time theory (Büker, Graffagnino, Hennig, & Kuckelberg, 2019) describes enhancements to the basic blocking time model in order to make it applicable for use on newly developed interlocking and signalling architecture.

3.3.1. ERTMS/ETCS

The paper by (Büker, Graffagnino, Hennig, & Kuckelberg, 2019) provides a model specific to ERTMS/ETCS Level 2 (ATP, cab signalling with fixed blocks). The principles of the blocking time model remain the same as the basic model. The time component in the model for ERTMS/ETCS Level 2 are the following:

- Route setup
    - MA request, issuing and transmission
    - Interlocking
- Sight/reaction time

    - Indication time
- Approach time
    - Driver reaction time
    - Brake build-up time (E-brake)
    - Braking distance (EBD)
- Running time
- Clearing time
- Route release

The adaptation of the standard blocking time model to ETCS characteristics can be found in the route setup and the approach times. The MA request, issuing and transmission is added into the route setup. According to a report on the assumptions for calculating follow-up/headway times (ProRail, 2018b), this adds 6s to the route setup times.

The largest difference can be seen in the approaching distance/time. In the new model, this is no longer the length of a full block. Instead the approach time is based on the ERTMS/ETCS braking curves. The approach distance can be seen as the distance between the Permitted (P) curve and end of authority (EoA) which is at the end of the emergency brake deployment (EBD) curve. The approach consists of the driver reaction, the brake build-up time and braking distance. The sight time consists of the time distance between the Indication (I) curve and the P curve. This indication time consists of the driver reaction time and brake build-up time according to the ERTMS/ETCS specifications.

According to standards set by the European Railway Agency (ERA) the indication time and driver reaction time (between I and EBI curves) is 13s for passenger trains plus the braking time of the train. Figure 18 below shows what this time consist of.

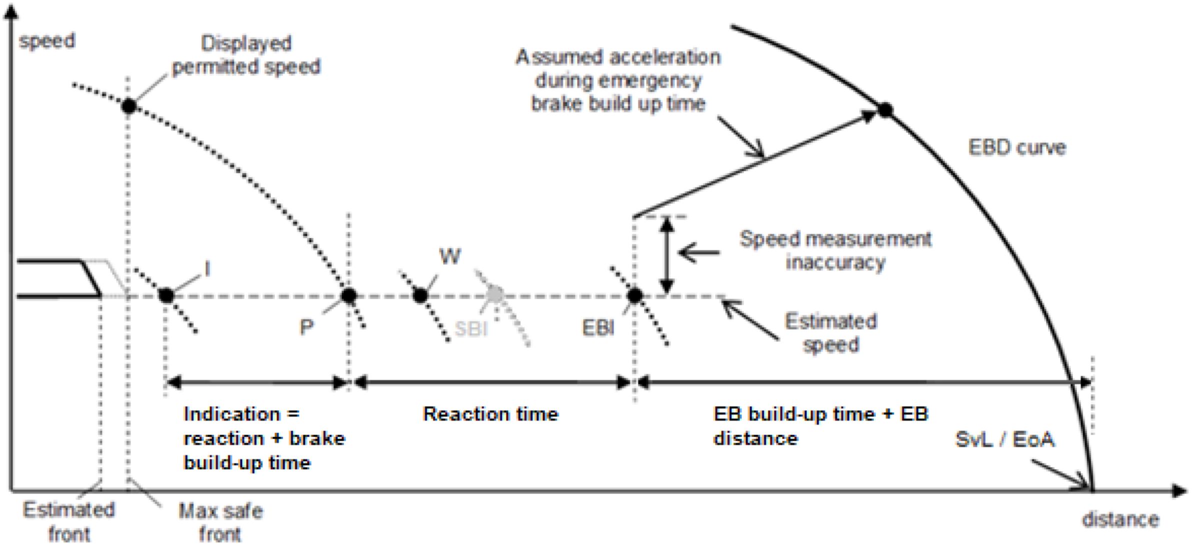


Figure 18 | Approach time based on braking curves. Source: (European Railway Agency, 2016a)

In the subset 26-3 v360 of the (European Railway Agency, 2016b), the indication time (in seconds) is determined by the following formula:

$$T_{indication} = max\{(0.8 \times T_{bs}), 5\} + T_{driver}$$

With:

$$T_{bs} = (service) brake\ build\ up\ time$$

$$T_{driver} = driver\ reaction\ time = 4s$$

The max {(0.8*T_{bs}), 5} is put into the formula due to the brake build-up time of freight trains being significantly longer than that of passenger trains. In the case of passenger trains, the 5s is applied. The driver reaction time is used twice in determining the approach time. The first time is in the indication time (between I and P) and the second time it is used as the time between the P and EBI curves. The braking distance and brake build-up times depend on the characteristics of the trains (length, weight, speed, etc).

The standard blocking time diagram (Hansen & Pachl, 2014) is adapted to ERTMS/ETCS Level 2 in Figure 19. The approach time is based on the permitted braking curve of the ERTMS/ETCS system. The approach distance equals the braking distance of the permitted curve.

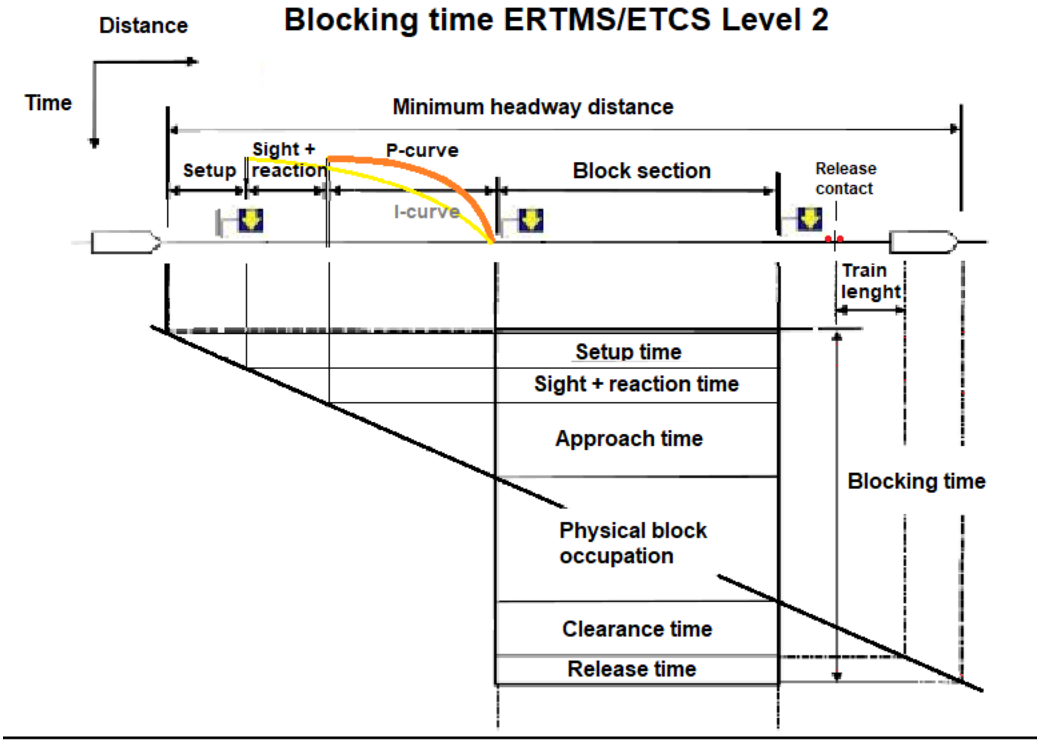


Figure 19 | Blocking time diagram for ERTMS/ETCS L2 based on the standard diagram (Hansen & Pachl, 2014)

In the case of the Hybrid Level 3 system, the blocking time consists of the same components as provided in Figure 19. The difference between the blocking time for the Level 2 and Hybrid Level 3 systems can be seen in the block occupation and the clearance time. The block reservations ahead of the trains under the Hybrid Level 3 system are based on the smaller virtual blocks. The route setup, sight + reaction and approach portion of the blocking time for the Hybrid Level 3 system follow the same principles shown in Figure 19.

Integer trains (trains with functioning TIM) release the virtual block sections at the location of the marker boards (SMB). The non-integer trains can only use the release contacts located at the edges of the physical block sections to release the physical block sections behind them, resulting in a longer block occupation compared to the integer trains. Figure 20 provides a blocking time diagram adapted to the Hybrid Level 3 system. The diagram contains a representation of the blocking times for integer and non-integer trains.

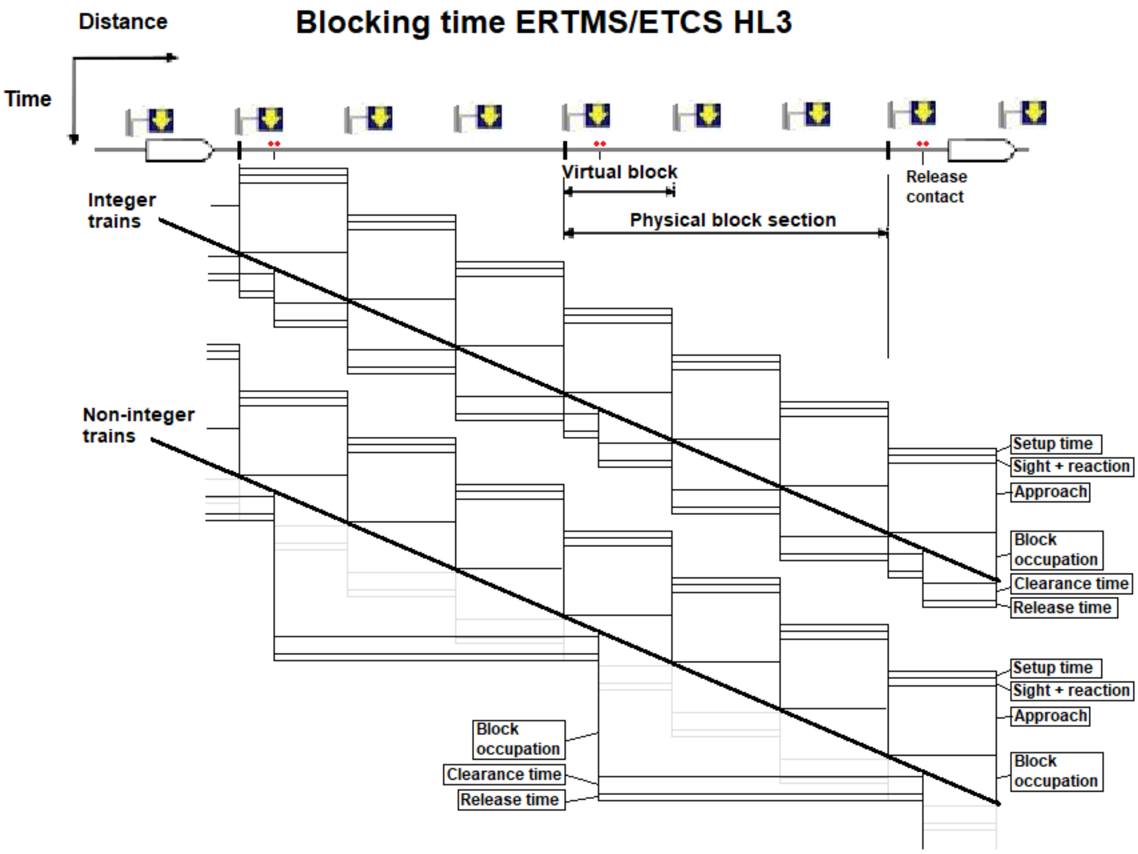


Figure 20 | Blocking time diagram comparing integer and non-integer trains under ERTMS/ETCS HL3

3.3.2. ATO and blocking time

Figure 21 contains a version of the blocking time model for use on the combination of ATO over ERTMS/ETCS has been proposed in (Büker, Graffagnino, Hennig, & Kuckelberg, 2019). Within this model it is assumed the ATO will determine the optimal speed profile for the train, without exceeding the ERTMS/ETCS speed limits. When braking is concerned, the ATO reacts different from the human driver. Where the human driver is supposed to follow the permitted curve when braking, the ATO will follow an ATO specific SBD curve. Similar as in the ERTMS/ETCS Level 2 model, the blocking time is based on the EBD and EBI curves. In order to avoid ERTMS/ETCS brake intervention, a buffer is added to ensure sufficient computation times for the ATO system to apply the service brake. In the model, the EBI curve is used as the reference point.

The block reservation for the ATO is based on the ATO specific indication curve (ATO-I curve). The ATO-I curve covers the ATO reaction and approach portion of the blocking time. The distance between the ATO-SBD and ATO-I curves equals the system reaction time + build-up time of the brake. The mentioned system reaction time buffer for the ATO is the time between the ATO-SBD curve and the EBI curve.

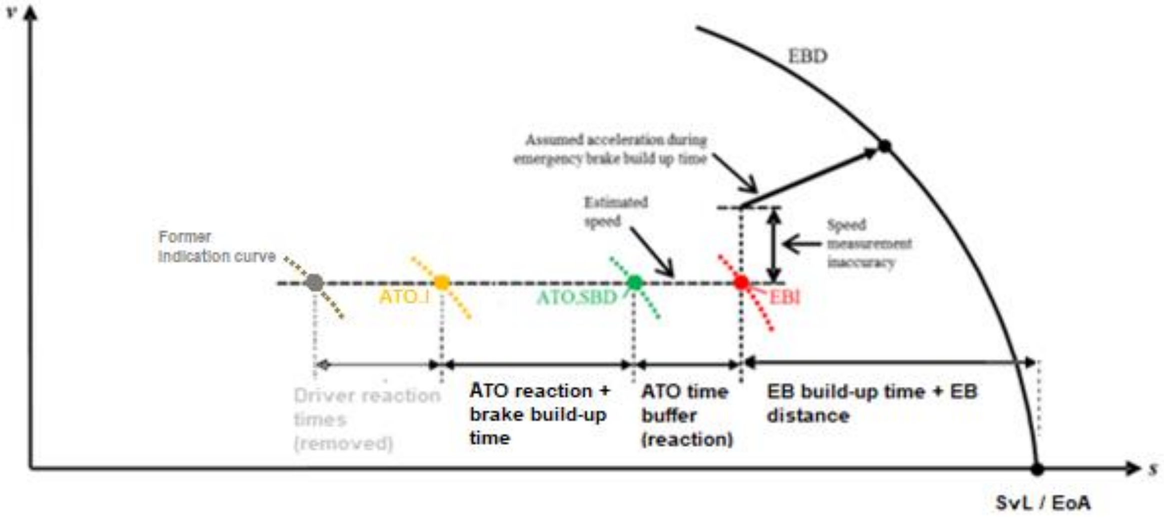


Figure 21 | Approach distance for ATO blocking time. Source: (Büker, Graffagnino, Hennig, & Kuckelberg, 2019)

The blocking time model for ATO contains the following time components:

- Route setup
    - MA request, issuing and transmission
    - Interlocking
- ATO reaction
    - ATO system reaction time
    - Brake build-up time
- Approach time
    - Brake build-up time (E-brake)
    - Braking distance (EBD)
    - ATO buffer time (system reaction time)
- Running time
- Clearing time
- Route release

The biggest differences between human driving and the ATO when computing blocking time under ETCS is the removal of the sight and driver reaction times. The driver reaction time is replaced by a reaction time of the ATO system. This system reaction time is smaller than the driver reaction time. This means that the ATO system can brake later than a human driver would, and at a higher braking rate. This shortens the approach distance and therefore also the allowed headways.

When translating the blocking time diagram for the human driver under ETCS to the ATO, the permitted curve used for the approach time for the human driver is replaced by the ATO service brake curve (ATO-SBD). Similarly, the indication curve is adapted to the ATO specific indication curve shown in Figure 21.

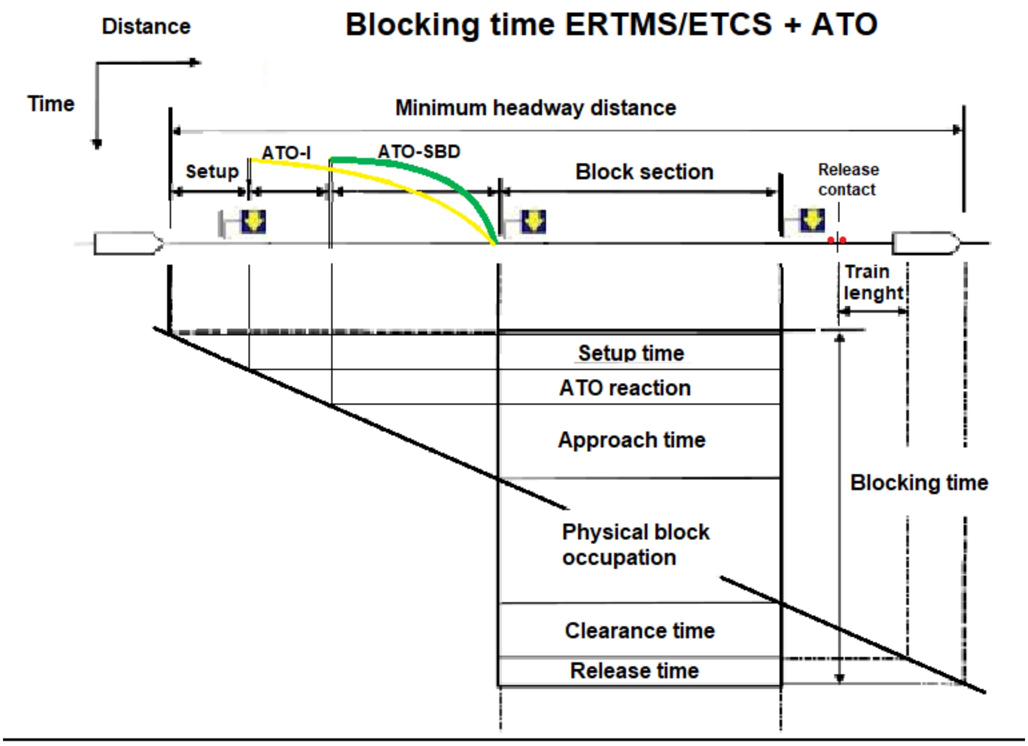


Figure 22 | Blocking time diagram from (Hansen & Pachl, 2014) converted for ERTMS/ETCS + ATO

Figure 22 translates the blocking time model shown in Figure 21 into the blocking time diagram. The ATO system reaction time combined with the brake build-up time is used as the distance between the ATO braking curve (ATO-SBD) and the ATO indication used for the block reservations. This system reaction and brake build-up time replaces the sight and reaction times used in the blocking time theory for human driving.

4. Modelling tool

This chapter will provide a comparison between the available modelling tools within ProRail. The modelling tool chosen for this study will be explained further in this chapter. The basics of the tool will be explained, including parameters and constraints within the software.

4.1. Tool comparison

Within ProRail a number of different modelling tools are used. The tools available within ProRail for modelling capacity on the rail network are Open Track, RailSys and FRISO. Out of these, FRISO has not been considered for use for this study due to it not containing the functionality to model the ETCS Hybrid Level 3 system that would be necessary for this study. For this reason, it has been excluded from the tool comparison. In this study, RailSys has been chosen as the tool for the modelling portion. In the following section the functions of the different tools will be explained, and a short comparison is made between the tools to clarify this choice.

4.1.1. Open Track

Open Track is commercial rail modelling software designed to model and solve complex problems in railway operations. The software is able to model various types of railway systems. Open Track is a simulation tool that can be used for a variety of simulations regarding timetable evaluations, delays or capacity studies. Figure 23 provides a schematic view of the different modules of Open Track.

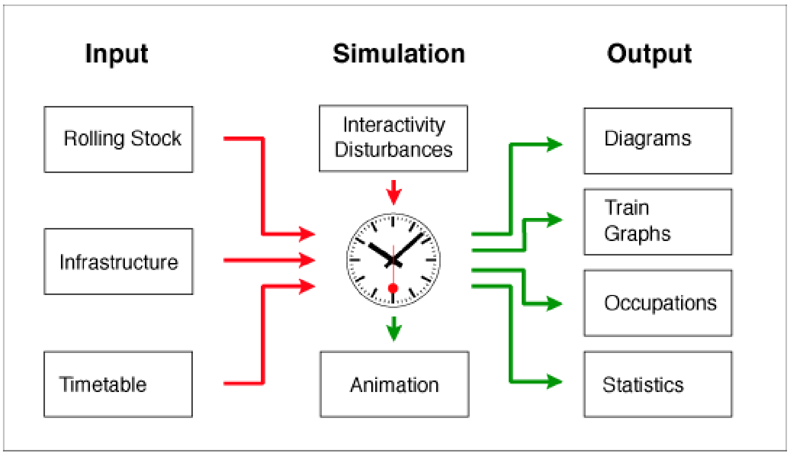


Figure 23 | Schematic showing simulation modules. Source: (Open Track Railway Technology, 2019)

Inputs

As shown in Figure 23, the model uses rolling stock, infrastructure and timetable modules as inputs for the simulation. The infrastructure module contains all the network data. A number of different signalling systems are available within Open Track including a variety of different ETCS systems and ATO. The rolling stock module contains a library of different locomotives, passenger and freight cars and full trainsets. The rolling stock is linked to the different train paths in the timetable module.

Within ProRail, the timetable modules are directly imported from the planning software DONS and DONNA. This allows for an easier build-up of the model. The timetable data contains sets of departure and arrival times, minimal stopping time and connections between trains (Open Track Railway Technology, 2019).

Simulation functions

Open Track is a simulation tool where a full simulation needs to be run before any type of results can be gathered from it. Since running a full simulation takes time, testing the effects of small changes and model tweaks is very time consuming. During the simulations, the train runs defined in the timetable module run on the network and try to adhere to the defined timetable. The train runs are calculated using the rollingstock and infrastructure data. The infrastructure and signalling systems are used as the constraints for the model's calculations.

While performing the simulation, an animation of the train movements can be viewed. The animation includes the infrastructure occupation, signal aspects and interaction between trains. After the simulation is completed a number of different evaluations can be done with the gathered simulation data. Data on the train movements can be viewed for individual trains. This data includes speed, acceleration, position and power consumption (Open Track Railway Technology, 2019). Open Track can run multiple simulations with different initial delays and delays in stations in order to assess the robustness of a timetable and network.

Open Track contains a headway calculator. The calculator can determine the minimal headways between two different train runs on a selected piece of the infrastructure. The critical block section where this minimal headway is determined can also be shown in the headway calculator. This tool within the software can be used for both fixed and moving block signalling systems. The minimum headways can then be used for compressing the timetable to determine the infrastructure occupation according to the methods described in the UIC 406 leaflet.

System configurations

In order to properly model the effects of the different driving behaviours and ATO on the capacity, it is necessary to adapt the braking behaviour under ERTMS/ETCS. Open Track uses an individual fixed braking curve for each train based on the programmed ERTMS/ETCS and rolling stock braking parameters. This fixed braking curve cannot easily be adapted to suit different braking behaviours.

4.1.2. RailSys

RailSys is commercial railway simulation and planning software. Similar to Open Track, RailSys consists of a number of modules containing different parts of the modelling process. The software consists of an infrastructure manager, timetable and simulation manager and an evaluation manager. Figure 24 contains a schematic of the RailSys workflow. The RailSys workflow moves along a line through the different modules, with each module providing inputs for the next.

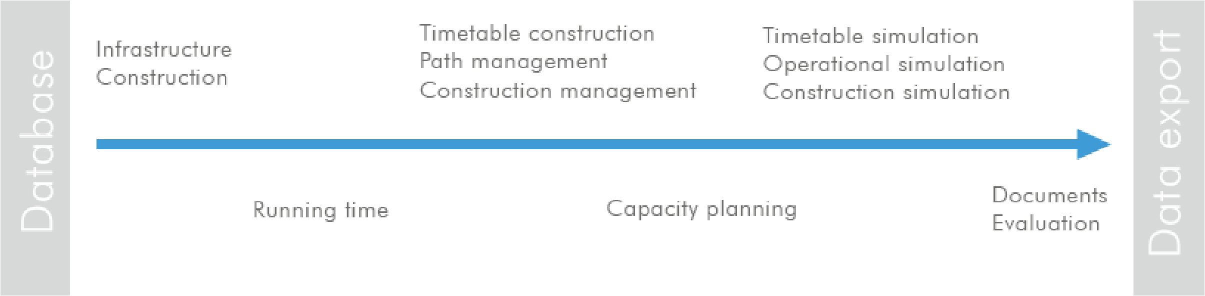


Figure 24 | Schematic of the RailSys workflow, source: (Rail Management Cosultants International GmbH, 2020)

Inputs

The input for the RailSys modelling software starts with the infrastructure manager module. It is used to build and edit the infrastructure and block sections related to the infrastructure. The infrastructure manager contains settings for a variety of signalling systems including the Dutch ATB system and several versions of ETCS. The signalling systems within RailSys can be configurated based on what version or national values need to be used. After the infrastructure itself and the block sections are created, a number of routes over the infrastructure can be created. These routes will be used later in the timetable manager to determine the train paths and running times.

The software automatically checks the validity of each input, providing warnings or error messages when the input is incomplete or outside the conventional range of the parameters. After infrastructure changes are applied, the infrastructure manager module needs to be loaded into the timetable manager. It is important to note that RailSys will not allow you to continue to the timetable manager when critical errors are detected in the infrastructure within the model. This helps to prevent larger errors made early on in the model to progress through to later stages and affect the quality and functionality of the simulations.

The timetable manager is the module where the timetable is put into the model. The timetable data consists of series of train paths containing requested arrival and departure times. The routing of the train paths is determined by the routes created in the infrastructure manager. These train paths are linked to rolling stock templates allowing for the calculation of the feasible running time and arrival/departure times. The timetable manager also contains the operational parameters of the signalling systems allowing for changes in driving behaviour to be input into the model.

Currently it is not possible to import premade timetables directly from other modelling tools, making the initial timetable input a time-consuming process. Importing timetables from other RailSys projects however is possible. Similar to the previous step, the program does not allow you to continue when critical errors are found in the timetable. Only when these are resolved, can the simulations be done.

Simulation functions

RailSys is a simulation and planning tool as mentioned earlier. The planning options in RailSys allow for a direct feedback. Every change in the timetable or infrastructure will give a direct result in the timetable manager module. This means that it is not necessary to run a full simulation to get results from the model. Before the simulations are done, the timetable manager already generated time-distance graphs for all trains according to the timetable. This includes occupational conflicts present in the timetable, to provide direct planning feedback. After the simulations are run, the time distance graphs are updated to show the feasible time distance graphs including delays caused by timetable conflicts.

A timetable compression function according to the UIC406 is present in the timetable manager. This function provides the occupation graphs and minimal headway data for the selected part of the infrastructure and timetable. Critical block sections are determined within the compression tool, indicating where the main bottlenecks in the selected infrastructure are located. After the timetable is compressed, extra train paths can be inserted automatically if the compression indicates that there is enough space.

RailSys can run either single or multiple simulations. The simulation itself is similar to Open Track. An animation of the simulation can be displayed showing train positions, signalling aspects and delays. The single simulation is used for testing the interactions between trains within the timetable and to test whether the timetable is stable in conventional operations. A station delay can be input into the model for the single simulation to assess how long it will propagate through the network. When running multiple simulations stochastic delays can be added to the model with a selected distribution. In order to model these delays, data on these delays needs to be input into the simulations manager module.

System configurations

RailSys has the option to adapt the ERTMS/ETCS settings to allow different driving behaviours. The software will provide warnings when parameter values outside the ERTMS/ETCS specifications are set. The possibilities to edit the settings of the signalling system and driving behaviour of the trains provides room for experimentation with new systems such as ATO and updates to ERTMS/ETCS baselines.

4.1.3. Tool comparison

Both modelling tools have their strong points and weaknesses. A number of modelling functionalities are needed for this research. The two modelling tools will be compared based on which fulfils the necessary functionalities the best.

In the research for this thesis the most important model functionalities are the following:

- Being able to model different signalling systems
- Capacity analysis through timetable compression
- Ability to model different driver behaviours
- Ability to adapt signalling system settings to allow ATO modelling

Both Open Track and RailSys contain all signalling systems necessary for this thesis. Both also contain tools for a capacity analysis. The headway calculator of Open Track allows for a more clear image of the relations between different individual train paths helping with creating a timetable, while the timetable compression tool of RailSys offers a more general relation between trains in the timetable.

The ability to model different driver behaviours and asses the effect of these on the capacity is one of the most important requirements necessary for this thesis. RailSys allows changes in settings regarding both signalling systems and driver behaviours. This makes it possible to assess how the different behaviours affect the capacity and feasibility of a timetable. The driver behaviours in Open Track cannot easily be adapted, limiting the usefulness for this part of the research. Both Open Track and RailSys have functionalities allowing the modelling of an ATO system. RailSys allows more settings on the signalling systems to be adapted.

Modelling tool choice
RailSys is chosen as the modelling tool for this study. The choice is made mainly due to the necessity to edit the braking behaviour and assess the effects of these different settings and behaviours. The direct feedback that the tool provides, making it more user friendly, especially when learning to use the tool is also a large factor in the decision.

4.2. Model parameters and constraints

There are a number of parameters that can be used to model different train driving styles. Most of these parameters are to do with the ERTMS/ETCS settings within the model. Within the software, these parameters can be altered within a certain range. This range provide some constraints to what is possible within the model. The parameters, their effect and the constraints to them are explained below.

ERTMS/ETCS baseline
The ERTMS/ETCS baseline is the set of system requirement specifications that the on board DMI has to meet/comply with. In the current version of RailSys, the ERTMS/ETCS can be set according to two different baselines. The options that can be selected are ERTMS/ETCS baselines: B3MR1 (subset-026 version 3.4.0) and B3R2 (subset-026 version 3.6.0). The differences relevant to the capacity between the two baselines that are present in the modelling software are the following.

Baseline B3MR1 subset-026 version 3.4.0
- Uses a pre-indication for the block reservations. The pre-indication placed 7 seconds (T_pre-indication) ahead of the indication curve at maximum line speed
- The indication curve is located 5 seconds (max (0,8*t_sb, 5) ahead of the permitted curve.
- The reservations are based on maximum line speed.

Baseline B3R2 subset-026 version 3.6.0
- Pre-indication is removed.
- The Indication curve is moved an additional 4 seconds (T_driver) further ahead of the Permitted curve (meaning the distance between them equals 5s + T_driver).
- The Indication curve is used for block reservations.
- The reservations are now based on the trains actual speed.

The Dutch government has currently decided on implementing baseline 3 release 2 on the infrastructure. The program decision report (Rijksoverheid, 2019c) states that the trains operating on the sections equipped with ERTMS/ETCS will at least need to have to be compatible with this baseline. Therefore, within all versions of the model containing ERTMS/ETCS, the baseline B3R2 (subset-026 version 3.6.0) will be selected.

Reservation
The model gives the option to select what braking curve the ERTMS/ETCS uses for the reservation of blocks ahead of the train. The options given in the model are the pre-indication, Indication and Permitted curves. As stated above, the chosen baseline requires use of the Indication curve for block reservation. All versions of the model containing ERTMS/ETCS have the reservation option set to the Indication curve. Within the model the indication curve is always at least 5s ahead of the permitted curve, with the exact location depending on the selected baseline and T_driver value.

Simplified braking
The simplified braking option sets all braking parameters to a set value. When used under ATB, the simplified braking option sets the braking rate of the trains to the simplified set rate. The simplified rate chosen is 0,5m/s^2. This is conform values used within ProRail for modelling studies.

When the simplified braking option is used under ERTMS/ETCS, the EBD curve is set to the selected simplified braking rate of 0,5m/s^2. The rest of the ERTMS/ETCS braking curves are still based on the EBD curve and the other ERTMS/ETCS parameters. To set the actual braking behaviour of the trains under ERTMS/ETCS to the simplified rate, the Permitted braking curve (used by the model for the trains driving behaviour) needs to be set equal to the EBD curve using the T_driver and T_eb parameters which will be explained below.

T_driver
The T_driver is an ERTMS/ETCS parameter that symbolises the reaction time of the driver to ERTMS/ETCS barking commands. Within the system, it is used as the time between the EBI curve and Permitted curve. As stated earlier, this parameter is also used as the time between the Indication and the Permitted curve. The T_driver is set to 4 seconds as standard in the system settings used in the Netherlands.

Within the RailSys modelling software, the trains operating under ERTMS/ETCS will always follow the Permitted curve. To alter the braking behaviour of the trains under ERTMS/ETCS, the Permitted curves need to be altered using the T_driver parameter. A number of different values for T_driver have been used in the different ERTMS/ETCS models. These values will be explained further in the model scenarios.

Within RailSys, the T_driver parameter can be altered within a set range. Only whole numbers between 0 and 9 can be entered for this parameter. This means that the permitted curve can be moved within the range of 0 to 9 seconds in front of the EBI curve.

T_eb
The T_eb parameter represents the time distance between the EBD and EBI curves. It is the time needed for the brakes to activate fully after the braking command is given. This parameter is part of the train specific gamma parameters. Within the models, this parameter is set as an individual rollingstock parameter. The standard value of T_eb is roughly 2s for all passenger rolling stock types.

Driver reaction time

The driver reaction time parameter is used in the model as the reaction time for signal upgrades. This means that the time it takes for the driver to react to a speed increase within their MA. It is also used for pre-occupation after a stop. There are some standard values used with the ATB and ERTMS/ETCS systems. These values will be explained further in section 7.2.1 covering the model scenarios.

Buffer time

The buffer time is a parameter in the timetable settings of the model. The buffer time is used to keep the infrastructure occupied after a train has fully cleared a track section. It is only used to prevent other trains from reserving block sections too close behind the preceding trains within the model. The timetable compression function used for the capacity calculations do not use this parameter for the calculations.

The buffer has been included in the capacity calculations using a different set of model parameters in the infrastructure module. For use in the capacity calculations, the buffer time has been included in the signal release time. This allows the model to include it in the compression graphs. While it does not conform to the UIC406 method, it does allow for a more complete demonstration of capacity benefits of ATO.

4.3. Infrastructure settings

The different signalling systems require their own settings within the modelling software. These different settings will affect the blocking time.

Interlocking/signal setup

The ATB/NS’54 signalling contains two different types of block sections in the modelling software, automatic and controlled. Controlled block sections are sections that contain movable objects like switches/turnouts or crossings. The signals for these sections are controlled by the dispatcher, hence the name, controlled signals/block sections. These sections need a longer setup time than the automatic sections. Automatic sections are the sections not containing any movable objects and use automatic signals. The controlled signals/block sections require a setup time of 12s. This is due to the setup time for the interlocking. Automatic signals do not require this setup time due to the lack of movable objects within their section.

ERTMS/ETCS has a similar split in block types within the model. The block types are again based on the presence of movable objects. The block sections not containing any movable objects have a setup time of 6s due to the communications between train and RBC. Block sections containing movable objects need 15s to set up with ERTSM/ETCS, including the 6s for the MA communications.

Signal release
The release time for the different systems varies some. The release time for the ATB/NS’54 signalling is 3s. The signals are released using the trackside train detection (i.e. track circuits). Partial block release is possible using the trackside train detection. Signal release for the ERTMS/ETCS Level 2 system is done with trackside train detection, through the use of axle counters. The signal release time for the Level 2 system is 1s. Partial block release at interlocking areas is possible using the trackside train detection.

For the Hybrid Level 3 signalling, the virtual blocks used by integer trains (equipped with a TIM) are released at the SMBs. The non-integer trains can only release a block section through the use of trackside train detection. The signal release time for the Hybrid Level 3 signalling is 1s. Partial block release is possible through the use of trackside train detection at the interlocking areas.

Table 3 | Infrastructure settings within the RailSys model

	ATB/NS’54	**ERTMS/ETCS L2**	**ERTMS/ETCS HL3 integer**	**ERTMS/ETCS HL3 non-integer**
Setup time automatic	0s	6s	6s	6s
Setup time controlled	12s	15s	15s	15s
Approach distance	1 block length	Based on P curve	Based on P curve	Based on P curve
Block release	TTD	TTD	SMB	TTD
Release time	3s	1s	1s	1s
Partial release	TTD	TTD	TTD	TTD

Table 3 contains an overview of the settings for the infrastructure. Figure 25 shows how these settings affect the blocking time.

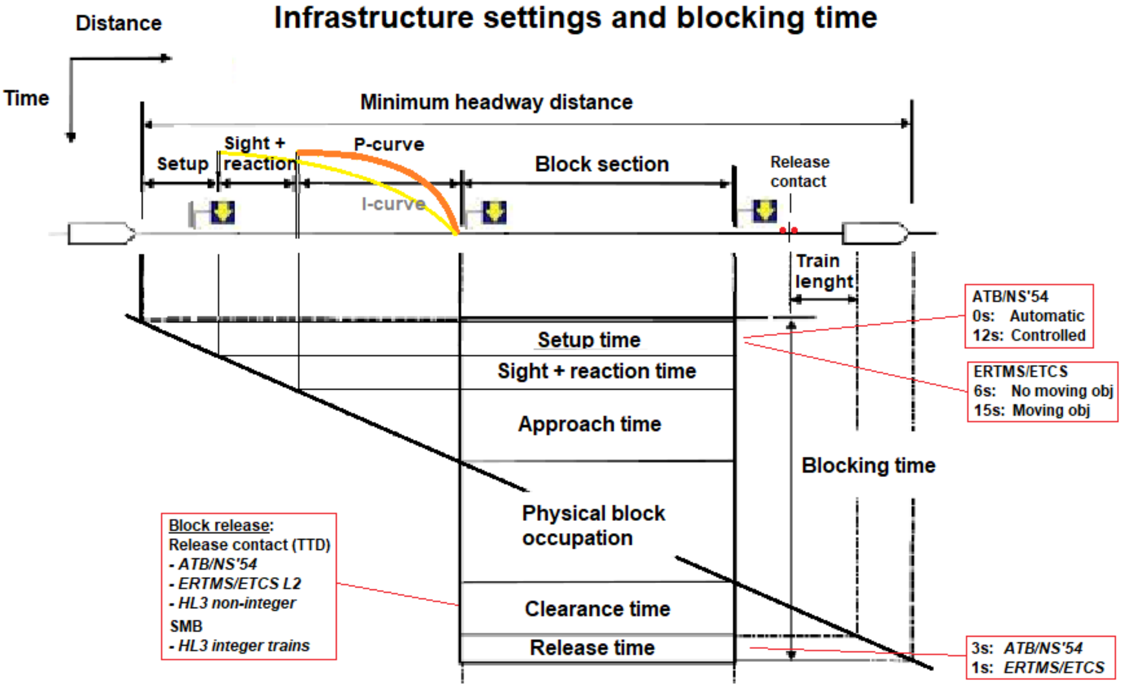


Figure 25 | Relation between infrastructure settings and blocking time

5. Driver behaviour modelling

5.1. Driver behaviour

There is currently no clear consensus in the Netherlands on how the to model the braking behaviour of the human drivers under ERTMS/ETCS. This is partly due to the lack of experience with ERTMS/ETCS operations on mixed traffic lines with higher amounts of stops and brake applications. ProRail uses a constant braking rate of 0,5 m/s2 for modelling the drivers braking behaviour under the ATB and NS'54 signalling systems. The ATB/NS'54 signalling giver the driver the freedom to brake how they see fit, as long as the proper speed is reached before the next signal. The signal distance of the NS'54 signalling is designed with the worst performing trains (i.e. freight trains) in mind. They will have to be able to brake in time before passing the next signal. This results in the space between signals being rather large for passenger trains. This large space between signals allows the drivers of the passenger trains to apply a slower braking rate, to brake trains more gradually.

A master thesis by (Grincell, 2019) researched the deceleration behaviour of passenger trains in the Netherlands. The thesis showed average braking rates in different situations to be between 0,45 and 0,65 m/s^2. These numbers were acquired from operations under ATB with the NS54 signalling system. The range of braking rates found by Grincell suggests the braking rate assumption made by ProRail to be accurate for modelling driver behaviour under the ATB/NS'54 system.

An ERTMS/ETCS pilot held on the Amsterdam-Utrecht line equipped with NS54 and ERTMS/ETCS Level 2 dual signalling provided ProRail with data on how driver would react to the ERTMS/ETCS signalling. The pilot was held with SLT Sprinter trains and the ICE trains operating on the line. A report on the pilot (ERTMS-pilot, 2015) focussed on the driver behaviour concluded that drivers mostly follow the same behaviour they are used to when driving under ERTMS/ETCS. The braking curves are not necessarily followed. Often drivers will start applying the brakes considerably (more than 500m) earlier than necessary under ERTMS/ETCS. The driver interviews held under the pilot found this was due to drivers being used to braking earlier and a bit smoother than what the ERTMS/ETCS braking curves indicate.

The conclusion of the pilot was that drivers will continue to dive in a similarly under ERTMS/ETCS to what they are used to doing now. This was partly due to the timetables design (designed for NS'54). They included plenty of time to recover from delays. Drivers also stated in the pilot that while they could follow the permitted curve more closely, but due to the margin in the timetable it was not necessarily required for the normal operation. It should also be noted that the pilot project used the dual signalling system on that corridor. One of the causes of the observed behaviour could be the dual signalling system that is in place on this corridor. The NS'54 signalling could have influenced the drivers braking behaviour. It is uncertain however if this was a factor in causing the observed behaviour.

A second factor that should be considered is the energy efficient driving style that NS asks drivers to follow. When the trains run on time the drivers are instructed to stop traction application and coast. The brake application will than depend on the signal aspects shown to the driver. This energy efficient driving behaviour could influence the braking rates and result in the observed behaviour.

The assumption could be made that with the current timetable, the average braking rates found by Grincell could be representable for the driver behaviour in operations under ERTMS/ETCS also. As mentioned before, in capacity studies ProRail uses a constant braking rate of 0,5 m/s^2 to represent the driver behaviour. A learning curve in driver behaviour can be expected where the drivers start braking according to their usual behaviour and over time adapt to a braking regime closer to the ERTMS/ETCS braking curves. An adaptation of the timetable to the ERTMS/ETCS systems could also help adapt driver behaviour.

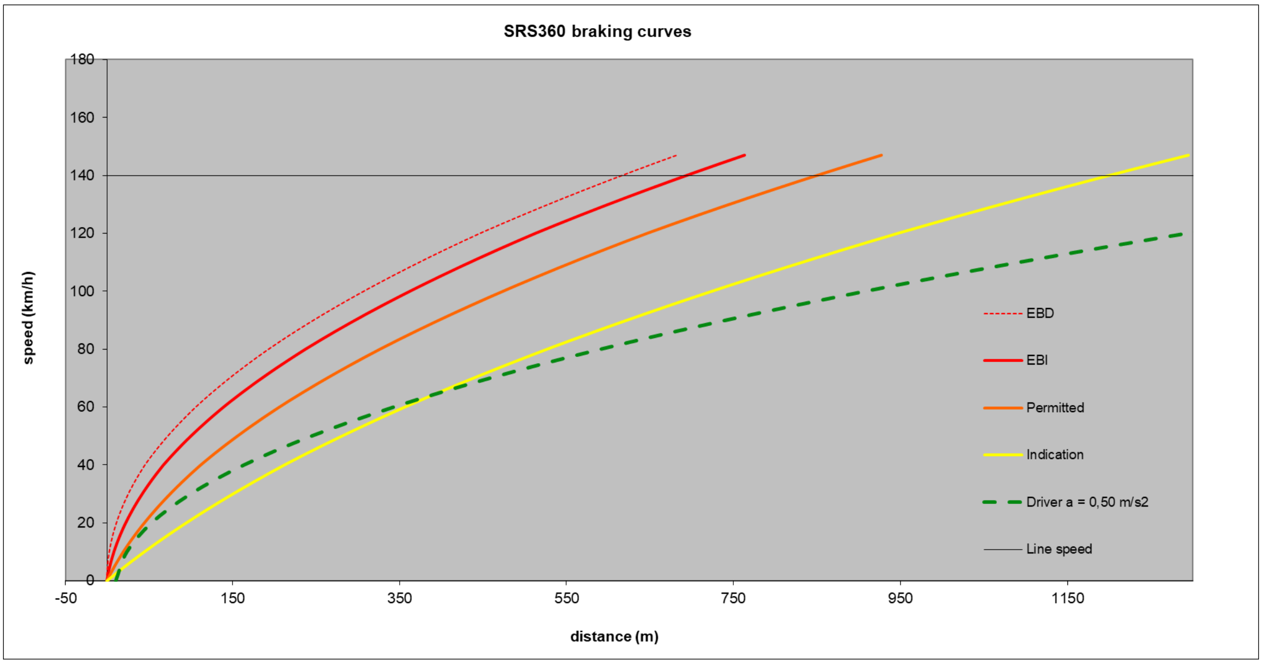


Figure 26 | Braking behaviour, constant braking rate 0,5 m/s^2 vs ERTMS/ETCS braking curves.

Figure 26 shows the differences between the constant braking rate assumed by ProRail for capacity studies and the ERTMS/ETCS braking curves. The constant braking rate of 0,5m/s2 is not likely to be seen under pure (not dual signalling) ERTMS/ETCS operations. The ERTMS/ETCS system does not provide a clear way to support this type of braking behaviour. To adhere to the constant braking rate of roughly 0,5m/s^2 that the drivers are used to under the legacy signalling system, the drivers will (at the higher speeds) have to start braking before they have passed the indication curve of the ERTMS/ETCS system. Figure 26 shows this clearly for the speeds above 60km/h. This means that they would have to guess in these situations whether or not their movement authority (MA) would be extended when they approached the Indication curve. It is safe to assume that drivers will not want to do this constantly.

When approaching a stop location in Target Speed Monitoring (TSM), it is more likely that drivers will adapt their braking behaviour to one of the ERTMS/ETCS braking curves. It is assumed that drivers start braking after the indication curve has been passed. Drivers will than make sure not to pass the permitted braking curve. Generally, a driver reaction time of 4s is agreed upon in blocking time calculations. If these 4s are used in this case, a braking curve

4s behind the indication curve would be assumed. This braking curve is situated 5s before the permitted curve (referred to as P - 5s in report).

NS is currently looking into the modelling of driver behaviour under ERTMS/ETCS. Here it is assumed that when in TSM (i.e. after passing the indication curve) drivers will start braking a certain distance or time before the permitted curve is reached. The target distance on the DMI or just a set time after the indication could both be used for choosing when to start braking. After that it is assumed that the driver will follow a speed below the permitted until close to the stop location.

An experienced train driver under ERTMS/ETCS explained how the braking behaviour under ERTMS/ETCS is developed from experience. The drivers start with a more conservative braking rate, closer to what they are used to. Once they have more experience with the system, braking behaviour will be adapted to more closely mimic the ERTMS/ETCS braking curves. A braking behaviour where the driver remains a set speed below the permitted curve was mentioned. With this driving behaviour, the driver will start braking some distance or time before the permitted and remain roughly 5km/h below the permitted curve until he can have a constant deceleration towards the stop location. Figure 27 provides an example of two of the above mentioned assumed braking behaviours, comparing the set speed below the permitted (P - 5 km/h) and a set time before the permitted (P - 5s).

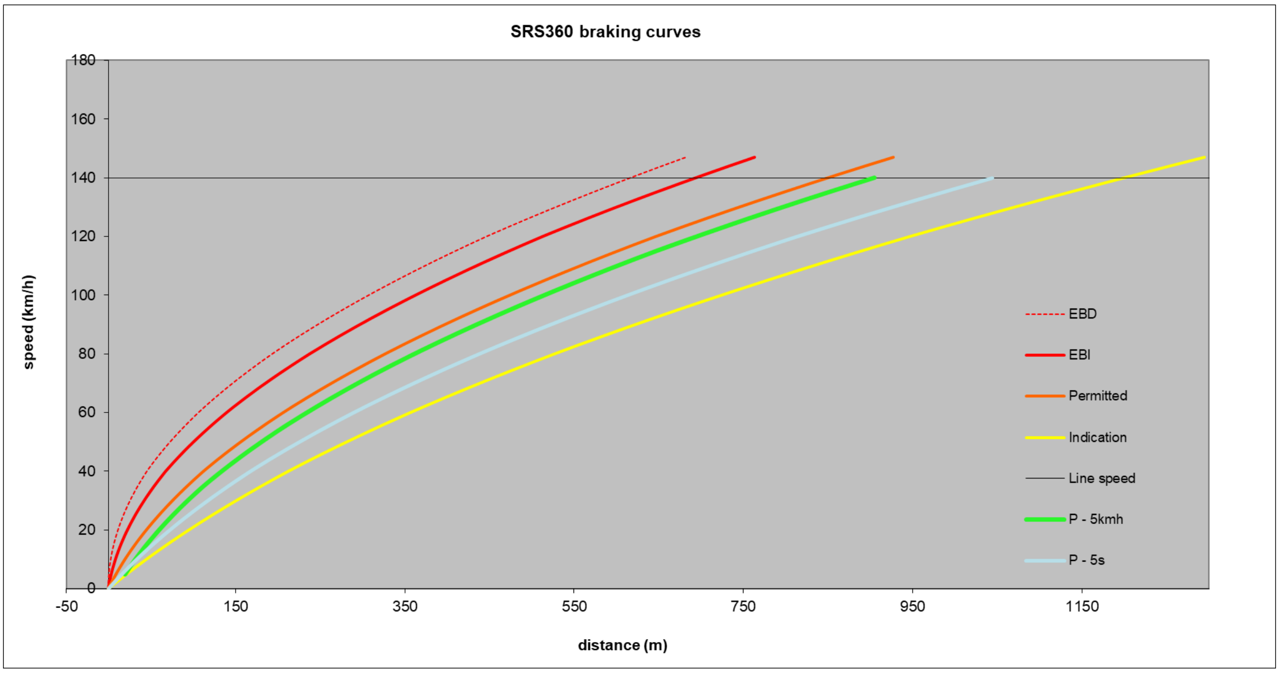


Figure 27 | Example of braking behaviours, comparing the P - 5 km/h and P - 5s

5.2. Modelling constrains

The driver behaviour described above provides a number of possibilities for use within the RailSys ERTMS/ETCS model. A number of constraints should be set to guarantee realistic modelled behaviour. The modelling software itself provides a number of constraints in what is possible to be modelled. The rest of the constraints will come from the ERTMS/ETCS system specifications.

Software constraints

Within the modelling software, trains will drive according to the set ERTMS/ETCS permitted curve. A number of parameters within the model can be used to change the permitted curve used by the trains, to adapt the driving behaviour of the trains.

The T_driver parameter can only be a whole number between 0 and 9. The standard T_driver value is 4s. The range of 0 to 9 limits the amount that the permitted curve can be moved.

The T_eb can also be used to move the permitted curve. Within the model this parameter is used as the distance between the EBD and EBI curves. Changing the distance between these curves moves the rest of the curves also.

ERTMS/ETCS constraints

To be able to compare the results of the model properly, the ERTMS/ETCS system needs to be functioning properly. The block reservations are done according to the indication curve. The indication curve is placed 5s + T_driver ahead of the permitted curve. The block reservations need to remain the same as with conventional ERTMS/ETCS settings.

In conventional ERTMS/ETCS settings the following distances between the curves can be seen. Table 4 provides an overview of the relations between the braking curves found in the ERTMS/ETCS specifications.

Table 4 | Positions of ERTMS/ETCS braking curves

ERTMS/ETCS braking curve	**Position**	**Conventional settings**
EBI	EBD - T_eb	EBD - 2s
Permitted	EBI - T_driver	EBD - 6s
Indication	P - T_driver - 5s	EBD - 15s

The permitted curve is the curve that the trains will be following within the model. Therefor the permitted curve will need to be changed to change the driver behaviour. It is important to keep the location of the indication curve the same to ensure a constant block reservation for the ERTMS/ETCS system over the different driving behaviours. The standard location of the indication curve is EBD - 15s, meaning 15s in front of the EBD curve. This provides an extra constraint for the parameters used for the driver behaviour.

$$Indication = P - T\_driver - 5 = EBI - 2 * T\_driver - 5$$
$$= EBD - T\_eb - 2T\_driver - 5$$
$$Indication = EBD - 15$$
$$T\_eb + 2T\_driver + 5 = 15$$
$$Permitted = EBD - T\_eb - T\_driver$$

Based on the desired behaviour, the T_eb and T_driver can be determined.

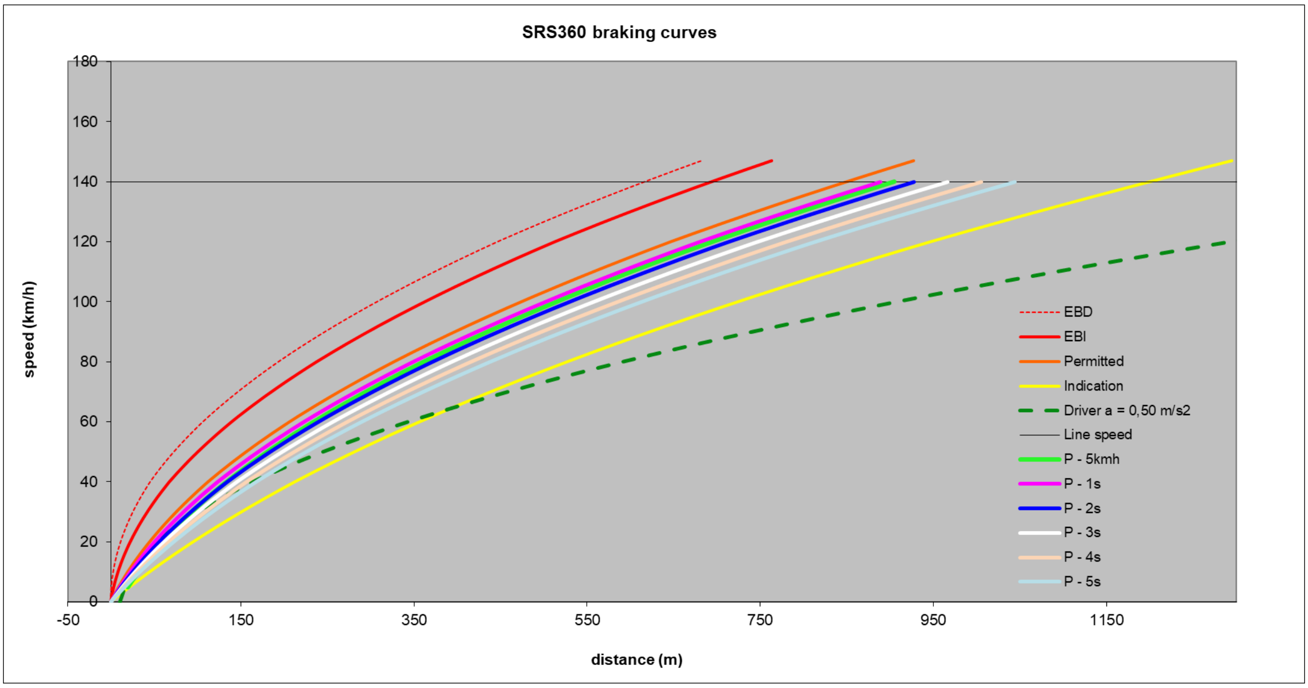


Figure 28 | Overview of considered braking behaviours under ERTMS/ETCS

5.3. Behaviour vs model constraints

Given the constraints, a number of the described behaviours can be modelled and a number of them can be eliminated. Figure 28 gives an overview of all the braking behaviours subjected to the constraints and tested.

Constant braking rate.

The constant braking rate can be achieved in the modelling software. This however completely reworks the ERTMS/ETCS curves, since these are not based on a constant braking rate. The indication curve cannot remain in the original position when a constant braking rate is modelled. Therefor this is not a completely reliable way of modelling driver behaviour. The choice is made to still model this behaviour at request, for comparison with other capacity studies within ProRail (not only within this study).

Constant speed below the permitted

A constant speed below the permitted cannot fully be modelled. It can be put into the model as a running time supplement or performance reduction, but these inputs will not work anymore in the compressions and once delays are added into the model. One of the reasons for this is that the acceleration and line speed will also be changed with these settings. One way to approach this behaviour in the model is to move the permitted curve by a set time, similar to the speed change. This will allow you to model similar braking behaviour without adapting the other performance aspects.

Constant time before the permitted (P - n)

Moving the permitted curve by a set time distance allows the desired driver behaviour without adapting the performance aspects of the trains. It is important to tune the parameters correctly to create the desired behaviour within the given constraints.

Table 5 | Parameters for braking behaviours complying with constraints

	T_eb (s)	T_driver (s)	EBD-PERM (s)	EBD-IND (s)
P	2	4	6	15
P - 1	4	3	7	15
P - 2	6	2	8	15
P - 3	8	1	9	15
P - 4	10	0	10	15

Table 5 shows all possible options of moving the permitted curve without changing the indication and block reservation. Due to the minimal space of 5 seconds between the permitted and indication curve, the maximum the permitted curve can be moved without moving the indication is 4 seconds.

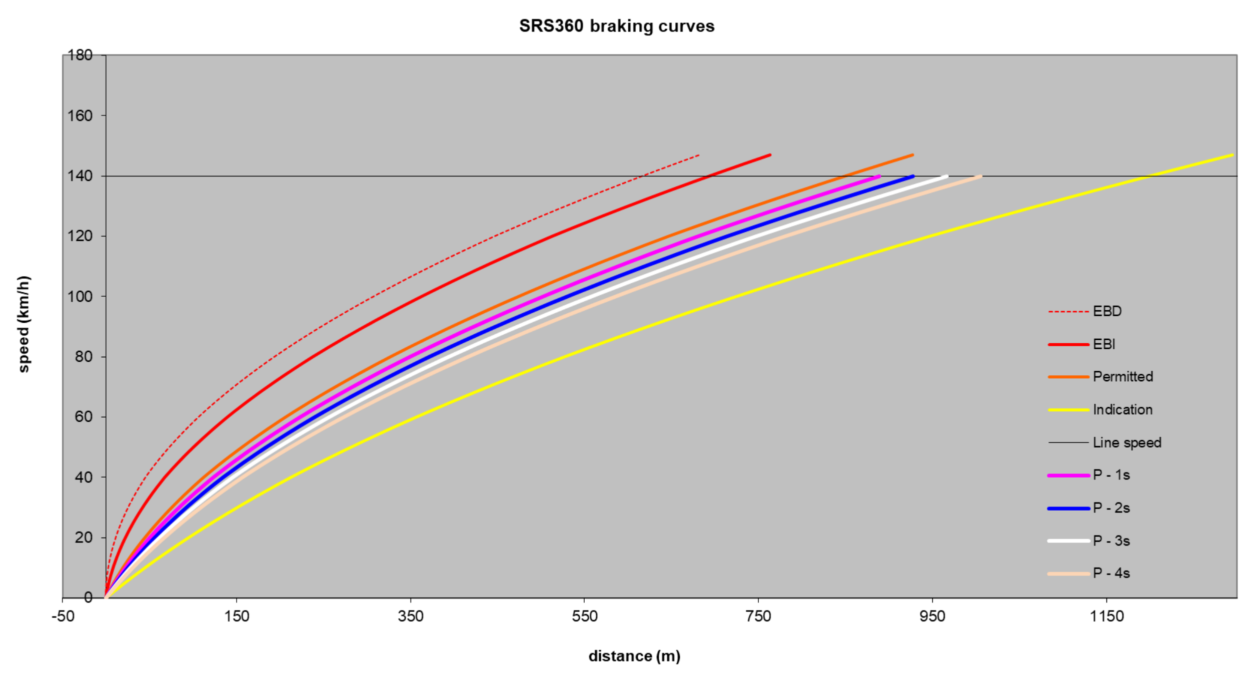


Figure 29 | Overview of braking behaviour complying with the models' constraints

5.4. Modelling ERTMS/ETCS driving behaviour

Given the constraints from both the modelling tool and the ETCS system, a choice can be made in what behaviour to model in the capacity study. The capacity study is set for the 2030 situation. In the year 2030, a number of experience learning programs for the ETCS systems have already been done according to the planning set by the government (Rijksoverheid, 2019c). The assumption can be made that by 2030 a number of drivers will already be experienced driving under ETCS. Assuming that the behaviour will improve with experience, driving behaviour close to the earlier mentioned 5km/h below the permitted curve can be expected. The constraints from the ETCS system and the modelling tool regarding the possible values for the parameters finalise the choice of modelled behaviour. The P - 2s option gets the closest to the desired braking behaviour, therefor this option is chosen to model the driver behaviour. The constant braking rate option will also be modelled at request of ProRail, to provide a comparison to other capacity studies where this option is also used. Figure 30 contains a graph showing the driving/braking behaviour that will be used within the model for the human drivers.

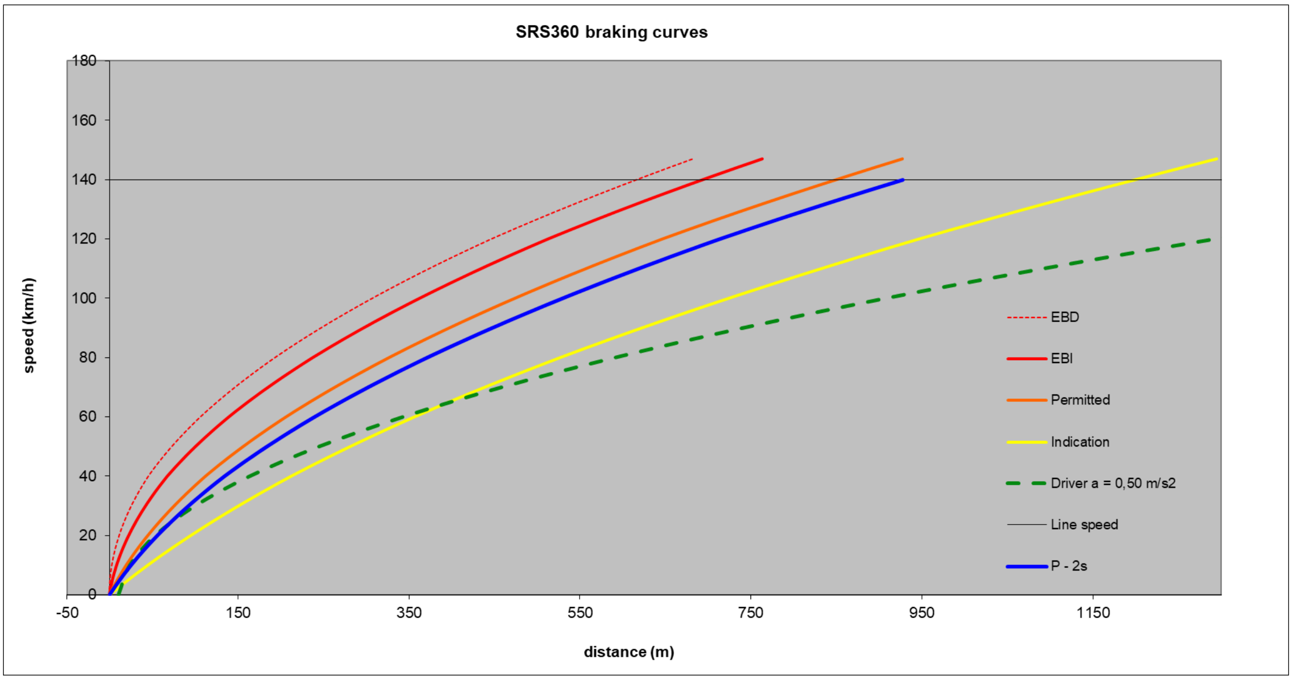


Figure 30 | Braking behaviour chosen for the model

6. How to model the effect of ATO

To fully understand how to model the effects of ATO, it is crucial to first understand what the functions of the ATO system are and how these functions affect operations. The regulations of the ERA, designed to guarantee safety, describe the limits of the functionalities of the ATO system combined with ERTMS/ETCS.

An important part of ATO is the removal of human factors from train operations. Human factors regarding driver behaviour have to be inserted into the model to get a full overview of the effects of the ATO system. The national planning norms have been inspected and adapted by ProRail for use on future systems including ATO. The effects of these changes in planning norms on operations will be taken into account in the modelling of the automatic operations.

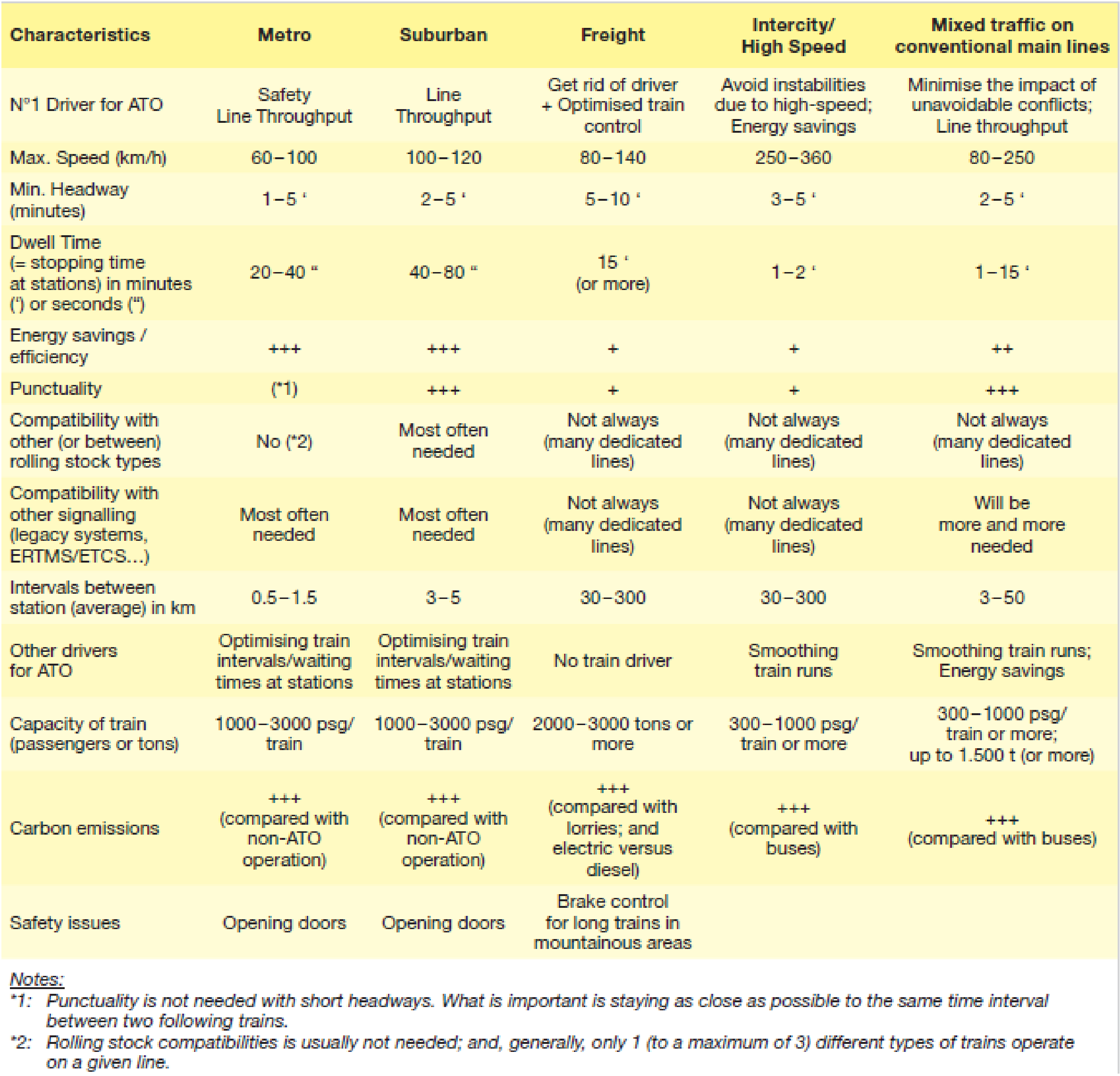
6.1. Functions of the ATO system

ATO consists of an on-board component (ATO-OB) and a trackside component (ATO-TS). The ATO-TS provides the ATO-OB with the with journey and track segment profile containing all information necessary to calculate the optimal speed profile for the journey, resulting in a more precise control of the trains. This will allow the ATO system to minimise the variations between train runs.

The ATO-TS receives the plan with activities and targets for timing points from the TMS (Traffic management system). The plan used by the TSM is created by the planning system. During operations, the plan is updated by the TMS or dispatchers. The updated plan is forwarded to the ATO-TS. The ATO-TS converts the plan into journey and track segment profiles and sends it to the trains (ATO-OB).

An article on ATO by (Poré, 2010) describes the functionalities of ATO for suburban and main line train operations. These functionalities are focussed on improving punctuality, reliability of the service, energy efficiency and capacity. All of these functionalities provide a drive for the rail sector to implement ATO on different types of lines. The main business driver for ATO on suburban lines is to increase throughput of trains, meaning to increase the capacity and optimise train running. To achieve this, the ATO must be able to reduce the headways between train, and provide a more constant, punctual operation than the current situation.

Figure 31 provides an overview of the benefits and importance of different ATO functions per type of rail operation. For the scope of this thesis a combination of suburban and mixed traffic on main lines are relevant. The line throughput (capacity) and minimising the impact of conflicts are given as the most important drivers for ATO on these types of lines.



Characteristics	**Metro**	**Suburban**	**Freight**	**Intercity/ High Speed**	**Mixed traffic on conventional main lines**
N°1 Driver for ATO	Safety Line Throughput	Line Throughput	Get rid of driver + Optimised train control	Avoid instabilities due to high-speed; Energy savings	Minimise the impact of unavoidable conflicts; Line throughput
Max. Speed (km/h)	60–100	100–120	80–140	250–360	80–250
Min. Headway (minutes)	1–5 '	2–5 '	5–10 '	3–5 '	2–5 '
Dwell Time (= stopping time at stations) in minutes (') or seconds (")	20–40 "	40–80 "	15 ' (or more)	1–2 '	1–15 '
Energy savings / efficiency	+++	+++	+	+	++
Punctuality	(*1)	+++	+	+	+++
Compatibility with other (or between) rolling stock types	No (*2)	Most often needed	Not always (many dedicated lines)	Not always (many dedicated lines)	Not always (many dedicated lines)
Compatibility with other signalling (legacy systems, ERTMS/ETCS…)	Most often needed	Most often needed	Not always (many dedicated lines)	Not always (many dedicated lines)	Will be more and more needed
Intervals between station (average) in km	0.5–1.5	3–5	30–300	30–300	3–50
Other drivers for ATO	Optimising train intervals/waiting times at stations	Optimising train intervals/waiting times at stations	No train driver	Smoothing train runs	Smoothing train runs; Energy savings
Capacity of train (passengers or tons)	1000–3000 psg/ train	1000–3000 psg/ train	2000–3000 tons or more	300–1000 psg/ train or more	300–1000 psg/ train or more; up to 1.500 t (or more)
Carbon emissions	+++ (compared with non-ATO operation)	+++ (compared with non-ATO operation)	+++ (compared with lorries; and electric versus diesel)	+++ (compared with buses)	+++ (compared with buses)
Safety issues	Opening doors	Opening doors	Brake control for long trains in mountainous areas		

Notes:

*1: *Punctuality is not needed with short headways. What is important is staying as close as possible to the same time interval between two following trains.*

*2: *Rolling stock compatibilities is usually not needed; and, generally, only 1 (to a maximum of 3) different types of trains operate on a given line.*

Figure 31 | Characteristics of line types and benefits of ATO. Source: (Poré, 2010)

A large number of the benefits and drivers mentioned in Figure 31 are created by limiting the stochastics in the operations. Limiting the differences between train runs allows a size reduction of the planning buffers that are currently used to counteract these stochastics. This reduction in buffer reduces the headways between trains, allowing for a higher throughput.

The ATO-OB can be programmed for specific braking behaviour. Braking behaviour varies between train drivers due to their education and other human factors. The ATO system can brake a train at a faster rate than human drivers would be used to, or comfortable with. The ATO will however always have to operate within the safe boundaries of the ATP systems present on the line on which it operates.

6.2. Regulations and safety

In order to guarantee safety, a number of specifications and regulations are in place, which the systems will have to comply with. The ATO itself is not safety critical. It is designed to work under the supervision of a SIL 4 (Safety Integrity Level 4, specified by European CENELEC norms) continuous brake curve supervision ATP system. The ATP provides the safety net to ensure the train operates under safe conditions. The ATO and ERTMS/ETCS combination is an example of this. The ATO controls the train movements, and the ERTMS/ETCS supervises and intervenes when the ATO's control inputs bring the train outside of the specified safe operating envelope. When the ATO is put in control of more functionalities of the train, the need for a higher safety level and more supporting/supervising systems.

The SUBSET-125 from the ERA (European Railway Agency, 2018) specified a number of requirements for the implementation of ATO over ERTMS/ETCS. One of the most important safety related requirements is regarding the priority of control commands. The ATO GoA 2 system will operate according to the following priorities in commands:

1. Manual emergency brake application
2. ETCS braking command (emergency brake)
3. Driver braking command (ATO will be disengaged)
4. ATO braking command (when ATO is active))

Basically, the braking command with highest braking rate will be followed by the train. Braking commands always have priority over traction commands in the ATO system. Braking commands from the driver will cause the ATO-OB to disengage and the ETCS-OB to revert back to manual driver mode. This means that there is always a layer of protection/intervention on top of the ATO-OB system.

ATO affects the operations and planning in a number of ways. The modelling will focus on three aspects, the braking rates, headways/buffer times and the running time supplements. The effects of ATO on these points will be elaborated upon in the following sections.

6.3. ATO vs human braking behaviour

The main benefits from the ATO system are expected to come from getting rid of driver behaviour to optimise the driving style of trains in terms of capacity. Using a braking curve Excel tool of the ERTMS User Group, the braking distances are calculated for the speed of 140 km/h. From these distances the assumption is made that the driver brakes according to a constant braking rate. The tool uses a number of standard values specified for ERTMS/ETCS to calculate the braking curves using the gamma braking parameters of the Dutch VIRM rolling stock. A release speed of 15 km/h (from national values) is used in the calculations. The calculations are made for dry conditions with no gradient.

Using the calculated stopping distances, deceleration rates and stopping times, the running time gain per braking curve over the drivers assumed current behaviours can be determined using the braking curve calculations. Using the P - 2s braking behaviour and the ProRail standard of 0,5 m/s^2 for the driver behaviour curves, the running time gain when ERTMS/ETCS curves are followed has been calculated.

This running time gain calculation is done for braking from a speed of 140 km/h to the release speed of 15 km/h. This range is shown in Figure 32 by the two horizontal lines. The running time gain has been determined by comparing the breaking rates and curves between line speed and release speed. Below the release speed the driver is free to choose his own braking behaviour. The assumption that the driver will keep applying the same braking rate below the release speed is unrealistic. Therefore, the calculation has been done for speeds between 140 km/h and the release speed of 15 km/h. The braking curve tool has been adapted to calculate the running time gain between any two speeds selected inside the range between the line speed and the release speed. Using the modified tool, a theoretical running time gain for the use of ATO could be determined for a train path.

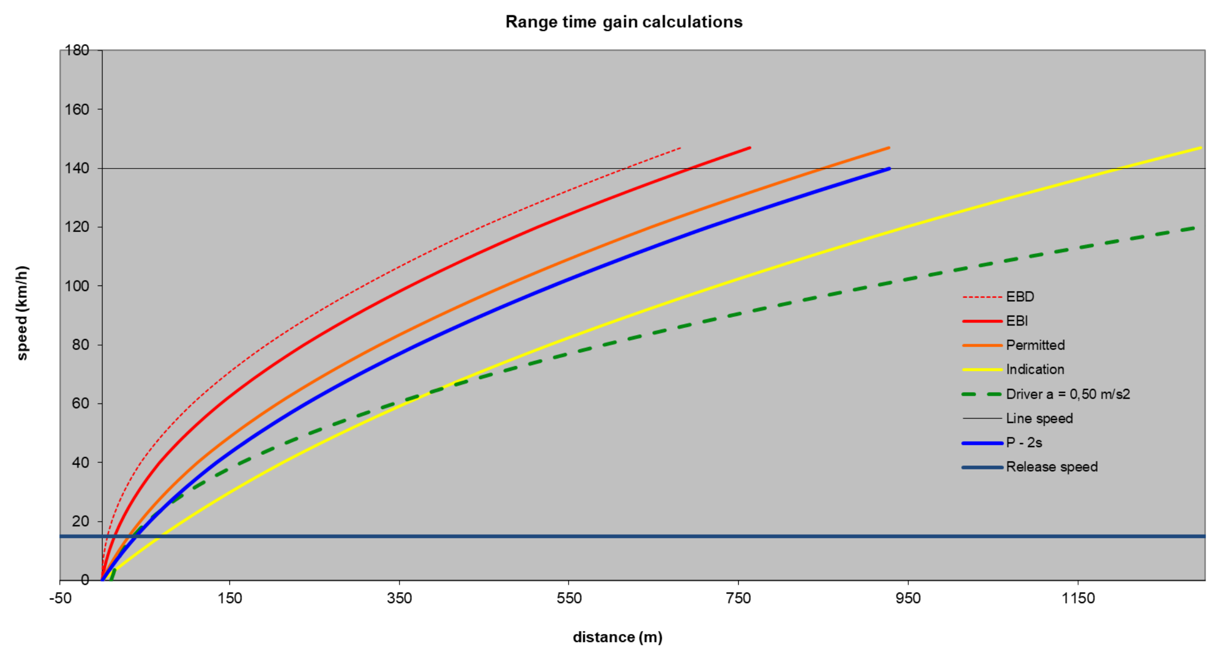


Figure 32 | Running time gain calculations are done between line- and release speed.

Table 6 gives the running time gains that can be achieved if the driver brakes according the ERTMS/ETCS curves compared to the assumed driver behaviour described above. It can be seen that when the permitted curve would be followed, a significant time gain could already be achieved compared to the constant braking rate of 0,5 m/s^2. This time gain is possible already under ERTMS/ETCS. ATO can be used to drive the train on, or even past the permitted curve. The table shows that the running time gain the ATO could provide over the driver behaviour, varies a lot depending on the driver behaviour.

Table 6 | Running time gain in delayed braking from 140 km/h to 15 km/h compared to driver behaviour

	Driver: 0,5 m/s^2	**Driver: P - 2s**
Indication curve (I)	2,3 s	-8,7 s
Permitted curve (P)	13,5 s	2,5 s
EBI curve	18,5 s	7,5 s
ATO curve (2s before EBI)	16,0 s	5,0 s

According to the ERA Subset-125 (European Railway Agency, 2018) the ATO-OB is allowed to ignore all non-safety critical braking curves (I, P, W curves). The ATO curve used in the calculation is put 2s before the EBI curve, this is where the location of the W curve. The reason for this is to account for the system reaction time of the ATO-OB, the size of which is speculated to be between 1 and 2 seconds.

As explained in section 3.3.2 the block reservation used with the ATO system is based on a ATO indication curve. The distance between the ATO indication and the ATO curve in Figure

33 is the 2s system reaction time plus the brake application time (generally around 2s). Placing it 4s before the ATO curve would be a reasonable setting. The model constrains limit this distance to a minimum of 5s.

The tool shows the main benefit of ATO in terms of delayed braking to be the ability to fully utilise the capacity benefits of ERTMS/ETCS. A running time gain of between 5 and 16 second (depending on driver behaviour) for every train stop can make a difference in the feasibility of a tight timetable. To further illustrate the differences in braking distance between the driver behaviour, the ERTMS/ETCS curves and the ATO Figure 33 shows a graph of these curves braking from maximum line speed of 140 km/h.

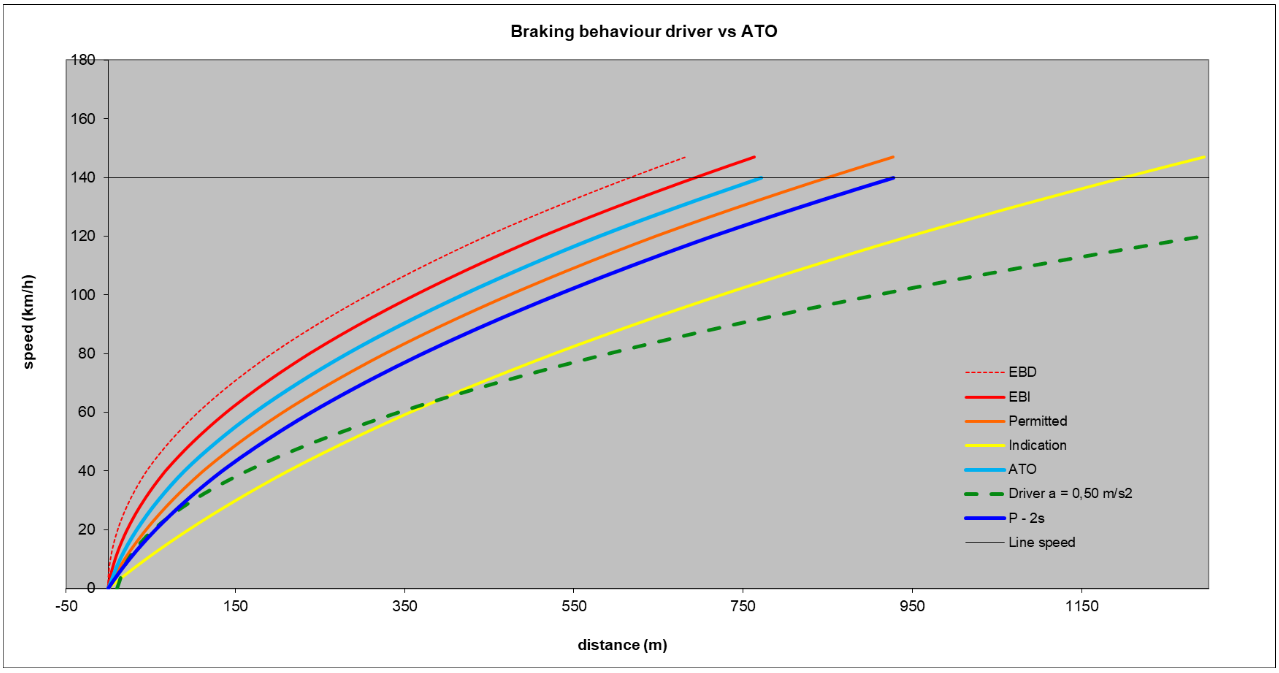


Figure 33 | Braking curves, ERTMS/ETCS and ATO vs driver behaviour

6.4. Operational planning norms

The national operational planning norms of ProRail contain a number of values for buffers and running times supplements to provide a stable timetable. These buffers and supplements are meant to counter variations in operations. The variations can be influenced by the ATO system.

6.4.1. Headway buffers

The current planning for the main lines (Hoofdrailnet) uses a 60s buffer between train, rounded up to the nearest tenth of a minute (6s) in the schedule. This buffer is meant to reduce the propagation of delays caused by stochastics in the operations. A large portion of these stochastics (differences between train runs) are caused by the train drivers individual driving behaviours.

The regional lines in the north, east and south of the Netherlands, use a different buffer time. A buffer of 30s is used on these lines. It has been observed by the Prestatie Analyse Bureau (PAB, Performance Analysis Bureau) of ProRail that on lines where one-man operation is the norm, the differences in running times and running profiles are smaller than on the main lines where multiple people drive/control the same train. This suggest that limiting or removing the human factor would homogenise the operations and could therefor limit the size of the buffer. An internal proposal document of ProRail (ProRail, 2019a) for adaptations in the current planning norms to account for the usage of new technologies provides a base that can be used in the capacity study for ATO. It is stated in the document that future developments will impact the minimal running times, necessary buffer times and running time allowances. The different expected effects on these times are determined through expert judgement and summarised.

The PAB concluded from studies into the effectiveness of these buffer times in mitigating delays that in the first 30s of the buffer have the largest effect. When the homogenisation effect of ATO on the train runs is considered, a buffer time of 30s is expected to be enough for main line operations.

6.4.2. Running time supplement

The functions of the running time supplement are to counteract the variation in (unhindered) running times, dwell times and the hindrance from other (conflicting) trains. In current planning of main-line operations, a running time supplement of at least 7,5-8% is used. In one-man operations on the regional lines a smaller supplement of 4% is being used. Data from the PAB indicated that in the one-man operation, the running times are more homogeneous, and the variations are smaller, allowing the planning to be set up with a lower running time allowance and buffer times.

One of the leading drivers for implementing ATO is the ability to limit or even remove the variation in running times. The hindrance from other trains can be limited through the ATO with the more precise control done by the on board ATO systems. A small running time supplement is still necessary due to the variation in dwell times and weather and track conditions (slippery tracks, etc.). This variation can only be removed when GoA3/4 is considered. The ATO considered in the study is GoA2. A small running time supplement of 2% is mentioned for the use of ATO GoA2 to get the maximum capacity out of the system (ProRail, 2019a).

The running time supplement is also used for economic and energy efficient driving. ATO could also be used to optimise the energy efficiency of the train operations. It is very likely that the operators would prefer to keep the running time supplement for these reasons. With the lowered running time that the ERTMS/ETCS and ATO could bring, the running time supplement would already be slightly smaller. Due to the use of the running time supplement for energy efficiency and it being integrated in the timetable, the decision has been made to keep the supplement used within the timetable (7,5-8%) in all versions of the model.

6.5. ATO modelling parameters

The expected effects of ATO GoA 2 on the capacity have been described above. The ability to fully utilise the delayed braking possibilities of ERTMS/ETCS and the increase in homogeneity in train runs can create some extra capacity. In order to accurately model the effects of ATO on the capacity the following two parameters are chosen to be used in the model.

- Buffer time of 30s instead of the current 60s
- ATO braking curve to be followed by the trains, placed 2s before the EBI curve
- ATO indication curve placed 5s in front of the ATO braking curve
- The regular running time allowance within the timetable will be used for ATO

The simulations without ATO will be calibrated to drive according to the mentioned assumed driver behaviour. The braking curves simulating driver behaviour that will be used are the constant braking rate of 0,5 m/s^2 and the P - 2s curve, 2 seconds before the permitted curve of ERTMS/ETCS. Modelling the assumed driver behaviour will allow the model to show the capacity benefits ATO can bring, compared to the human drivers under ERTMS/ETCS operations. The exact translation of the parameters chosen for ATO into the model parameters will be explained in section 7.2 when covering the ATO scenarios within the model.

7. Model construction

This chapter will cover the construction of the model, providing an insight in how the model is build up and explaining the different scenarios.

7.1. Model setup

The modelling will compare the functionality of NS’54 + ATB and the different levels of ERTMS/ETCS (L2 and HL3) with and without ATO GoA 2 applied. For the analysis, the infrastructure and timetable of 2030 will be used. The timetable will be the constant factor in the model, with each model variant containing the exact same timetable. This constant factor allows for a better comparison of the capacity provided by each system.

7.1.1. Model boundaries

The RailSys model contains the entire Dutch rail network. Only the SAAL corridor itself and a few branches off of it are used for this research. The boundaries set in the model are shown in Figure 34 by the red markings. The purple markings on the figure indicate the locations of interlocking where different lines merge and diverge. This indicates the complexity of the corridor with the amount of connections. To prevent the inclusion of conflicts outside the scope of the research area, the boundaries are set at the following stations:

- Hoofddorp
- Amsterdam Lelylaan (Asdl in Figure 34)
- Amsterdam Centraal
- Amsterdam Bijlmer/Arena
- Hilversum
- Lelystad Centrum

The route between Amsterdam Centraal and the Bijlmer/Arena station is included due to the large amount of traffic entering, exiting and crossing the SAAL corridor from this route. The boundary at Amsterdam Lelylaan is chosen to provide a timing point for traffic entering and leaving the SAAL corridor at the Riekerpolder aansluiting (Asra in Figure 34, east of Schiphol). The rest of the boundaries are placed at the edges of the SAAL corridor.

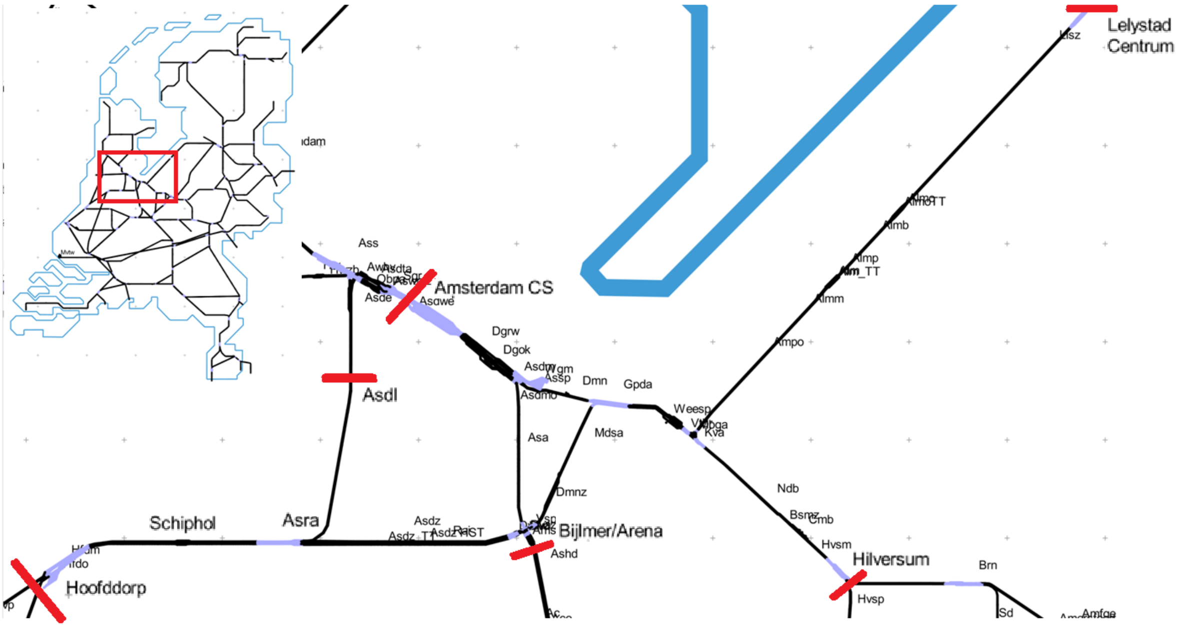


Figure 34 | Model boundaries set in RailSys

7.1.2. Infrastructures changes

While the capacity benefits that the new systems promise might be enough to diminish the need for infrastructure expansion projects, the planned infrastructure expansions and adaptations will be put into the model to provide a fair comparison between the different systems. The desired 2030 timetable also has been developed with these infrastructure expansions in mind. The changes made to the infrastructure will be explained below.
Changes have been applied in the following places:

- Amsterdam Centraal (Asd)
- Amsterdam Zuid (Asdz)
- Weesp (Wp)

Amsterdam Centraal
Amsterdam Centraal (central station) has been remodelled to the planned 2030 situation. Figure 35 provides an overview of the current and 2030 layouts of the central station of Amsterdam. The top figure shows the current layout containing a large number of switches/points providing easy diversion possibilities and a wide range platform access for trains from every direction. The downside of this layout is the high number of switches increases the chance of a failure and therefore disruption in the train services.

The number of tracks and switches/points will be reduced to create a more robust service and timetable as part of the PHS (Programma Hoogfrequent Spoor) project. The lower figure of Figure 35 shows the layout in for the 2030 situation. The infrastructure surrounding the station has been simplified to optimise the operations and increase the speed limits and throughput of the station. The station has been redesigned for a more corridor-based operation. The volume of crossing traffic is severely limited in the new design, allowing for more robust operation and a higher throughput.

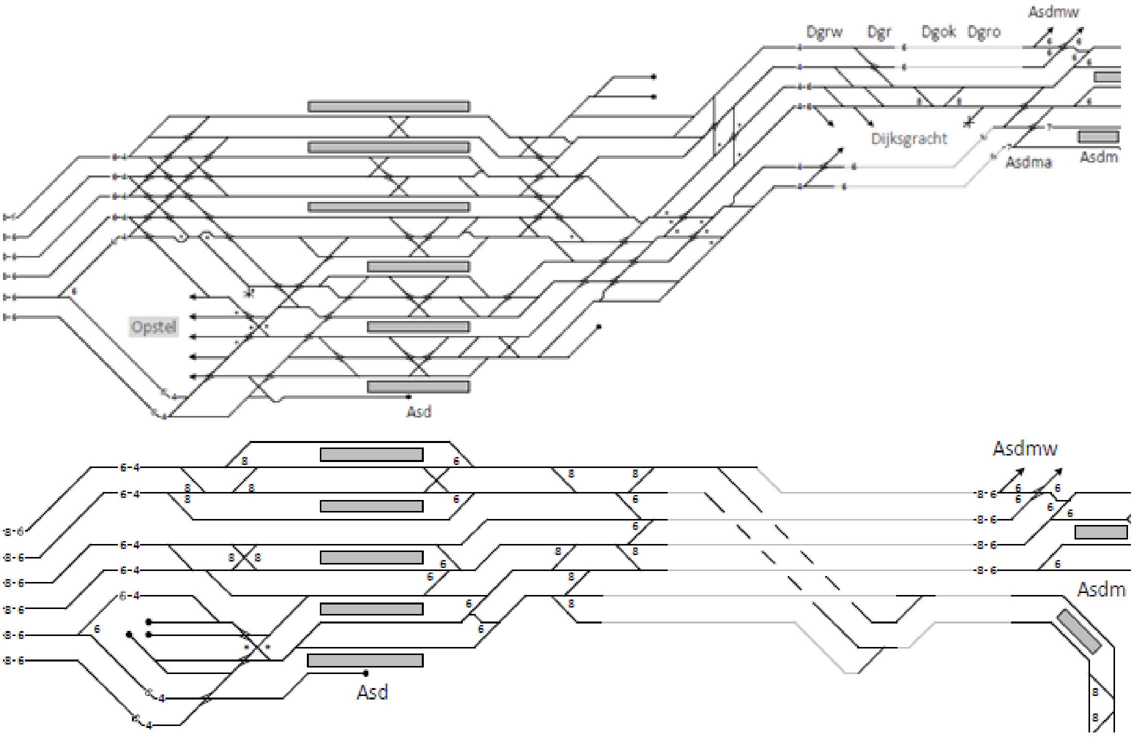


Figure 35 | Track layout for Amsterdam Centraal (Asd) in 2020 (top) and 2030 (bottom). Source: (Hofstra)

Amsterdam Zuid

Amsterdam Zuid station will be overhauled in the coming years. The international services in the directions of Brussels will be routed to Amsterdam Zuid instead of the central station. To accommodate these services, two extra tracks will be added to the station. These two tracks will be used to house and turn around the international trains (Thalys, Eurostar and IC Brussels). Figure 36 gives an overview of the infrastructure changes in Amsterdam Zuid, based on the most recent designs of ProRail.

The station in current (2020) situation is shown in the upper figure in black and the future (2030) changes are shown in the bottom figure in red. The only thing that will remain unchanged in the location of the current two island platforms. On the south side of the station, a third island platform will be added. The middle platform will be extended to provide a separate customs area for the Eurostar services to London. This results in the middle platform becoming over 800m long. Three tailtracks are added to the east (right in figure) side of the station for use by the international trains.

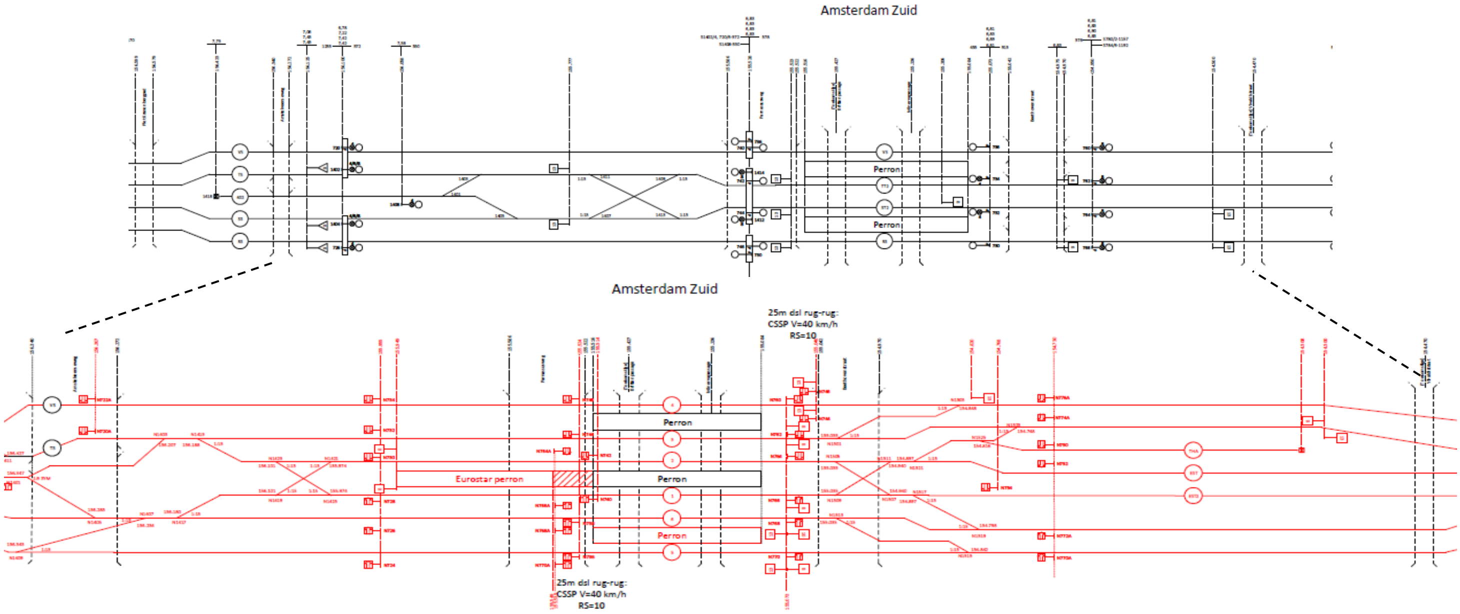


Figure 36 | Track layout Amsterdam Zuid in 2020 (top), 2030 (bottom). Source: (ProRail, 2019b)

Weesp

The station of Weesp will be expanded to allow more trains to overtake each other. Two extra passing tracks are added on the outer sides of the station. This is part of the PHS program to increase the number of trains on this part of the network. The expansion of the station of Weesp is still under discussion. The expansion is included in the model due to the available 2030 timetable being designed for this expanded situation. Different versions of the timetable designed for the current (2019) situation in Weesp have not been made available, therefore the decision was made to include the expansion of Weesp in the model.

Figure 37 provides a schematic view for the current situation of Weesp on the left and the 2030 situation on the right. Next to the expansion of the station, a number of switches/points have been removed to simplify the layout and improve robustness. The numbers indicate the speed limits active on the track sections. In the 2030 design, the traffic to and from Almere and to and from Hilversum has been fully separated. The outer tracks handle the traffic to and from Almere and the inner tracks handle all traffic to and from Hilversum.

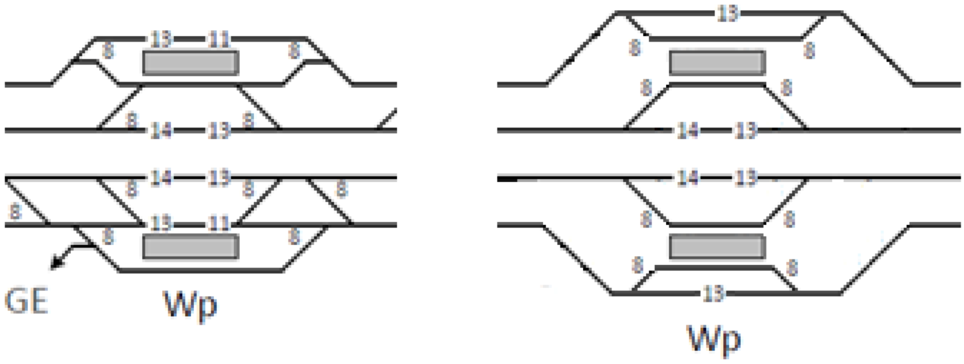


Figure 37 | Track layout of Weesp in 2019 situation (left) and 2030 situation (right).

7.1.3. Timetable

A timetable variant for 2030 has been provided by the capacity management department of ProRail for use in the modelling portion of this research. As mentioned in section 7.1, this timetable is used a constant factor in the modelling portion of the research. The timetable is an early stage rough design, created with the planning software DONS used by ProRail for the creation of future timetables for planning studies. The entire timetable is made up of base hourly patterns with the trains being planned in tenth of a minute (6s) accuracy at set timing point on the network (mostly station and important nodes).

The timetable consists a number of key service patterns that are discussed in the Netherlands for future operations. The most important of which are the airport Sprinter and the international trains at Amsterdam Zuid station. The airport Sprinter consists of a regular metro style Sprinter service between Hoofddorp, Schiphol airport and Amsterdam Central station operating 8 times per hour per direction. In the provided timetable, these Sprinter services are the only direct connection between the airport and the central station of Amsterdam.

Amsterdam Zuid will function as an international hub with 4 international trains per hour departing in the direction of Brussels. This combined with the regular intercity services and the airport Sprinter, means the track sections surrounding the station of Schiphol sees a total of 68 trains per hour. Figure 38 shows a BSO (platform/track occupation pattern) for the station of Schiphol indicating the platform occupation for the station for an hourly period. The centre 2 tracks are reserved for the Sprinter trains shown in red. The outer tracks are reserved for the intercity shown in blue and international trains shown in green.

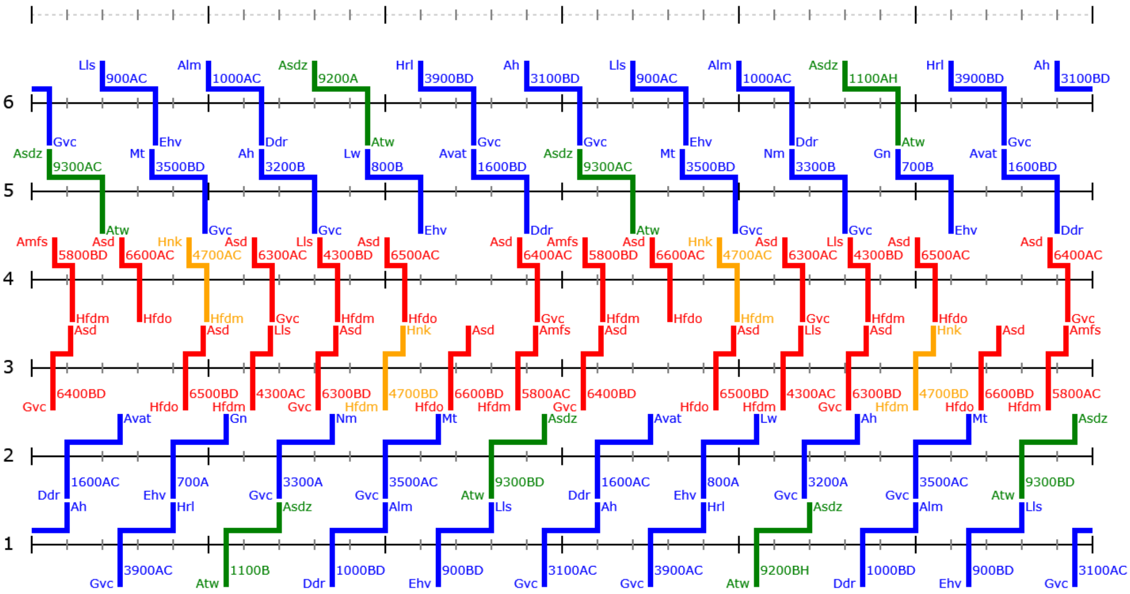


Figure 38 | Platform occupation pattern of Schiphol, retrieved from the timetable files in DONS

7.1.4. Trains

A number of different train types can be found on the SAAL corridor. In order to make the model more realistic, the different rolling stock types will all be included. The allocation of rollingstock types in the timetable has been done according to the current (2019) timetable and available (through capacity management tool) future rolling stock plans of NS. The rolling stock types are present in the RailSys software, included with the individual rolling stock types parameters (braking, acceleration, etc). An overview of the rollingstock types used inside the model is provided in Table 7 sorted by service type.

Table 7 | Rollingstock used in the RailSys model

Train type		V max	Length	Remark
Freight				
TRAXX E186 + freight 2000 tons		95 km/h	569m	No TIM unit available for freight train
International				
Thalys	TGV PBA	300 km/h	200m	Vmax 160km/h under 1500V DC
Eurostar	Velaro E320	320 km/h	399m	Vmax 200km/h under 1500V DC
ICE	Velaro 406	320 km/h	200m	Vmax 200km/h under 1500V DC
IC Berlijn	E1700 + 9 DB coaches	160 km/h	278m	Replacement train on order by DB, for 2023. TIM unit possible, counted as integer train
Intercity				
ICNG-8		200 km/h	165m	IC Brussels uses 2xICNG-8
VIRM-6		160 km/h	162m	
Sprinter				
SNG-4		160 km/h	76m	
SLT-6		160 km/h	101m	

All trains are subjected to the speed limits of the infrastructure and signalling systems. Inside the modelled area all trains will run on 1500V DC, limiting the maximum speeds and traction power of the international (high speed) trains. An important note given in Table 7 regards the rolling stock for the IC Berlijn trains. In the modelled configuration with an NS E1700 locomotive with 9 DB intercity coaches, the train cannot realistically run as an integer train under ERTMS/ETCS HL3. The Deutsche Bahn however has new rolling stock on order to replace the current sets used on the IC Berlijn service starting 2023 (Railway Gazette, 2019). This new rollingstock can be fitted with a TIM unit to provide an integer train for HL3 operations. For this reason, the IC Berlijn trains used in the model will be seen as integer trains in the HL3 model.

7.2. Model scenarios

A number of different model versions and scenarios have been made to compare the capacity effects of the different systems. The base model uses the ATB system with NS'54 signalling. A number of separate model versions have been made for the ERTMS/ETCS systems, each containing a separate version of the infrastructure. The ERTMS/ETCS model versions are Level 2 long block, Level 2 short block, Hybrid Level 3. The model versions contain a number of different scenarios. These scenarios vary in driving style (human driver behaviour) and in system settings (conventional ERTMS/ETCS or ATO).

The model scenarios without ATO are calibrated to portray the realistic driver behaviour as explained in chapter 4. This means that the maximum capacity that the ATB and ERTMS/ETCS systems could provide will not necessarily be usable due to the train drivers behaviour. The model calibration for driver behaviour consists of changing the braking parameters to adapts the trains braking behaviour. A running time supplement of 8% is incorporated into the timetable and a headway buffer of 60s is added to comply with the national planning norms.

The ATO scenarios are calibrated to portray the behaviour possible with the use of the ATO system. The simplified braking rate has been turned off and the trains are calibrated to follow a Permitted braking curve made for the ATO system as described in section 6.3. This allows the trains to brake at a later stage than possible in the standard ERTMS/ETCS configurations. The parameters discussed in section 6.5 will be applied in the configuration of the ATO scenarios to comply with ProRails proposed planning norms for operations under ATO.

7.2.1. Base model: ATB/NS’54

The base model is the model where the ATB/NS’54 signalling is active on all the lines. The infrastructure itself will be in the 2030 state. The only difference will be that the ERTMS/ETCS will not be applied in this version of the model. The new infrastructure at the stations of Amsterdam Zuid and Weesp will likely not be constructed with the ATB and NS’54 systems, since by the time these are completed, the SAAL corridor will be equipped with ERTMS/ETCS. The signal placements and signal relations are based on design drawings of the new infrastructure.

The ATB model only contains one scenario that uses a number of standard model values from ProRail regarding the buffer time and driver reaction time. The buffer time is set to 60s in the ATB model and the driver reaction time is set to 9 seconds, as explained in section 4.2. The braking behaviour for the trains is set to the braking value of 0,5 m/s^2, to mirror the estimated driver behaviour used in modelling studies at ProRail.

7.2.2. ERTMS/ETCS Level 2

The ERTMS/ETCS Level 2 model consists of 2 model versions and 5 scenarios in total. Two infrastructure versions have been made differing only in the block formations of the signalling system, the first being a Level 2 long block and the second a Level 2 short block version.

Level 2 long block
The Level 2 long block model is designed according to the planned 2030 situation. Here the SAAL corridor is entirely equipped with ERTMS/ETCS Level 2. The area surrounding the central station of Amsterdam is still equipped with ATB and the NS’54 signalling system in all the versions of the model. The placement of the ERTMS/ETCS marker boards, and size of the block sections were all based on existing ATB/NS’54 blocks. This allows for a direct comparison between the ATB and ERTMS/ETCS systems.

The Level 2 long block version of the model contains 4 different scenarios. The first two are made to represent the driver drivers braking behaviour discussed in chapter 5, the constant braking rate of 0,5 m/s^2 and the P-2s.

Driver behaviour 0,5 m/s^2
The constant braking rate scenario uses the simplified braking option to set the EBD braking curve for all trains to the desired 0,5m/s^2. Since the permitted curve is used for the trains

braking behaviour, the T_eb and T_driver parameters are set to 0s to set the permitted curve equal to the EBD curve. The driver reaction time is set to 4s and the buffer time is set to 60s.

Driver behaviour P-2s
In this scenario the permitted curve is moved to 2 seconds before its original position by adapting the T_eb and T_driver parameters to provide the desired braking behaviour. The T_driver parameter is set to 2s and the T_eb is set to 6s in order to move the permitted curve while keeping the indication curve in the same position. Similar to the previous scenario the driver reaction time is set to 4s and the buffer time is set to 60s. The block reservation is set to reserve according to the indication curve, as is standard for the selected baseline B3R2 subset-026 version 3.6.0

Driver follows permitted
This scenario is added to provide an indication of the maximum capacity possible is this block configuration without using ATO. In this scenario the drivers follow the permitted curve exactly. The system parameters are set to the standard values provided by the ERA. The T_eb is set to 2s, the T_driver is set to 4s and the block reservation is set to the indication curve as standard for the baseline B3R2. The driver reaction time is set to 4s and the buffer time is set to 60s.

ATO
In the ATO scenario the permitted curve is moved 2s closer to the EBD curve to create the desired braking behaviour. The block reservation for the ATO scenario is minimised in the model. In section 6.3 the system reaction time for the ATO is described to be 2s at maximum. The system will be able to react very quickly to a change in the MA, meaning a shorter reservation can be used. The shortest reservation possible within the model based on the indication curve is 5s in front of the permitted. With the system reaction time of 2s, this is considered to be sufficient to start braking up to the ATO braking curve.

The parameter settings used for the ATO scenario are the following. The T_eb is set to 4s, to set the permitted curve in the desired position. The T_driver is set to 0s, placing the indication curve 5s in front of the permitted curve. The driver reaction time is set to 2s, equal to the ATO system reaction time. The buffer time is set to 30s as explained in section 6.5.

Level 2 short block
The Level 2 short block infrastructure is made according to an optimised version of the ERTMS/ETCS designs for the SAAL corridor. The placement of the ERTMS/ETCS marker boards, and size of the block sections were all based on existing designs and drawings from ProRail. This model version has been added to provide an insight into the effects shorter blocks have on the capacity (within Level 2) and to see what is the maximum capacity that can be attained with ERTMS/ETCS Level 2 on the SAAL corridor. The level 2 short block version is similar to the Hybrid Level 3 in that it contains shorter blocks. The differences are that the blocks all have trackside train detection equipment in place. The downside is that the large amount of trackside detection equipment makes a short block Level 2 system very expensive. This model version only contains an ATO scenario. This will show the maximum capacity that can be reached with the Level 2 system on the SAAL corridor. The system settings for this scenario are the same as the long block ATO scenario.

7.2.3. ERTMS/ETCS Hybrid Level 3

In the Hybrid model, the blocks used in the Level 2 long block model are used as the physical blocks containing the trackside train detection equipment. These physical blocks are used by the trains that are not equipped with a TIM unit (only the freight trains) for releasing a section of their route after using it. Axle counters are used for the trackside train detection and are placed at the edges of the physical block sections. The physical blocks are divided into smaller virtual blocks used by the trains equipped with TIM units. The size of these virtual blocks varies based on the size and location of the physical block sections. The design regulations for ERTMS/ETCS (ProRail, Assetmanagement, 2019) have been used to determine the placements for the markerboards of the virtual block sections surrounding switches and other movable objects.

In the thesis by (Jansen, 2019) an optimal block length of 100m is mentioned to be used on the critical parts of the network. Blocks of around 100m are used on the bottlenecks on the corridor and near the stations where very short headways are present in the timetable. On the rest of the corridor, virtual block sections of around 200m are used. The exact length varies based on locations and size of the physical block sections. Trackside train detection equipment is still in place around switches and other moving objects (movable bridges etc). The ale counters can also be used by the system to clear a part of the block sections.

The Hybrid Level 3 model contains the same 4 scenarios as the long block Level 2 model. The driver behaviour will again be modelled with the constant braking rate of 0,5 m/s^2 and the P-2s scenarios. The maximum capacity that just the Hybrid Level 3 system on its own can bring is studied with the “Permitted” scenario, where drivers would exactly be following the permitted curves. The forth scenario contains the ATO system. It will contain both the benefits of the very short blocks and the ATO system. This ATO scenario is expected to provide the maximum capacity off all the scenarios investigated within this research. Table 8 contains an overview of all the parameter setting for the model scenarios. The parameter settings for the scenarios in the Hybrid Level 3 model are the same as the scenarios for the Level 2 model, as can be seen within the table.

Table 8 | Overview of model parameters for all scenarios

Model	Baseline	Reservation	Simp braking	T_Driver	T_eb	Driver reaction	Buffer
ATB	-	-	0,5 m/s^2	-	-	9s	60s
L2 Driver 0,5 m/s2	3.6.0	Ind	0,5 m/s^2	**0**	**0**	4s	60s
L2 Driver P-2s	3.6.0	Ind	Off	**2**	**2+4**	4s	60s
L2 Permitted	3.6.0	Ind	Off	4	2	4s	60s
L2 ATO	3.6.0	Ind	Off	**0**	**2+2**	**0s**	**30s**
L2 ATO short block	3.6.0	Ind	Off	**0**	**2+2**	**0s**	**30s**
HL3 Driver 0,5 m/s^2	3.6.0	Ind	0,5 m/s^2	**0**	**0**	4s	60s
HL3 Driver P-2s	3.6.0	Ind	Off	**2**	**2+4**	4s	60s
HL3 Permitted	3.6.0	Ind	Off	4	2	4s	60s
HL3 ATO	3.6.0	Ind	Off	**0**	**2+2**	**0s**	**30s**

8. Capacity calculation/assessment

8.1. Timetable compression

The capacity calculations are performed using a timetable compression tool within RailSys. The buffer times are included in the compressions to provide a complete overview of the benefits of the ATO system. The buffer has been put into the model by extending the signal release times (by 60s for the human drivers and 30s for the ATO models) of the modelled systems to include the buffer times.

The compressions are done similarly to the principles in the UIC 406 leaflet. Two things were changed in order to provide a more complete picture of the capacity the different systems provide and also include the interaction between trains on different routes. The compression graphs are made along 4 stretches of the SAAL corridor, that all have different service patterns and route characteristics (stations, track layout, etc). Figure 39 shows a map indicating these sections of the corridor chosen for the capacity calculations. Each of these locations is indicated on the map in a different colour.

- Hvs – Gpda: Hilversum to Gaasperdammerweg aansluiting
- Alm – Gpda: Almere to Gaasperdammerweg aansluiting
- Gpda – Asra: Gasperdammerweg aansluiting to Amsterdam Riekerpolder aansluiting
- Asra – Hfd: Amsterdam Riekerpolder aansluiting to Hoofddorp

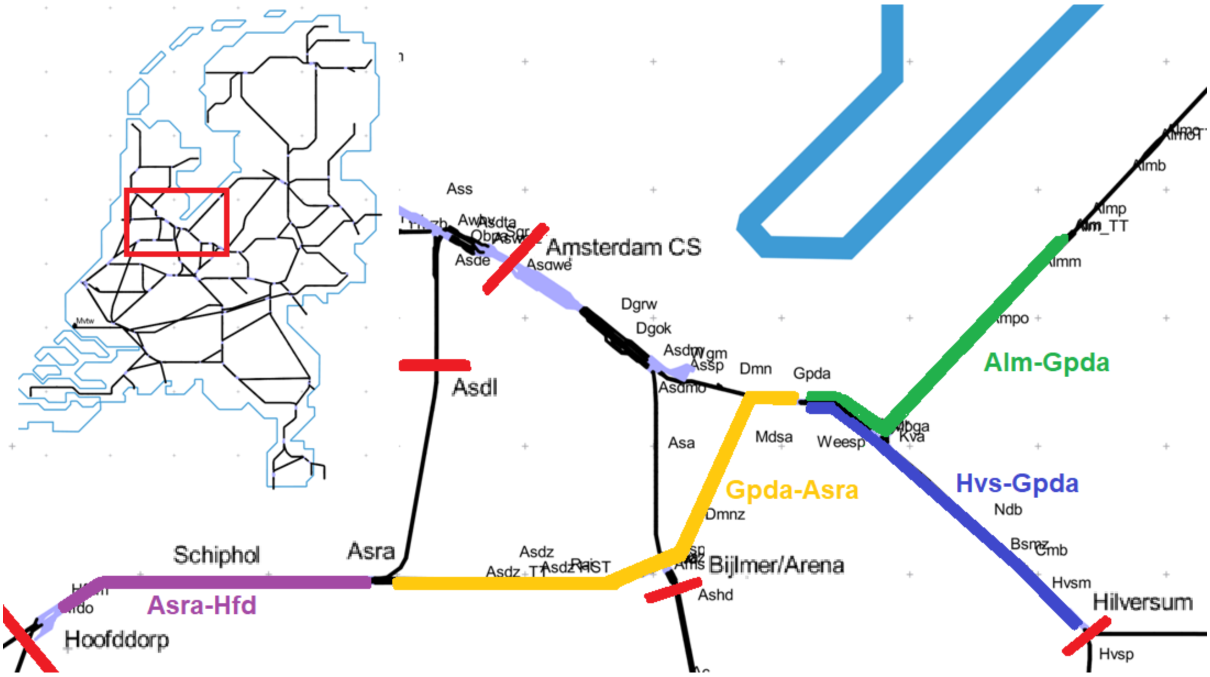


Figure 39 | Map of compression graph locations

Hvs-Gpda

This section of the corridor has a very diverse service pattern containing freight trains, international trains, Intercity and Sprinter trains. This will show the effect of the service pattern on the capacity when comparing the different systems. This route contains an overtaking opportunity at Weesp, where the Sprinter trains can be passed by the intercity and international trains. The Hvs-Gpda section is shown in blue on the map of Figure 39.

Alm-Gpda

The section from Almere to Gpda contains only intercity and Sprinter traffic. The much more homogenous service pattern provides a good comparison with the Hvs-Gpda section to see the effect of the service pattern. This route also contains an overtaking opportunity at the station of Weesp. The map in Figure 39 shows this route in green.

Both the Alm-Gpda and Hvs-Gpda routes run through the station of Weesp, as can be seen on the map in Figure 39. These two routes both run through Weesp to Gpda on separate tracks. At Gpda they merge and then split again with one part continuing to the central station, and the other part continuing to Amsterdam Zuid and Schiphol.

Gpda-Asra

Gpda-Asra is a section of the route continuing to Amsterdam Zuid and Schiphol. The map in Figure 39 shows this section in yellow. This section is chosen because it is a critical part of the corridor in terms of capacity due to the large amount of interactions between merging and diverging traffic. Around Duivendrecht in the middle of the section, the freight trains and a number of intercity trains merge onto or divert from the corridor. The station of Amsterdam Zuid also provides some interaction between trains due to the intercity and international trains changing tracks.

Asra-Hfd

The section between Asra and Hoofddorp is shown in Figure 39 in purple. This section is the busiest of the whole SAAL corridor. It consists of 4 tracks, with intercity and international trains using the outer 2 tracks, and the Sprinter trains using the inner 2 tracks. The separation of these flows allows for a (almost) completely homogenous service pattern. This allows for a very high number of trains to pass this section each hour. The inner and outer tracks are considered separately in the capacity calculations. The inner tracks containing only Sprinter trains will be denoted with (S) and the outer tracks with intercity and international trains will be denoted with (IC) in further tables and figures.

Sections not considered

The section between Almere and Lelystad is not considered for the capacity calculation. Almost half of the trains on the section between Gpda and Lelystad start and end at Almere, and don’t continue on to Lelystad. The infrastructure layout between Almere and Lelystad is similar to that between Gpda and Almere, but the number of trains is a lot lower. Including this section in the calculations will not add anything significant. For this reason, it is left out.

The section between Gpda and the central station of Amsterdam is also not considered in the calculations. Due to this section containing the transition zones between systems, with the area surrounding the central station running on the ATB/NS’54 signalling and only a short section using the ERTMS/ETCS system. This means that the effects on capacity of changing these systems can’t fully be judged on this section.

Settings used for compression
The timetable compressions are performed over a 1-hour calculation period from 12:00 to 13:00 in the timetable for all selected track sections. The minimal run and dwell times are used for the calculations. Dwell time minimums are 54s for intercity trains and 42s for Sprinter trains, conform the minimum values used by ProRail in timetable planning. All overtakings present in the timetable will remain in the timetable compression. The compressions are executed for both directions of traffic.

8.2. Results Timetable compression

The timetable compressions provide an overview of capacity occupation rates. Due to the added 60s buffer, an occupation rate of above 100% does not necessarily mean a conflict free timetable is not possible. On paper it could be possible, but these timetables will not satisfy the buffer time norms and in practice these timetables will likely be unstable. With the time buffer included, the occupation rates below 100% implies a feasible and stable timetable. Occupation rates above 100% without the buffer, as shown in section 8.3, imply that a conflict free timetable is not possible.

8.2.1. Base: ATB/NS’54

The legacy ATB/NS’54 system provides the base for comparison of the capacity the different systems can provide. It also provides an overview of where the main bottlenecks in terms of capacity are located within the corridor under the legacy signalling system.

Figure 40 contains a graph of the timetable compression for the Hvs-Gpda track section. Critical block sections are marked with coloured shades in the top part of the figure, and arrows in the compression graphs. The colours of the arrows indicate the frequency a section is labelled as critical. With yellow indicating a low frequency, orange being labelled as medium, and red indicating a high frequency. The graph contains all 4 train types present on the corridor.

- Intercity trains (green)
- Sprinter trains (blue)
- International trains (pink)
- Freight trains (brown)

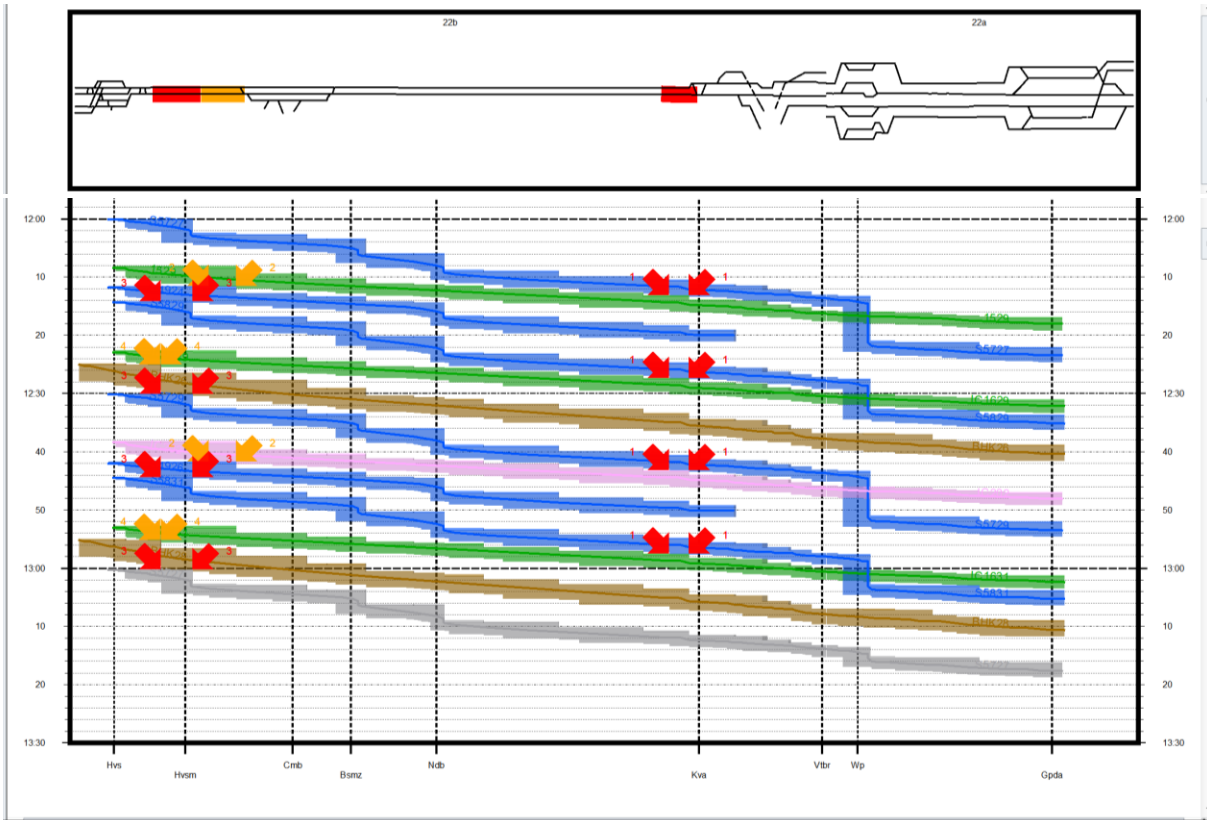


Figure 40 | Compression graph ATB/NS'54 for the Hvs-Gpda section containing all train types

The train shown in grey within Figure 40 is the first train excluded from the timetable compression. It is used to determine the point where the compression ends. Further compression graphs for the different system variants can be found in Appendix A.

Table 9 contains the results from the timetable compressions with the ATB/NS'54 system. The results are percentages of infrastructure occupation. As explained in section 3.1.3, the occupancy time rate is determined by dividing the occupancy time by the defined time period for the calculation. As explained in section 8.1 the 4-track section between Asra and Hfd is split in 2 sections representing the inner 2 tracks (S) and outer 2 tracks (IC).

Table 9 | Results of timetable compression (occupation rate) in the ATB/NS'54 model

	Hvs-Gpda	**Gpda-Hvs**	**Alm-Gpda**	**Gpda-Alm**	**Gpda-Asra**	**Asra-Gpda**	**Asra-Hfd (S)**	**Asra-Hfd (IC)**	**Hfd-Asra (S)**	**Hfd-Asra (IC)**
ATB/NS'54	100,4	97,7	93,3	89,9	130,1	133,9	101,1	101,6	99,9	110,8

Table 9 contains the results of the timetable compression in the base ATB/NS'54 model. On a number of parts on the corridor, the basic hourly pattern of the timetable will not fit within the hour. The biggest problem with the capacity can be seen at the section between Gpda and Asra. The biggest bottleneck in this section is the area surrounding Duivendrecht station. At this location, the freight trains merge onto the corridor at a low speed, using up a lot of capacity. The area around Schiphol airport also shows a lack of capacity under the ATB/NS'54 signalling, that could be addressed by the ERTMS/ETCS and ATO systems.

8.2.2. ERTMS/ETCS Level 2

A large advantage of the ERTMS/ETCS system over the legacy signalling is the delayed braking possibilities. Within the ERTMS/ETCS L2 model the different driving behaviours provide a further insight into the effect of this delayed braking on the capacity consumption. Table 10 contains the capacity occupation results from the driver behaviour scenarios. An overall decrease of the capacity occupation is visible in the table when the braking is delayed.

Table 10 | Timetable compression results for the ERTMS/ETCS L2 model compared to the ATB/NS'54 system

	Hvs-Gpda	Gpda-Hvs	Alm-Gpda	Gpda-Alm	Gpda-Asra	Asra-Gpda	Asra-Hfd (S)	Asra-Hfd (IC)	Hfd-Asra (S)	Hfd-Asra (IC)
ATB/NS'54	100,4	97,7	93,3	89,9	130,1	133,9	101,1	101,6	99,9	110,8
L2 Driver 0.5	98,9	104,3	93,2	91,1	111,7	116,9	92,7	96,6	95,0	86,9
L2 Driver P-2s	97,0	97,7	90,7	87,6	112,1	115,6	93,1	94,5	94,3	87,1
L2 Permitted	94,7	96,4	88,8	86,0	108,9	113,0	88,6	92,6	90,1	84,2

L2 Driver 0.5

Since the modelling software is not designed to input a set constant braking rate for all trains under ERTMS/ETCS operations, the capacity consumption figures gathered from the timetable compression will not be completely accurate. They do however provide an indication for what the effect of this type of braking behaviour would do to the capacity consumption figures. Normally the ERTMS/ETCS curves are based on the different rollingstock dependant braking characteristics. The constant braking rate settings set all the braking curves for the different rollingstock types to the same values. This creates a homogenous braking behaviour and also homogenises the block reservations. On average a decrease in occupation rate of 7,1 percent point is observed compared to the ATB/NS'54 signalling. The maximum observed occupation rate on the corridor is found within the bottleneck observed earlier between Gpda and Asra. The maximum occupation rate for this driver behaviour comes to 116,9%.

The timetable compression results for the constant braking rate under ERTMS/ETCS indicate that even with similar braking behaviour as used under the legacy system, removing the necessity of early braking due to the signal aspects already has a large effect on the capacity. A higher occupation rate with the ERTMS/ETCS system could be due to the slightly larger set-up time (extra 6s) due to the communication between train and RBC.

L2 Driver P-2s

The driver behaviour explained by the experienced ERTMS/ETCS drivers generally provides an improvement over the constant braking rate when looking at the occupation. Figure 41 provides a more visual representation of Table 10, providing a comparison between the capacity consumed with ATB/NS'54 and the different driving behaviours for ERTMS/ETCS. An improvement in occupation is visible with driver behaviour coming closest to the permitted curve of ERTMS/ETCS. When comparing it to the results for the ATB/NS'54 signalling system, it indicates that a significant capacity increase will be achieved on the SAAL corridor with the implementation of ERTMS/ETCS.

The results for the timetable compression provide a realistic indication of the occupation rates for ERTMS/ETCS operations. When P-2s scenario is compared to the ATB/NS'54, an average decrease of 8,9 percent point is visible. The maximum occupation rates can be found between Gpda and Asra, with the maximum occupation rate from the compression being 115,6%.

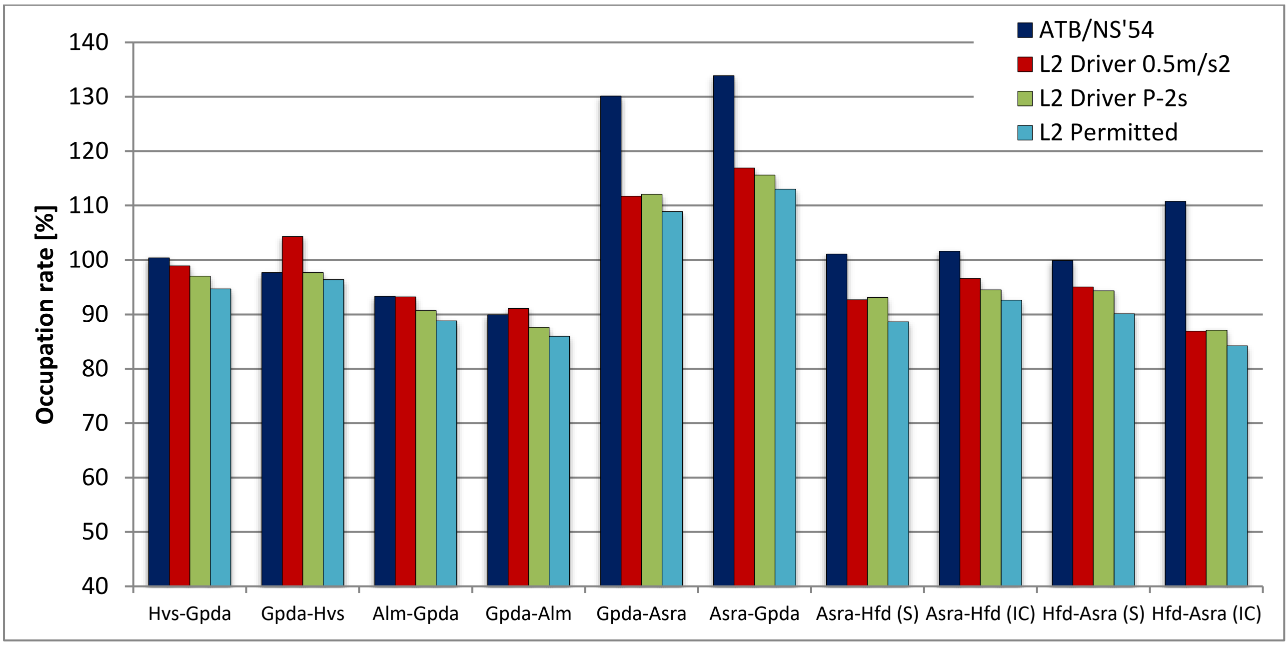


Figure 41 | Comparison between ATB/NS'54 and ERTMS/ETCS Level 2

L2 Permitted

This model scenario provides the optimal capacity that the ERTMS/ETCS Level 2 system could bring in the current block formation. With the Level 2 system, the timetable fits on the largest part of the corridor. The bottleneck on the Gpda-Asra section is the only place on the corridor where the hourly pattern will not fit with this block configuration of the Level 2 system. The maximum occupation rate in this scenario of 113% is observed within the Gpda-Asra bottleneck. A clear difference is observed between the capacity consumption of the driver behaviour models and that of the Permitted model. Differences of between 2 and 5 percent point are observed. When compared to the ATB/NS'54 signalling, the average reduction in occupation rate comes to 11,5 percent point.

Comparison driver behaviours

When comparing the different driver behaviours, a clear link between the delayed braking and decrease in occupation rates can be seen. Comparing the constant braking rate of 0,5m/s^2 to the P-2s braking behaviour, an average decrease in the occupation rate of 2,1 percent point is observed. Similar results are found when the results of the P-2s and the Permitted scenarios are compared. The small delay in braking of 2s between the P-2s and Permitted is shown to have a sizable effect in the occupation rates, with an average decrease in occupation rate of 2,6 percent point on the corridor. The occupation difference between the Driver P-2s and the Permitted is purely due to delayed braking.

As explained in section 4.2, the constant braking rate behaviour within the model affects the functions of the ERTMS/ETCS system. Normally the ERTMS/ETCS curves are based on the different rollingstock dependant braking characteristics. The constant braking rate settings set all the braking curves for the different rollingstock types to the same values. This creates a homogenous braking behaviour and also homogenises the block reservations, since this is based on the indication curve. At the higher speeds (i.e. above 80km/h) the block reservation would take longer than normal, due to the braking curve of the constant braking rate being needing more distance than the indication, as can be seen in (link to figure). For the lower speeds, the reverse would be true with where the constant braking rate provides a more favourable braking behaviour than the ETREM/ETCS curves. Figure 42 provides a comparison between the different braking behaviours at lower speeds. Due to the simplified braking settings, the curve used for the block reservations becomes more favourable at low speeds than the regular indication curve causing the Driver 0.5 behaviour to score better in these situations.

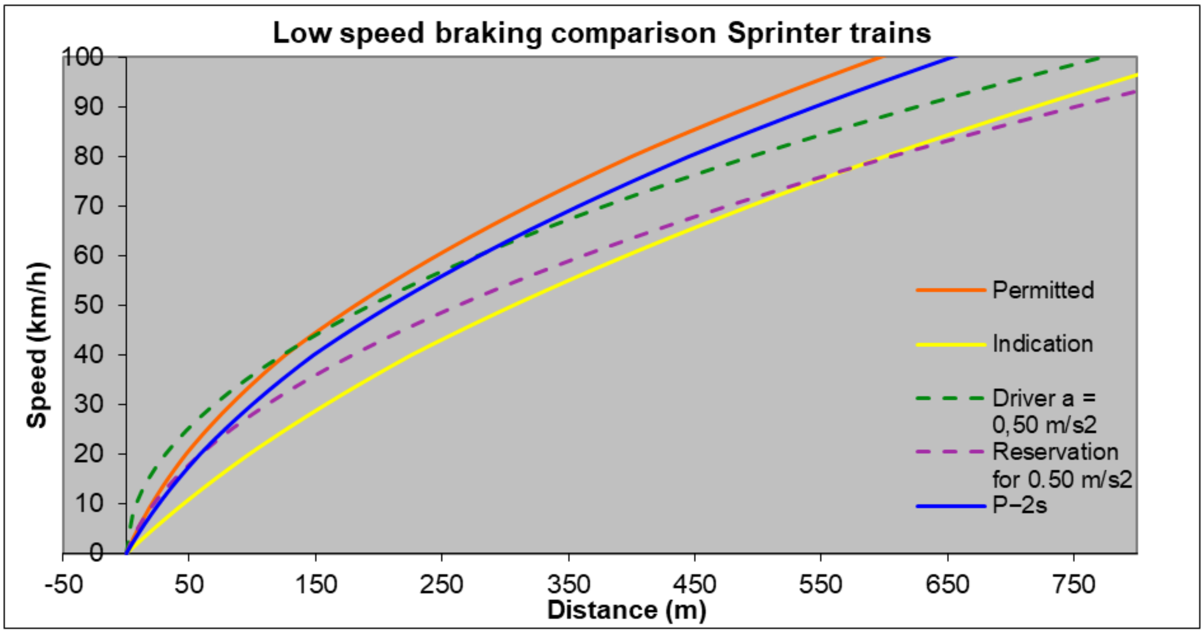


Figure 42 | Low speed braking comparison between driver behaviours

The more homogenous behaviour could be beneficial to the capacity, especially on locations where a large number of trains have a stop in the timetable at the same station. This is visible at in the Gpda-Asra section with the stations Duivendrecht and Amsterdam Zuid, and the Asra-Hfd section containing Schiphol. On the Gpda-Asra section and between Asra and Hfd, the P-2s behaviour results in a slightly higher occupation rate than the constant braking rate behaviour. The more homogenous braking behaviour combined with the change in reservations due to the altered braking curves are the most likely causes for the constant braking rate behaviour to score better on these sections which include lower track speed limits and stops for all trains.

If the constant braking rate behaviour under ERTMS/ETCS is to be realistically modelled in future studies, an adaptation to the modelling software in general (not just RailSys) needs to be made to include the option to change the driving behaviour within the model, without changing the braking curves within the ERTMS/ETCS systems.

8.2.3. ERTMS/ETCS Hybrid Level 3

The ERTMS/ETCS Hybrid Level 3 system provides shorter virtual blocks over the Level 2 system. As explained in section 7.2.3 the block length is shortened up to between 200 and 100m. Comparing the Hybrid Level 3 system with the Level 2 will show the effects of the shorter virtual blocks on the capacity of the corridor. Similar effects of the driver behaviours can be observed with the HL3 system.

HL3 Driver 0.5

The constant braking rate scenario for Hybrid Level 3 suffers from the same problems in the modelling tool as in the Level 2 system. Table 11 contains the results of the timetable compression for all scenarios containing the human drivers. A significant decrease in the occupation rate is seen in the table for all selected sections of the corridor. Comparing the results for the constant braking rate for Level 2 and Hybrid Level 3, shows an average decrease in occupation rate of 16,5 percent point for the Hybrid Level 3 system.

HL3 Driver P-2s

When the P-2s behaviour is compared to the constant braking rate for Hybrid Level 3, a similar result can be seen as for Level 2. An overall improvement in terms of occupation is observed. An average decrease in occupation rate between the P-2s and constant braking rate of 1,2 percent point is observed. Comparing the P-2s behaviour under the Level 2 and Hybrid Level 3 systems an average decrease of 15,9 percent point is observed.

Table 11 | Timetable compression results for all human driver scenarios

	Hvs-Gpda	**Gpda-Hvs**	**Alm-Gpda**	**Gpda-Alm**	**Gpda-Asra**	**Asra-Gpda**	**Asra-Hfd (S)**	**Asra-Hfd (IC)**	**Hfd-Asra (S)**	**Hfd-Asra (IC)**
ATB/NS'54	100,4	97,7	93,3	89,9	130,1	133,9	101,1	101,6	99,9	110,8
L2 Driver 0.5	98,9	104,3	93,2	91,1	111,7	116,9	92,7	96,6	95,0	86,9
L2 Driver P-2s	97,0	97,7	90,7	87,6	112,1	115,6	93,1	94,5	94,3	87,1
L2 Permitted	94,7	96,4	88,8	86,0	108,9	113,0	88,6	92,6	90,1	84,2
HL3 Driver 0.5	86,1	82,7	74,6	74,2	96,4	108,7	70,5	80,0	67,2	81,9
HL3 Driver P-2s	83,8	80,6	73,1	71,9	95,4	105,5	73,1	77,1	69,8	80,3
HL3 Permitted	81,3	77,7	70,7	69,3	92,8	103,2	69,3	75,2	66,6	77,5

Hl3 Permitted

The timetable compression results shown in Table 11 indicate that even with the shorter blocks the Hybrid Level 3 system provides, the occupation rate on the Asra-Gpda section still exceeds the 100%. With the buffer time of the current planning norms included, the basic patterns of the timetable will not completely fit on the main bottleneck of the corridor. An average decrease in occupation rate of 16 percent point when compared to the L2 Permitted scenario is observed. When comparing the results for the Hybrid Level 3 scenarios with their Level 2 counterparts, all have shown a roughly 16 percent point lower occupation rate. This indicates that shorter block sections are a very effective solution in creating more capacity.

Figure 43 contains a visual representation of Table 11. The graph shows the differences in occupation varying between the different sections of the corridor. These differences will be covered further in chapter 9.

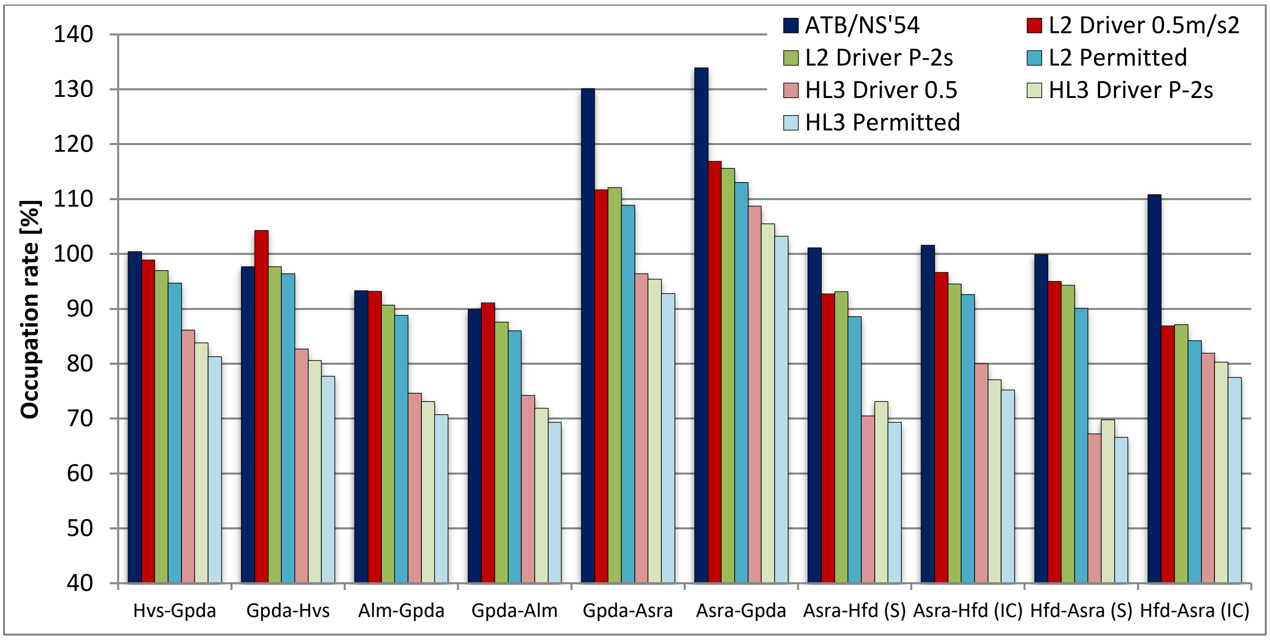


Figure 43 | Graph of the timetable compression results for all systems using human drivers

8.2.4. ERTMS/ETCS + ATO

With the timetable not fitting on the corridor, even with the shorter blocks provided by ERTMS/ETCS Hybrid Level 3, ATO will be necessary to make it fit completely. As describes in section 6.5 the ATO system will allow for delayed braking 2s after the permitted curve and makes it possible to reduce the time buffers between trains. This will result in lower occupation rates. Table 12 provides the table of timetable compression results showing the effects of ATO on the occupation rate. The effects of ATO are investigated in 2 separate stages, starting with the delayed braking portion portrayed by the “ATO 60s” in Table 12. The effect of the buffer time reduction is investigated in section 8.2.5.

Table 12 | Complete occupation rate table showing results for all model scenarios

	Hvs-Gpda	**Gpda-Hvs**	**Alm-Gpda**	**Gpda-Alm**	**Gpda-Asra**	**Asra-Gpda**	**Asra-Hfd (S)**	**Asra-Hfd (IC)**	**Hfd-Asra (S)**	**Hfd-Asra (IC)**
ATB/NS'54	100,4	97,7	93,3	89,9	130,1	133,9	101,1	101,6	99,9	110,8
L2 Driver 0.5	98,9	104,3	93,2	91,1	111,7	116,9	92,7	96,6	95,0	86,9
L2 Driver P-2s	97,0	97,7	90,7	87,6	112,1	115,6	93,1	94,5	94,3	87,1
L2 Permitted	94,7	96,4	88,8	86,0	108,9	113,0	88,6	92,6	90,1	84,2
L2 ATO 60s	92,7	94,2	86,8	83,6	104,0	110,0	86,0	90,7	87,6	82,1
L2 Short ATO 60s	80,4	77,0	75,4	70,0	98,6	106,2	67,2	77,4	64,6	76,0
HL3 Driver 0.5	86,1	82,7	74,6	74,2	96,4	108,7	70,5	80,0	67,2	81,9
HL3 Driver P-2s	83,8	80,6	73,1	71,9	95,4	105,5	73,1	77,1	69,8	80,3
HL3 Permitted	81,3	77,7	70,7	69,3	92,8	103,2	69,3	75,2	66,6	77,5
HL3 ATO 60s	79,8	75,3	68,2	66,8	89,6	99,6	67,2	70,8	64,6	73,3

L2 + ATO

Adding the ATO system to the ERTMS/ETCS Level 2 system with the same block configuration as the ATB/NS’54 signalling does not lower the occupation rate enough to make the timetable fit without applying the buffer time reduction. Figure 44 contains a graph providing a visual representation of the timetable compression results shown in Table 12. The ATO system when combined with the ERTMS/ETCS Level 2 signalling results in an average reduction of the occupation rate of 2,6 percent point on the SAAL corridor. When the ATO is compared to the human driver behaviour of the P-2s scenario, this reduction in occupation rate grows to 5,2 percent point. Compared to the ATB/NS'54 system an average occupation rate reduction of 14,1 percent point is observed.

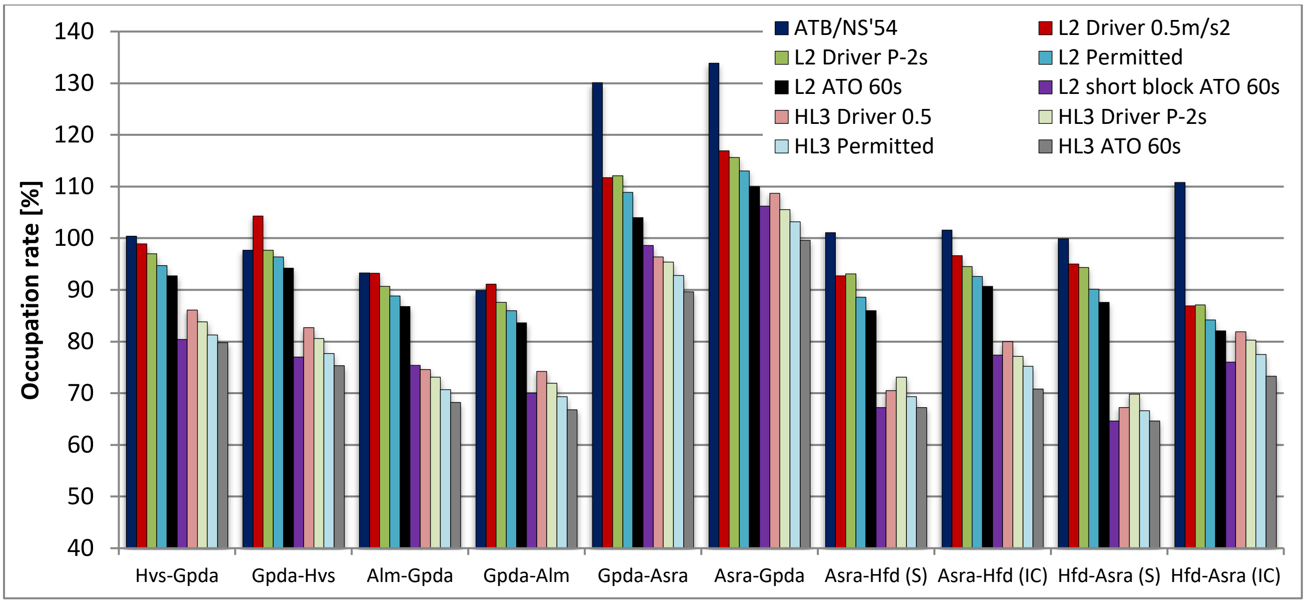


Figure 44 | Graph of all compression results with 60s buffer time

HL3 + ATO

The use of ERTMS/ETCS Hybrid Level 3 combined with ATO is expected to provide the highest possible capacity of all the investigated system configurations. Table 12 supports this hypothesis. The timetable compression result for the Hybrid Level 3 + ATO scenario shows an average reduction in occupation rate of 2,8 percent point compared to the Hybrid Level 3 system without ATO. When the P-2s driver behaviour is included in the comparison, the average reduction grows to 5,5 percent point. In line with the earlier comparisons between the Level 2 and Hybrid Level 3 systems, the HL3 + ATO scenario provided an average reduction of 16,3 percent point over the L2 scenario due to the short blocks. Compared to the ATB/NS'54 system, the HL3 + ATO combination provided an average occupation rate reduction of 30,4 percent point. The results in Table 12 show that the use of ATO on top of the Hybrid Level 3 system provides enough capacity to fit the timetable on the SAAL corridor, even without a reduction in buffer time.

Optimised L2 short block

The L2 short block infrastructure is based on an optimised Level 2 design from ProRail. This is scenario is made to assess what the optimised design would add in terms of capacity and to see what the maximum capacity is that the Level 2 system with ATO could provide. The optimised design, provides an average reduction of the occupation rate of 12,5 percent point on the corridor over the longer block configuration Level 2 scenario. The difference in occupation rates between the HL3 and the optimised L2 short block scenario is smaller. Occupation rates for HL3 system are on average roughly 4 percent point lower. The amount of trackside train detection necessary for the optimised L2 design will increase the infrastructure costs.

8.2.5. Buffer time reduction ATO

In section 6.5 a possible buffer time reduction for ATO of 30s is assumed. The effect of such a buffer time reduction on the capacity is shown in Table 13. The table contains the results of all the timetable compressions with buffer times included. The buffer time reduction is expected to result in a large reduction in occupation rates.

L2 + ATO 30s

The reduction of the buffer time to 30s lowers the occupation rate for the L2 long block ATO scenario by an average of 13,3 percent point. The compression results provided in Table 13 indicates that the reduction in buffer time provides enough capacity to make the timetable fit. Compared to the ATB/NS’54 system an average occupation rate reduction of 27,5 percent point is observed.

L2 short block ATO 30s

Figure 45 contains a graph providing a visual representation of the timetable compression results shown in Table 13. Similar to the other ATO scenarios, the reduction in buffer time in the L2 short block ATO scenario provides an average occupation rate reduction of 13,4 percent point. The reduction in buffer time allows the timetable to fit on the corridor. Compared to the ATB/NS’54 scenario, an average reduction in occupation rate of 39,9 percent point.

Table 13 | Occupation rates for investigated ATO model scenarios

	Hvs-Gpda	**Gpda-Hvs**	**Alm-Gpda**	**Gpda-Alm**	**Gpda-Asra**	**Asra-Gpda**	**Asra-Hfd (S)**	**Asra-Hfd (IC)**	**Hfd-Asra (S)**	**Hfd-Asra (IC)**
ATB/NS'54	100,4	97,7	93,3	89,9	130,1	133,9	101,1	101,6	99,9	110,8
L2 Permitted	94,7	96,4	88,8	86,0	108,9	113,0	88,6	92,6	90,1	84,2
L2 ATO 60s	92,7	94,2	86,8	83,6	104,0	110,0	86,0	90,7	87,6	82,1
L2 ATO 30s	82,7	84,2	75,2	71,1	88,2	93,4	74,3	74,1	75,9	65,4
L2 Short ATO 60s	80,4	77,0	75,4	70,0	98,6	106,2	67,2	77,4	64,6	76,0
L2 Short ATO 30s	70,4	67,0	63,7	57,5	82,7	89,7	55,4	60,7	52,6	59,3
HL3 Permitted	81,3	77,7	70,7	69,3	92,8	103,2	69,3	75,2	66,6	77,5
HL3 ATO 60s	79,8	75,3	68,2	66,8	89,6	99,6	67,2	70,8	64,6	73,3
HL3 ATO 30s	69,8	65,3	56,5	54,3	73,8	81,4	55,4	54,2	52,6	56,7

HL3 + ATO 30s

The timetable compression result for the Hybrid Level 3 + ATO 30s scenario shows an average reduction in occupation rate of 13,5 percent point compared to the HL3 ATO 60s scenario without the buffer time reduction. In line with the earlier comparisons between the Level 2 and Hybrid Level 3 systems, the HL3 + ATO scenario provided an average reduction of 16,4 percent point over the L2 scenario. Compared to the ATB/NS’54 system, the HL3 + ATO combination with buffer reduction provided an average occupation rate reduction of 43,9 percent point.

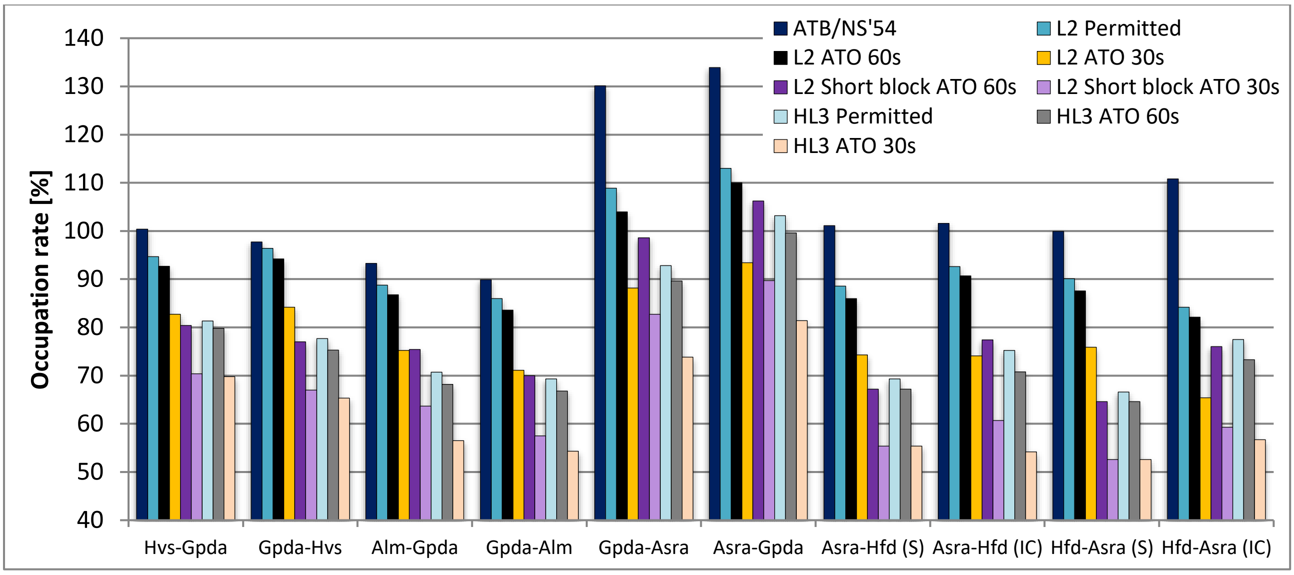


Figure 45 | Occupation rates for the ATO scenarios

8.2.6. Summary of results

When using the current ATB/NS’54 systems, the 2030 timetable for the SAAL corridor is not considered to be stable. The average occupation rate with the ATB/NS’54 system in the case study came to 105,9%, with the maximum value reaching 133,9%. The ERTMS/ETCS Hybrid Level 3 system combined with the ATO system provided a significant decrease in occupation rates compared to the ATB/NS’54 system, with the average occupation rate coming to 62,0% and a maximum observed occupation rate of 81,4%. The reduction of 43,9 percent point observed in the case study consists of the following parts:

- Use of ETCS braking curves vs the stepwise progressive braking of the ATB/NS’54 system (8,9 percent point)
- Shorter virtual block sections provided by the Hybrid Level 3 system (16,0 percent point)
- Optimised driving style with further delayed braking provided by the ATO (5,5 percent point)
- Buffer time reduction assumed possible with ATO (13,5 percent point)

8.3. UIC capacity analysis

The methods used in section 8.2 are specified to the Dutch timetable planning norms, where a set buffer behind every train is used. The results provided in section 8.2 will be translated to the UIC recommendations. In the Method described in the UIC 406 leaflet, the assessment of capacity is done through timetable compressions without the use of any buffer times.

Table 14 | UIC timetable compression results

	Hvs-Gpda	Gpda-Hvs	Alm-Gpda	Gpda-Alm	Gpda-Asra	Asra-Gpda	Asra-Hfd (S)	Asra-Hfd (IC)	Hfd-Asra (S)	Hfd-Asra (IC)
ATB/NS'54	80,4	76,8	69,9	64,9	96,8	103,9	77,8	68,2	76,6	77,4
L2 Permitted	74,7	76,4	65,4	61,0	77,2	80,1	65,3	59,5	66,7	54,1
L2 ATO	72,7	74,2	63,5	58,6	72,3	77,7	62,7	57,6	64,3	52,3
L2 short ATO	60,4	57,0	52,1	45,1	66,9	74,8	43,9	45,5	41,3	43,9
HL3 Permitted	61,3	57,7	47,3	44,3	62,2	68,6	46,0	44,9	43,2	46,1
HL3 ATO	59,8	55,3	44,8	41,8	59,6	65,4	43,9	40,3	41,3	41,1

The UIC defined a number of occupation rates for different types of railway lines. According to the UIC, these occupation rates are recommended to provide an acceptable quality of service. The recommendations are based on a generalisation of timetable characteristics of existing timetables and respective delays.

Table 14 provides the results of the timetable compressions done according to the methods described in the UIC 406 leaflet. Table 15 contains the occupancy rates recommended by the UIC. The recommended rates for the peak hours will be used for the comparison. The track sections selected for the timetable compression could be divided in two different line types. The Asra-Hfd (s) and Hfd-Asra (s) sections only contain the local Sprinter trains, meaning they could be classified as dedicated suburban passenger lines. The rest of the sections contains a mixture of service types, classifying them as mixed traffic lines. Due to the close relations and interactions between the sections on the SAAL corridor, the choice is made to treat the entire corridor as a mixed traffic line.

Table 15 | UIC recommended maximum occupation rates. Source: (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%

Comparing the occupation rates from the timetable compressions in Table 14 with the recommended rates in Table 15, it can be seen that only some of the track sections already comply with the recommended rates under the ATB/NS'54 system. The sections between Alm and Gpda and one of the sections between Asra and Hfd have an occupation rate lower than the recommended maximum.

The Asra-Gpda section shows an occupation rate higher than the recommended maximum with the ERTMS/ETCS Level 2 system, even when ATO is applied. When the short block Level 2 design is combined with ATO the occupation rates for the entire corridor comply with the recommended values. The occupation rate for the Asra-Gpda section is 74,8%, indicating that without the ATO the short block Level 2 design will not comply with the recommended rate of 75%. When the Hybrid Level 3 is applied, the occupation rates lower enough to comply with the recommended maximum on all sections. This indicates that shorter block sections are a necessity to provide an acceptable quality of service on the SAAL corridor. This will be further tested by applying the additional time rates (buffers) defined by the UIC.

Additional time rate (buffer times) are recommended for the different types of lines. These additional time rates are based on the recommended occupation rates. Table 16 contains the additional time rates recommended by the UIC. These additional time rates are defined according to the following formula.

$$Additional\ time\ rate\ [\%] = \left(\frac{100}{occupation\ rate} - 1\right) \times 100$$

Table 16 | UIC proposed additional time rates for lines. Source: (International Union of Railways, 2013)

Type of line	**Peak hour**	**Daily period**
Dedicated suburban passenger traffic	18%	43%
Dedicated high-speed line	33%	67%
Mixed-traffic lines	33%	67%

The occupation rates combined with the additional time rates (buffers) are called the capacity consumption by the UIC. The capacity consumption figures are similar to the occupation rates with the buffers included that have been used in section 8.2. Table 17 contains the capacity consumption data attained using the UIC method. The proposed additional time rates provided by Table 16 have been added to the results from Table 14. The capacity consumption is determined by the following formula.

$$Capacity\ consumption\ [\%] = \left(\frac{Occupance\ time\ \times (1 + additional\ time\ rate)}{Defined\ time\ period}\right) \times 100$$

Table 17 | Capacity consumption determined according to UIC method

	Hvs-Gpda	**Gpda-Hvs**	**Alm-Gpda**	**Gpda-Alm**	**Gpda-Asra**	**Asra-Gpda**	**Asra-Hfd (S)**	**Asra-Hfd (IC)**	**Hfd-Asra (S)**	**Hfd-Asra (IC)**
ATB/NS'54	106,9	102,1	93,0	86,3	128,7	138,2	91,8	90,7	90,4	102,9
L2 Permitted	99,4	101,6	87,0	81,1	102,7	106,5	77,1	79,1	78,7	72,0
L2 ATO	96,7	98,7	84,5	77,9	96,2	103,3	74,0	76,6	75,9	69,6
L2 short ATO	80,3	75,8	69,3	60,0	89,0	99,5	58,4	60,5	54,9	58,4
HL3 Permitted	81,5	76,7	62,9	58,9	82,7	91,2	54,3	59,7	51,0	61,3
HL3 ATO	79,5	73,5	59,6	55,6	79,3	87,0	51,8	53,6	48,7	54,7

A number of analysis criteria are provided by the UIC for the capacity consumption. A consumption of 100% and lower represents an acceptable quality of service. Numbers lower than 100% indicates there is room for possible extra train paths. Consumption rates higher than 100% indicate the presence of a bottleneck causing a lower service quality.

The results in Table 17 indicate a slightly more optimistic view of the capacity of the SAAL corridor. According to the UIC method, using the Level 2 system will only provide sufficient capacity when short blocks and ATO are applied. The use of the ERTMS/ETCS Hybrid Level 3 system will already provide enough capacity on its own. The compression results from Table 12 is section 8.2 indicate that with the set buffer/additional time of 60s used in the Netherlands for timetable planning, the addition of ATO is necessary to make the timetable fit completely.

The occupations and additional time rates proposed by the UIC do not take the used systems into account. The use of ATO for example will not change the recommended occupations and additional time rates. A case could be made for providing separate recommendations for occupation and additional time figures for the use of capacity increasing systems such as ATO.

8.4. System performance in perturbed scenario

Operations will not always go to plan, therefore the signalling systems also need to be able to handle disruptions. This has been tested on the Gpda-Hvs section of the SAAL corridor by introducing a deterministic perturbation in the form of a departure delay of 10 minutes at the station of Naarden Bussum (Ndb) for the Sprinter train S4907. The test is performed with the ATB/NS'54, Level 2, Hybrid Level 3 and ATO systems. This test is performed in two variations, one with a fixed timetable to see how each system reacts to the same disruption and one where the timetable is adapted to fully utilise the capacity each system provides. The timetable pattern used, and delay propagation graphs of the results are supplied in the Appendix B. Table 18 contains the results of the test with fixed timetable. The time it takes for the system to solve the delay, total delay at destination, the number of affected trains and the total delay at the destination is measured. The frequency mentioned in the table refers to the service frequency (i.e. the number of trains per hour) present in the timetable.

Table 18 | Results of perturbation test with a fixed timetable

	Frequency (trains/hour)	**Departure delay**	**Primary delay**	**Secondary delay**	**Perturbation solved after**	**No. of affected trains**
ATB/NS'54	12	00:10:00	00:09:50	00:29:01	00:37:07	7
L2 Permitted	12	00:10:00	00:09:51	00:23:17	00:34:38	6
L2 ATO 60s	12	00:10:00	00:09:51	00:21:30	00:28:55	5
HL3 Permitted	12	00:10:00	00:09:51	00:12:14	00:21:26	4
HL3 ATO 60s	12	00:10:00	00:09:51	00:11:32	00:21:18	4

Table 18 shows the primary delays to stay almost equal compared to the ATB/NS'54 system. The shorter running time achieved by using the ERTMS/ETCS and ATO system, results in a slightly smaller additional running time that can be used for delay reduction. Both the Level 2 and Hybrid Level 3 systems provide significant improvements in the robustness with the original timetable. Both systems lower the blocking time of each train. This effectively creates larger buffers between trains that can be used for reducing the secondary delays. This results in a lower number of trains being affected, less secondary delays and allows the perturbation to dissolve faster. In the case of the Hybrid Level 3 system, both the amount of delay and time it takes for the perturbation to be solved is cut in half.

In the case of the L2 ATO combination, the driving style optimised for capacity creation allowed for 1 less train to be affected by the perturbation. This explains the performance improvements shown in Table 18 for this system combination. With the HL3 ATO combination this is not the case, showing only a small improvement compared to the Hybrid Level 3 system without ATO.

With the use of systems such as Hybrid Level 3 and ATO, the headway between trains can be reduced. These shorter headways however will affect the robustness. A second test is performed to see how the different systems handle a perturbed scenario and see how the shorter headways affect the robustness. The test is performed with the ATB/NS'54, Level 2, Hybrid Level 3 and ATO with different buffer times. For each system, the timetable used is configurated by shortening the time between trains to the minimal headways between trains with the buffer times included. This will change the service frequency of the timetable to the maximum amount of trains per hour. This will slightly change the ration between Sprinter, intercity and freight trains between scenarios. The time it takes for the system to solve the delay, total delay at destination, the number of affected trains and the total delay at the destination is measured.

Table 19 | Results of perturbation test at maximum capacity

	Frequency (trains/hour)	**Departure delay**	**Primary delay**	**Secondary delay**	**Perturbation solved after**	**No. of affected trains**
ATB/NS'54	12	00:10:00	00:09:50	00:29:01	00:37:07	7
L2 Permitted	12	00:10:00	00:09:51	00:25:46	00:35:44	7
L2 ATO 60s	12	00:10:00	00:09:51	00:25:53	00:32:35	6
L2 ATO 30s	15	00:10:00	00:09:51	00:41:24	00:37:29	8
HL3 Permitted	16	00:10:00	00:09:51	00:27:25	00:27:11	6
HL3 ATO 60s	16	00:10:00	00:09:51	00:25:13	00:24:22	6
HL3 ATO 30s	18	00:10:00	00:09:51	00:38:33	00:28:47	8

Table 19 provides the results of the second perturbation test. Comparing these with the results from Table 18 shows how the shorter headway affect the robustness. Due to the shorter headways, more trains are affected, and delays are larger compared to the results in Table 18. It should be noted that even while operating at their maximum capacity on the modelled track section, improvements in performance for the ERTMS/ETCS can be seen compared to the ATB/NS'54 system.

In the case of ATO, the reduction of the buffer time between trains shows a clear increase in capacity. The reduction in buffer time also clearly affects the robustness, with an increase shown in secondary delays and the number of affected trains. It should be noted that in terms of size of the delays and the number of affected trains, the ATO systems with reduced buffers still provide a similar robustness compared to the current ATB/NS'54 system but with a significantly larger throughput of trains. A trade-off between capacity and robustness will need to be made when a reduction of these buffer times is considered.

9. Network characteristics

The results of the timetable compressions shown in sections 8.2 and 8.3 show that the effectiveness of the different signalling systems and the ATO varies per location. The results have been analysed further in order to explain these variations through the different network characteristics such as the service pattern and the infrastructure configuration.

9.1. Service pattern

The service pattern can influence the capacity of a section of track as all different combinations have their own minimum headways, as shown in the previous study (Jansen, 2019). In order to assess this effect within the SAAL corridor the track sections between Almere and Gpda, and between Hilversum and Gpda are compared further. These two sections are similar in terms of infrastructure, both double track sections of similar length with stations on the main line. Figure 46 contains a map of both track sections.

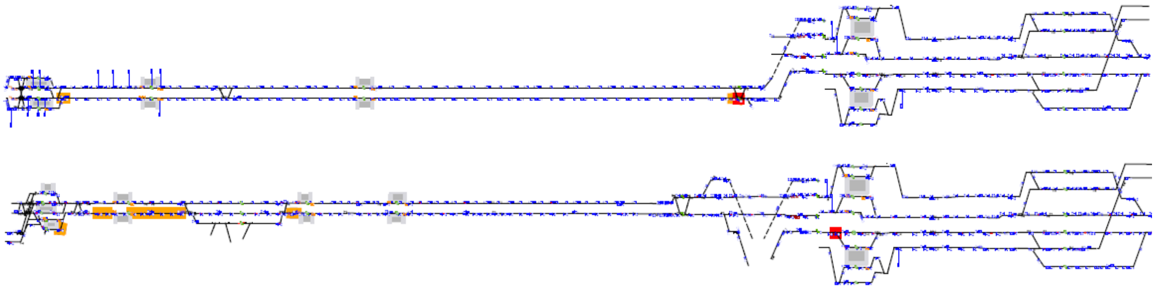


Figure 46 | Infrastructure map of the Alm-Gpda section (top) and Hvs-Gpda section (bottom)

Within the timetable these sections contain a very different service pattern. The section between Almere and Gpda contains a somewhat homogenous service pattern with multiple trains of the same type bundled up behind each other. The Hvs-Gpda section contains a more heterogeneous service pattern with more different types of trains. Figure 47 contains compression graphs from the L2 ATO model scenario for the Alm-Gpda and Hvs-Gpda sections for a 1-hour period.

Since the infrastructure is not exactly the same, the exact numbers for the occupation rates will not be directly compared with each other. However, it is possible to observe the effect of the service pattern on the occupation. On the Alm-Gpda section in the top of the figure, a lot less empty space between the train paths is visible compared to the Hvs-Gpda section in the bottom of the figure. The more homogenous service pattern on the Alm-Gpda section allows for 2 more trains to pass over this track section while still using up less capacity.

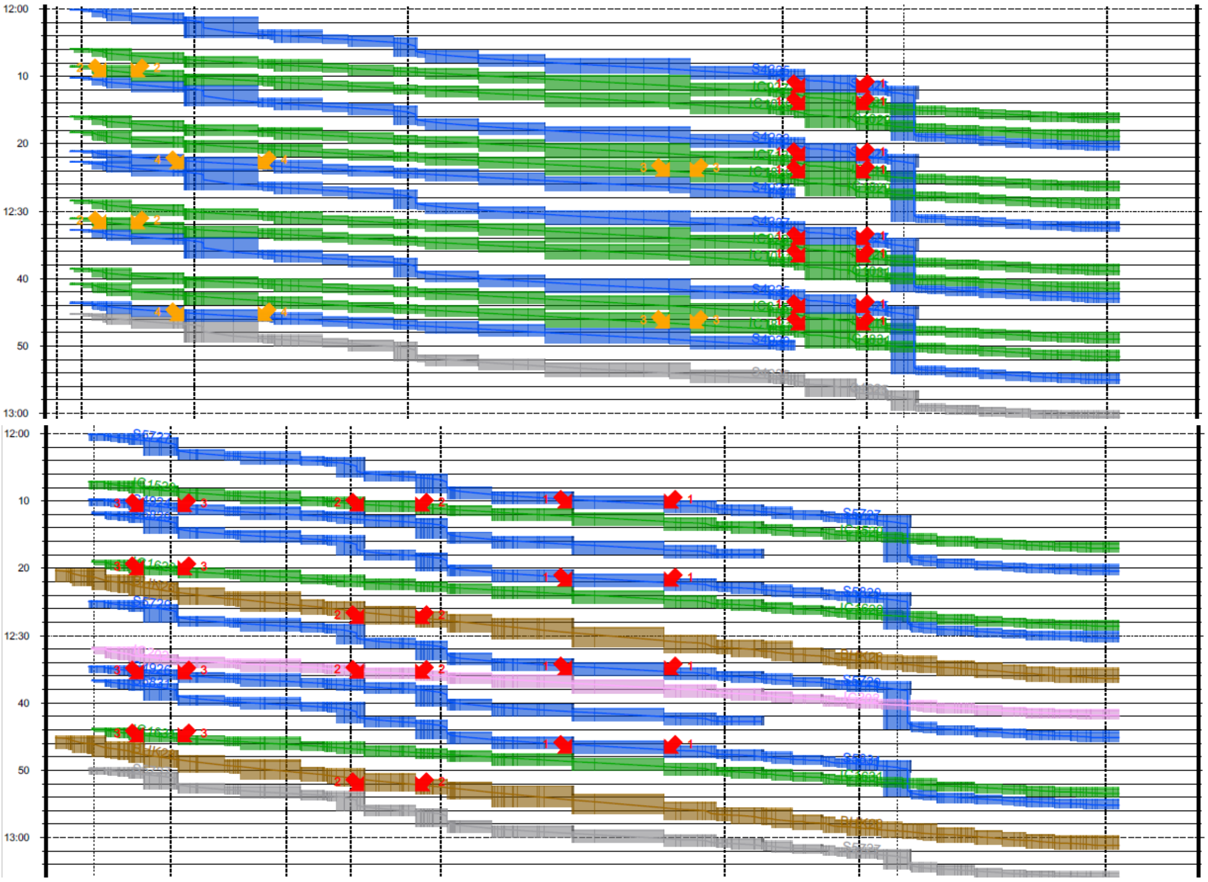


Figure 47 | Compression graphs from the L2 ATO scenario for the Alm-Gpda (top) and Hvs-Gpda section (bottom)

Making the same comparison for the Hybrid Level 3 infrastructure makes the effect of the service pattern clearer. The HL3 model contains blocks with a length of roughly 100m. With the HL3 system the difference in service pattern seems to have a larger effect on the capacity. The presence of the freight trains in the timetable on the Hvs-Gpda section is shown to be a large limitation for the capacity.

Figure 48 contains the compression graphs from the HL3 model for the Alm-Gpda and Hvs-Gpda sections. The arrows in the figure indicate the critical block sections, with the colours representing the frequency they occur as explained in section 8.2.1. The shorter blocks of the HL3 system allow the trains in the more homogenous pattern to follow each other more closely. This is especially visible with the intercity trains on the Alm-Gpda section in Figure 48.

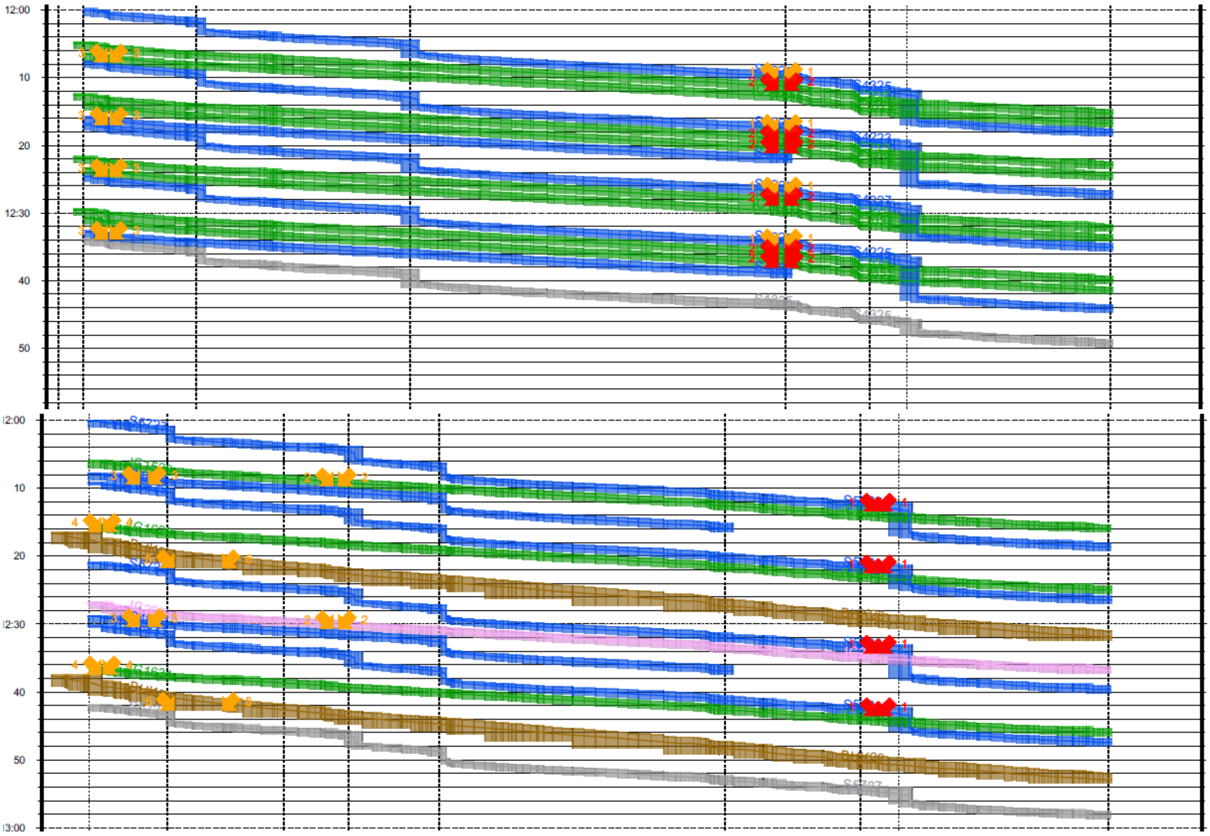


Figure 48 | Compression graphs from the HL3 ATO scenario for the Alm-Gpda (top) and Hvs-Gpda section (bottom)

Looking back to Table 12 in section 8.2.4, the effect of the service pattern on the capacity benefits of the different systems can be seen. The track sections containing a more homogenous service pattern are the sections between Almere and Gpda and the sections between Asra and Hoofddorp (Hfd). The latter contains patterns of only Sprinter trains (inner tracks) or only intercity and international trains (outer tracks), with all trains having to stop at the same station creating a completely homogenous service pattern.

The change in occupation rate throughout the different systems is larger for the sections with a more homogenous service pattern. The occupation rate difference between the Level 2 and Hybrid Level 3 systems becomes larger the more homogenous the service pattern becomes, with the decrease on the section between Alm and Gpda being around 20% and the sections between the Hfd and Asra up to 26%. For the sections with the more heterogenous service pattern this decrease is around 15%.

Changes in the driver behaviour and delayed braking both provide a similar decrease in occupation rate over all the different track sections. This indicates that the service pattern does not massively affect the benefits of delayed braking. When ATO was added in the case study without a buffer time reduction the optimised driving behaviour provided similar occupation reductions with all the different service patterns. In the case of the buffer time reductions the largest effects with ATO can be seen on the sections containing the highest number of trains. A more homogenous service pattern allows for this higher number of trains. In the case of the sections between Asra and Gpda, the part between Asra and Amsterdam Zuid contains a similar service pattern to the Hfd-Asra sections (homogenous with high volume of trains). This indicates that the room created by the buffer time reductions made possible with ATO can best be utilised when a homogenous service pattern is applied.

9.2. Infrastructure configuration

In the previous section the service pattern was shown to boost the effect of shorter block sections on the capacity. Some of the timetable compression results cannot be explained by the service pattern alone. In these locations looking further into the infrastructure configuration can provide a clarification of these results.

Block configuration (Hfd-Asra)

Figure 43 in section 8.2 shows a large variation in the occupation rates for the sections between Hfd and Asra. The Asra-Hfd (IC) and Hfd-Asra (IC) sections show very different results while they contain the exact same service pattern. This suggested that the difference in the results between these two would be due to the Infrastructure. A further look into these two track sections fount the infrastructure surrounding the station of Schiphol to be the cause of this variation in occupation rate.

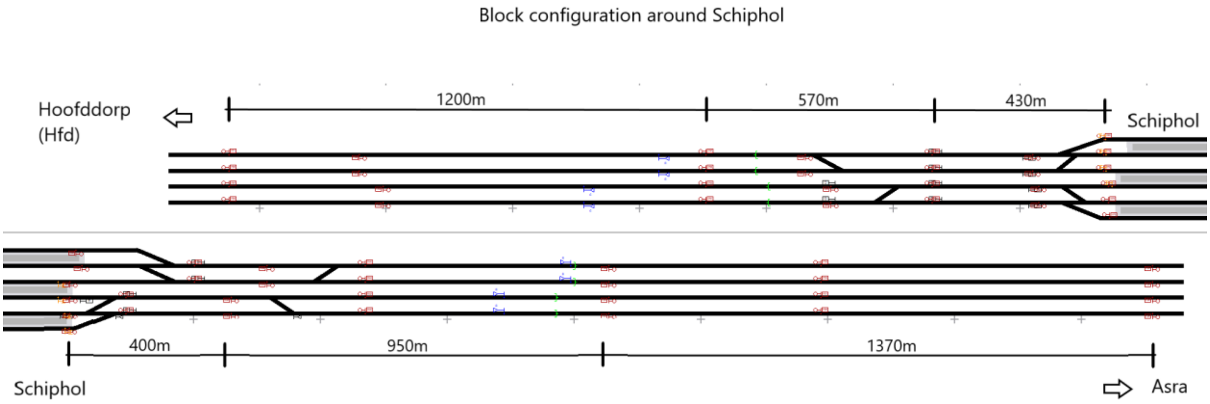


Figure 49 | ATB/NS'54 block configuration around Schiphol

In order to provide trains with an unhindered path, the ATB/NS'54 systems reserve a number of blocks ahead of the trains. The number of blocks reserved ahead depends on the signal relations (i.e. progressive braking steps) throughout these blocks. On both sections the ATB/NS'54 system reserves 3 block section of track ahead each train, just after leaving the station of Schiphol. The lengths of these block sections are what causes the difference in occupation rates between these two very similar track sections. Figure 49 shows the block configuration around Schiphol. On the Asra-Hfd (IC) section the 3 blocks provide a reserved space ahead of the train of roughly 2200 meters shown in the top half of Figure 49. On the Hfd-Asra (IC) section the 3 blocks provide a reserved space ahead of the train of roughly 2730m shown in the bottom half of the figure. With a track speed limit of 130 km/h, this 530m difference results in a block occupation that lasts roughly 14s longer for each train. With the high number of trains passing these sections each hour, this results in the difference in occupation rates on these sections for the ATB/NS'54 system shown in the timetable compression results.

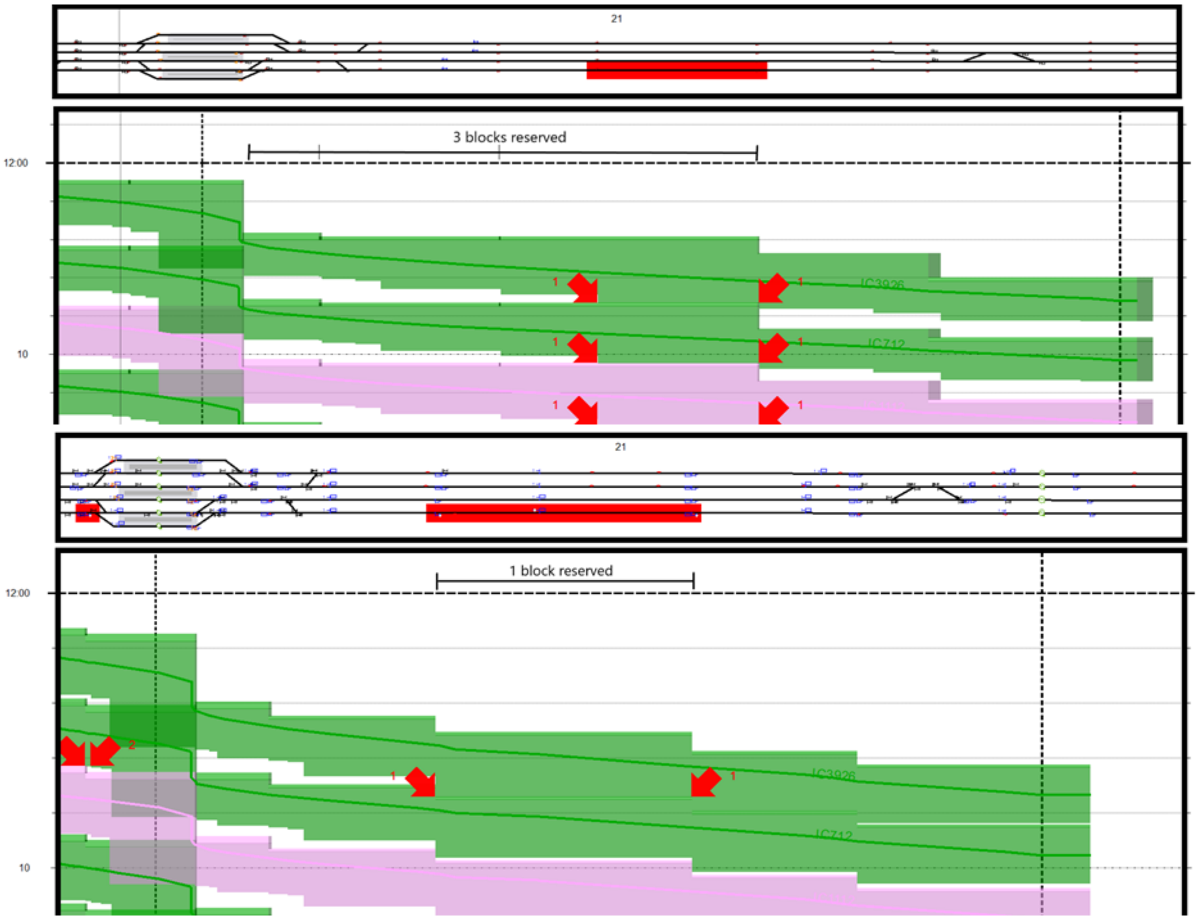


Figure 50 | Zoomed in timetable compression graphs for the Hfd-Asra (IC) section. ATB/NS'54 above, ERTMS/ETCS Level 2 below.

The block configuration of the Hfd-Asra (IC) section is also the reason that the introduction of the ETCS Level 2 system has a considerably larger effect here than in the opposite Asra-Hfd (IC) section. The use of the ETCS braking curves allows for a much shorter reservation ahead of the train of often only a single block section. Figure 50 contains a zoomed in image of the compression graphs for the Hfd-Asra (IC) section that shows the effect the use of the ETCS braking curves has on the reservation of block sections ahead of the train. The figure shows the trains follow each other more closely with the shorter block reservations.

The variation in effectiveness of shorter block sections visible in the timetable compression results for the Asra-Hfd (IC) and Hfd-Asra (IC) sections in Table 11 (section 8.2.3) depends on the original block configuration. Figure 51 shows an image of the compression graphs for these two sections for both the Level 2 and Hybrid Level 3 systems. On the Hfd-Asra section (right side of figure) half of the critical sections for the Level 2 and Hybrid Level 3 systems are the same, resulting in the difference in occupation rate between the two systems to be smaller compared to the Asra-Hfd section. This indicates that the original block configuration for the Hfd-Asra section is more effective for use with the Level 2 system.

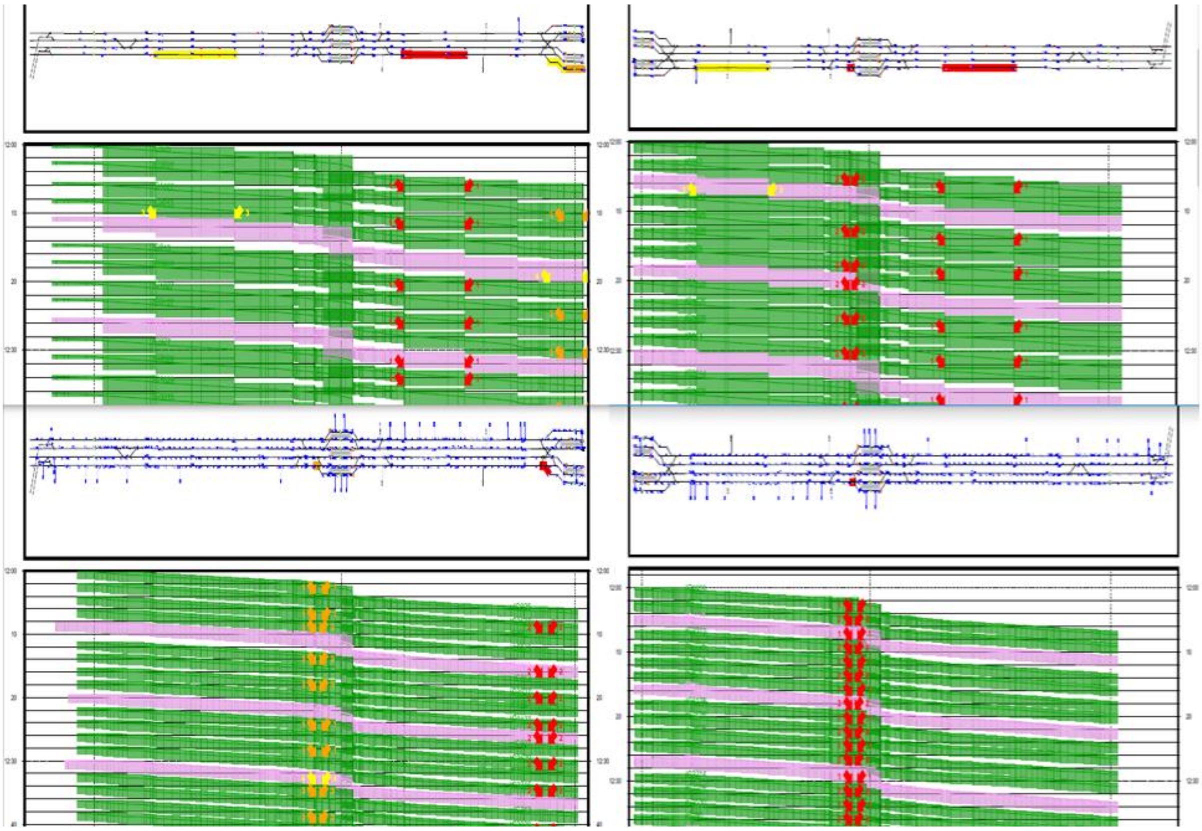


Figure 51 | Compression graphs for the Asra-Hfd (IC) (right) and Hfd-Asra (IC) (left) sections for the L2 (top) and HL3 (bottom) systems

Merging/diverging lines (Asra-Gpda)

The section between Asra and Gpda consistently shows the highest occupation rates in the timetable compression results of chapter 8. Figure 53 contains the compression graph for the Asra-Gpda section with the ATB/NS'54 system showing the season for this high occupation rate to be a combination of the infrastructure layout and configuration and the service pattern.

On this section there are 3 locations where traffic merges onto or exits from the corridor. These locations are at Amsterdam Zuid station (Asdz) and in two places (Dvaw and Dvaz) around Duivendrecht station. These points are highlighted on the map of the Asra-Gpda section shown in Figure 52. Out of the merging and diverging traffic, the freight trains entering the corridor at Dvaz affect the capacity the most.

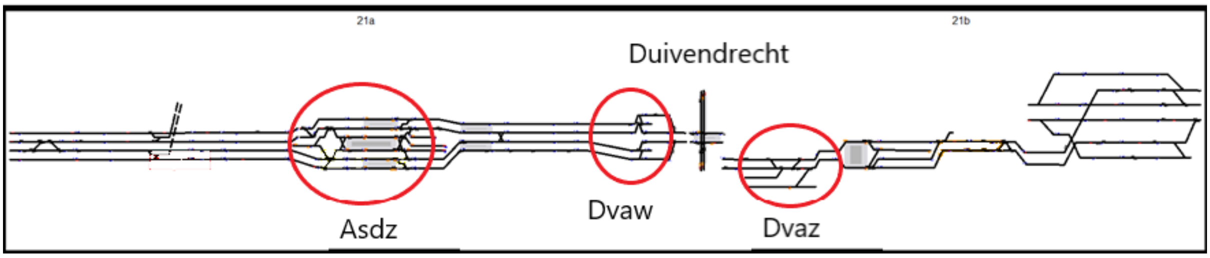


Figure 52 | Map of the infrastructure or the Asra-Gpda section highlighting the merging/diverging points

The compression graph for the Gpda-Asra section under ATB/NS'54 provided in Figure 53 shows that the merging traffic combined with the long block reservations use up a large amount of capacity. The two freight trains shown in brown in the figure both occupy the section for roughly 5 minutes each, using up a large amount of capacity. A number of intercity trains in the direction of Utrecht exit the corridor at Dvaw. These trains are split from the rest of the traffic at Asdz. Due to the high volume of trains, the interlocking area at Asdz becomes a bottleneck. The high frequency this section is labelled critical, is indicated by the red and orange arrows next to Asdz in Figure 53.

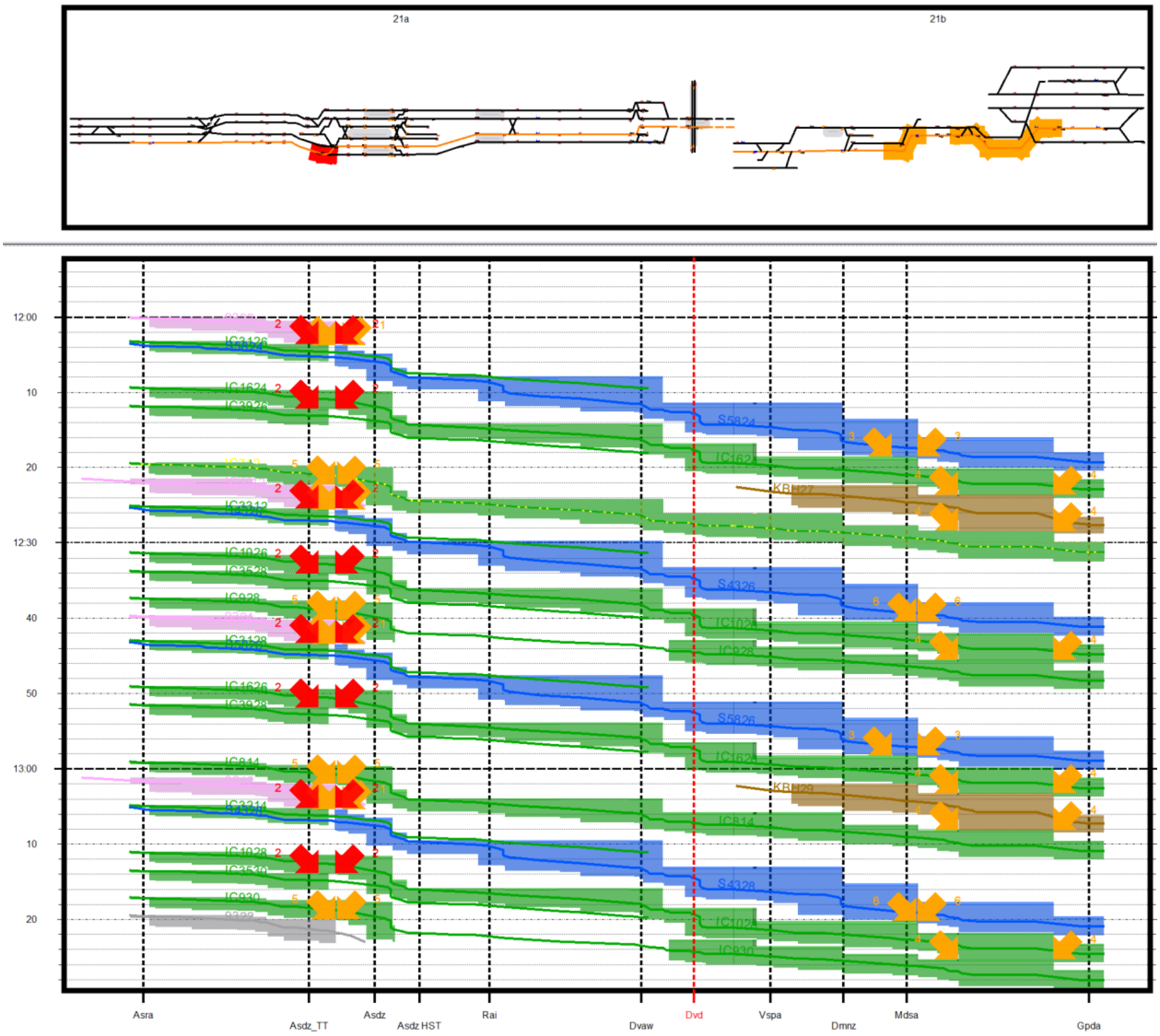


Figure 53 | Compression graph for the Asra-Gpda section from the ATB/NS'54 model

Similar to the Asra-Hfd section, the long reservation ahead of each train limits the capacity of the section under the ATB/NS'54 system. Shortening the block reservation by using the ERTMS/ETCS systems therefore provides a very large reduction in occupation rate. With all the modelled systems, the freight trains remain a large limiting factor on this section. Since the freight trains cannot fully utilise the Hybrid Level 3 system, the effect of the shorter virtual blocks (L2 vs HL3) on the capacity is smaller the effect of the ERTMS/ETCS braking curves (ATB vs L2). This can be observed in the further compression graphs provided in Appendix A. In the opposite direction (Gpda-Asra), the freight trains are less of a limiting factor for capacity, allowing for the shorter virtual blocks of the Hybrid Level 3 system to be fully utilised and causing the larger (than Asra-Gpda) occupation rate reduction visible in the timetable compression results.

When the buffer time reductions of the ATO are applied on this section, the high volume of trains merging and diverging from the corridor can fit more easily in the empty spaces created by the heterogeneity of the service pattern. This combination resulted in the large reduction in the occupation rate seen in the compression results.

9.3. Comparison with earlier studies

As mentioned in the introduction, this thesis is a follow-up study of a master thesis on ERTMS/ETCS Hybrid Level 3 (Jansen, 2019). Similar methods have been used in both studies to determine how the ERTMS/ETCS systems affect the capacity. The thesis of Jansen was partly focussed on reducing the amount of trackside train detection equipment with the use of the Hybrid Level 3 system. The corridor between Utrecht and Den Bosch was used as a case for that study.

This thesis is focussed more towards ATO and what the system can add to the ETRMS/ETCS systems in terms of capacity, with the SAAL corridor as a case for this study. The SAAL corridor contains more variety in service patterns and contains a higher amount of points where it interacts with other lines. A comparison between these two studies could provide further insight in how these factors affect the results.

Utrecht-Den Bosch corridor

The Utrecht-Den Bosch corridor contains a mixed timetable filled with intercity, local Sprinter trains and multiple freight trains in the hourly pattern. The freight trains on this corridor proved to be the largest limitation for the capacity. In the thesis by Jansen, the ATB/NS’54, ERTMS/ETCS Level 2 and Hybrid Level 3 systems have been compared. The difference in occupation between the ATB/NS’54 and ERTMS/ETCS Level 2 was larger than the difference in occupation between the Level 2 and Hybrid Level 3 systems. This indicates that the effect of the use of the ERTMS/ETCS braking curves was larger than the effect of the shorter virtual blocks in this case.

SAAL corridor

On the SAAL corridor a mix of different service patterns are present. The west side of the corridor contains the more homogeneous service patterns, while the east side of the corridor contains a more mixed pattern including freight trains that is similar to the pattern on the Utrecht-Den Bosch corridor. On the SAAL corridor the difference in occupation between the ATB/NS’54 and ERTMS/ETCS Level 2 system is smaller than the difference in occupation between the Level 2 and Hybrid Level 3 systems.

In both studies the Hybrid Level 3 system provided large capacity increases. The biggest difference lies in where the largest part of this capacity increase came from. In sections 9.1 and 9.2 the effects of the service pattern and infrastructure configuration have been explained. The use of shorter block sections was shown to be more effective with a more homogenous time table. Due to part of the SAAL corridor having a more homogenous timetable, the shorter blocks became more effective here than in the Utrecht-Den Bosch case. Differences like these indicate that results for one case will not necessarily be applicable for another. These kinds of systems should always be researched in a case by case basis to get a complete picture how effective they will be in achieving the set goals (in this case increase capacity). In the case of implementation of these systems, the question of how to most effectively fulfil the individual project requirements will always be used to determine whether or not to implement these systems.

10. Conclusion

This chapter contains the conclusion of the report. Section 10.1. covers the conclusions from the report. First each sub question will be answered separately. The main research question will be answered afterwards. Section 10.2. will cover recommendations for further research and developments.

10.1. Conclusion

Human driver behaviour

What kind of braking behaviour do drivers apply under ERTMS/ETCS operations and how can this braking behaviour realistically be modelled?

The braking behaviour observed under the ATB/NS'54 system is a relatively constant braking rate of roughly 0,5 m/s^2. Within ProRail, modelling studies with the ATB/NS'54 system use this constant braking rate for all passenger trains. This behaviour is the result of the energy efficient driving style prescribed by NS. The ERTMS/ETCS does not provide the driver with information to support this type of braking behaviour, instead a behaviour based on the systems braking curves is stimulated. Experienced drivers with the ERTMS/ETCS system described a braking behaviour they followed where they stay a set speed (around 5km/h) below the permitted braking curve.

Generally modelling software containing the ERTMS/ETCS systems use the permitted braking curve or something similar for the braking behaviour of the modelled trains under the ERTMS/ETCS systems. The RailSys software used within this study does this also. This function becomes an important constraint. When a constant braking rate needs to be modelled in combination with the ERTMS/ETCS systems, the entire system is changed to set the braking curves to a constant braking rate, affecting the quality of the models results. Braking behaviour based on the ERTMS/ETCS braking curves can be modelled easier. The permitted braking curve used in the model can be moved using system parameters without moving the rest of the braking curves, allowing for different braking behaviours to be modelled without affecting the rest of the ERTMS/ETCS systems functions. The behaviour described by the experienced drivers could be modelled by moving the permitted curve 2s closer to the indication curve.

Modelling ATO

How can the effects of ATO on the capacity realistically be modelled?

The main function of the ATO system is the removal of human factors from the train operations. The system can be used for different purposes from optimising energy efficiency to punctuality and capacity. In this study the focus was put on the capacity optimisation. It should be mentioned that the ATO system should never be safety critical and should always be functioning under the supervision of a failsafe ATP (automatic train protection) system with full brake supervision.

For this study ATO is combined with ERTMS/ETCS Level 2 and Hybrid Level 3. Operating under these system, the ATO can ignore all non-safety critical braking curves (i.e. I, P and W curves) (European Railway Agency, 2018). This means that the ATO systems could brake later than the human driver would be able to. A system reaction time of the ATO is estimated to be a maximum of 2s. The ATO system needs to keep the train from passing the EBI curve, preventing the ERTMS/ETCS system from applying the emergency brake. To achieve the maximum benefit through delayed braking, the ATO system would therefore need to stay 2s before the EBI curve to account for the systems reaction time. This braking behaviour is put into the model for the ATO system to achieve maximum capacity benefits.

By removing the individual driving styles of human drivers, the ATO is able to provide more homogenous train movements. The buffer time that is used in the timetable planning between consecutive trains to prevent delays due the differences in individual driving styles could be made smaller as a result of this. The assumption is made that the standard 60s buffer could be decreased to 30s with the ATO system. The assumption comes from the 30s buffer that is already successfully being used in one-man operations on the regional lines in the Netherlands without the ATO system.

Capacity benefits ATO

What is the effect in terms of capacity of adding ATO over the use of ERTMS/ETCS L2 and HL3?

The timetable compressions done inside the model provide an insight into the capacity effects of each system. A number of track sections with different layouts and service patterns are selected for the timetable compressions. Two variations of timetable compressions are performed, one containing the buffer times described in Dutch planning norms and a second according to the methods described in the UIC 406 leaflet (without set buffer times). The inclusion of the buffer time in the timetable compressions allows for a more complete assessment of the affect the ATO could have on capacity. A fixed timetable was used throughout the model. The compressions provided occupation rates for the selected track sections. When time buffers are included, occupation rates of above 100% mean that the timetable uses more capacity than there is available and therefore will in practice likely be unstable.

The ATO system affects the capacity in two ways. Optimising the driving style allows for a fuller utilisation of the ERTMS/ETCS systems. Within the case study the ATO provided an average reduction in occupation rate of just over 5 percent point over the human driver behaviour. Depending on the service pattern in the timetable this could be enough room to add extra train paths. The homogenisation of driving behaviour brought by the ATO allows for a reduction in buffer times between trains. The assumed buffer time reduction of 30s has been applied separately in the case study. The reduction in buffer time provided a large occupation rate reduction in the case study with both the Level 2 and Hybrid Level 3 systems. This shows that a large amount of capacity could be gained when shorter headways between trains are introduced. It should be noted however that the shorter headways do affect the robustness of the network and a trade-off between capacity and robustness needs to be made when a buffer time reduction is considered.

Infrastructure configuration and service patterns

How do the infrastructure configuration and service patterns influence the effect of the ERTMS/ETCS and ATO systems on the capacity?

The model contains a number of track sections with different service patterns. The results from the timetable compressions for each track section have been compared to assess the influence that the infrastructure and service pattern have on the ability of the ERTMS/ETCS and ATO systems to increase capacity. It is assumed that a more homogeneous service pattern is generally beneficial for the capacity. Comparing the timetable compression results indicates that this assumption is correct. Comparing the results for the different sections showed that the effect of shorter blocks (difference between L2 and HL3) on capacity is larger when the service pattern is more homogenous. The effect that the different driver behaviours had on the capacity within the case study did not show significant variations, indicating that the service patterns will not affect the capacity benefits of delayed braking.

The benefits of the use of ERTMS/ETCS braking curves instead of the stepwise progressive braking of the current ATB/NS'54 system varied widely between track sections containing the same service pattern within the case study. The ATB/NS'54 system reserves multiple blocks ahead of the train to provide it with an unhindered free path. With the ERTMS/ETCS system this is brought back to most often only a single block section ahead of the train. Depending on the configuration of the infrastructure (size and location of these blocks) this reduction in the size of the block reservations can have a large influence on the capacity. The effectiveness of shorter blocks also depends on the configuration of the original infrastructure. For example, if the critical section (bottle neck) on a stretch of track already contains short blocks, further shortening these will be less effective.

In the case of the ATO system, the benefits of the optimised driving behaviour remained relatively constant over the different track sections within the case study. The reduction of the buffer time between trains in the case study was most effective in places with homogenous service patterns and high volumes of trains. This indicates that the use of a homogenous service pattern will allow the capacity benefits created by the shorter buffer times to be optimally utilised.

Main research question
What is the contribution of ERTMS/ETCS Hybrid Level 3 combined with Automatic Train Operation over the current systems to the Dutch railway network in terms of capacity?

Using the current ATB/NS'54 system, the timetables that are expected to be necessary to handle future growths in rail transport are not feasible. The main problem is that trains need a lot of space to run unhindered through the network, making it difficult to achieve high service frequencies without having to expand the infrastructure. The use of systems such as ERTMS/ETCS Hybrid Level 3 and ATO have the potential to provide enough capacity to be able to achieve the desired increase in service frequency.

The case study of the SAAL corridor performed for this thesis provided some insights in what the Hybrid Level 3 and ATO could contribute to the Dutch railway network. When the current ATB/NS'54 systems are used, the 2030 timetable for the SAAL corridor is not considered to be stable by a large margin. The ERTMS/ETCS Hybrid Level 3 system combined with the ATO system provided a significant decrease in occupation rates, resulting in the timetable easily fitting within the capacity norms. The reduction in occupation rate observed in the case study consisted of the following parts:

- Use of ETCS braking curves vs the stepwise progressive braking of the ATB/NS’54 system
- Shorter virtual block sections provided by the Hybrid Level 3 system
- Optimised driving style with further delayed braking provided by the ATO
- Buffer time reduction assumed possible with ATO

Out of these four, the use of shorter blocks and the buffer reduction proved to be most effective.

The variation in case study results between the different locations (infrastructure configuration) and service patterns indicate that these results cannot be directly applied in other cases. The comparison made between the earlier capacity study with Hybrid Level 3 using the same methods on a different corridor, showed that the effectiveness of these systems will vary case by case. The result of such an analysis also depends on what norms and standards are used for assessing the capacity. For example, in the case of the SAAL corridor, according to the standards of the UIC 406 leaflet, the modelled configuration of the Hybrid Level 3 system provided enough capacity for the timetable to be implemented with a sufficient service quality. When the Dutch planning norms were used, the use of the ATO system was necessary in the case study to come to a sufficient capacity for the timetable to be implemented. While the exact case study results cannot directly be applied elsewhere, they do provide in indication on how effective different measures are for increasing capacity and where a necessary capacity increase could be gathered from.

When an increase in capacity is utilised by adding a number of extra train paths, shortening the headways between trains, the robustness of the timetable and the network are important factors to consider. In a performance test in perturbed scenarios the use of the Hybrid Level 3 system showed overall improvements in robustness, with less trains being affected by the disruptions and the overall amount of delay being lower. In the case of the ATO with a buffer time reduction, the system became less robust, with delays taking longer to solve than without the buffer reduction. When operating at maximum capacity the Hybrid Level 3 system combined with ATO (including the buffer reduction) still showed a similar performance in the perturbed scenario to the ATB/NS’54 system, while containing much (roughly 50% in the tested case) higher service frequency. This indicates that depending on the case and configuration, the Hybrid Level 3 and ATO systems have the ability to provide a significant increase in capacity.

In general, the capacity benefits shown by Hybrid Level 3 system combined with ATO could allow it to become a possible alternative for infrastructure expansion projects in locations where a capacity increase is necessary on the Dutch railway network. Therefore, further testing and development to support future implementation of these systems is recommended.

10.2. Recommendations

This thesis proved an insight into the capacity benefits possible with Hybrid Level 3 and ATO. This section will discuss trade-offs that need to be made when implementing these systems and point out some knowledge gaps for further research, ending with recommended improvements in the software used for this thesis.

Capacity vs costs

The Hybrid Level 3 can provide a large capacity increase and allows for reduction in trackside detection equipment, saving costs on the infrastructure compared to a Level 2 system with a similarly small block configuration. The train operators however will have a higher cost due to the necessity of the installation of the TIM units in the trains to be able to fully utilise the Hybrid Level 3 systems.

To be able to benefit from an ATO system, train operators will have a higher cost due to the necessity of the installation of the ATO-OB on their trains. If ATO is only in use on a small part of the network, the benefits for the train operators will be limited. The costs of implementing an ATO system will depend on the complexity of the system, with the cost rising with the complexity. For example, higher grade of automation will cost more to implement.

The TMS is one of the most complex systems necessary for ATO operations, as it needs to provide the ATO system with dynamic updates to the planned operations. In this thesis the capacity benefits of ATO combined with both ERTMS/ETCS Level 2 and Hybrid Level 3 have been studied. In the case of Hybrid Level 3, the planning system and TMS will need to take into account that the Hybrid Level 3 system works differently for integer and non-integer trains. The TMS will need to provide the right plan for the ATO to execute, to be able to fully utilise the Hybrid Level 3 systems functions. The increased complexity that comes with these systems will result in higher costs. Therefore, a trade-off needs to be made between the capacity and the costs of these systems.

Capacity vs robustness

For the ATO system, a similar trade-off needs to be made between capacity and robustness. In the short system performance test performed in this thesis, the buffer time reduction that is suggested to be possible with ATO significantly influences the robustness of the network. Further research in the form of stochastic delay analyses is necessary to find the right balance between capacity and robustness and determine the optimal capacity that can be achieved with an acceptable robustness.

Implementation of Hybrid Level 3 and ATO

The size of the capacity benefits of ATO depends largely on the size of the buffer time reduction that is applied. In the case study performed in this thesis the use of the Hybrid Level 3 system on average provided more capacity without ATO, than the Level 2 system with ATO and a buffer reduction. The Hybrid Level 3 system can be implemented to provide small virtual blocks on the critical sections of the infrastructure to lessen the severity of these bottlenecks.

Where a large capacity increase over ATB/NS’54 or ERTMS/ETCS Level 2 is necessary it is recommended to first look into using Hybrid Level 3 before ATO. In cases where this is less effective or insufficient, for example with a high number of non-integer trains, an ATO system could be used to increase the capacity. It should be noted that in high frequency operations, a dynamic TMS will be necessary to fully utilise the abilities ATO.

Future developments

A number of future improvements to the Dutch railway network are being looked into by ProRail. The switch from the current 1500V to 3kV for the catenary system is one of these possible improvements. This would allow for improvements in rolling stock performance. Further research in how this could influence the capacity benefits of the ERTMS/ETCS systems and ATO would provide a more complete image of what could be possible in terms of capacity.

The current TMS system used by ProRail is not able to fulfil the ATO requirements to continuously update the plans for the ATO to execute. Within ProRail a pilot for a more advanced TMS has started. This TMS needs to be able to take the actual situation of all trains, possible routes and impact of the updated plan into account. Further development of the TMS is required to support future ATO implementation.

Driver behaviour

One of the points touched upon in this thesis is that the effectiveness of the ERTMS/ETCS systems partly depends on the driver behaviour. An assumption of the driver behaviour for ERTMS/ETCS was made for this thesis. Since these systems are still relatively new to the Dutch railway network, not enough is currently known about how drivers will react to the braking regimes provided by the ERTMS/ETCS systems. When it comes to the Hybrid Level 3 system, the reaction of drivers to a constantly changing MA in small jumps ahead, versus the less frequent larger jumps ahead of Level 2 should be studied, as this could affect driver reactions.

Modelling software improvements

During the modelling phase of this thesis a number of functionalities of the software were used as a workaround to perform functions that were not completely present yet in the software. An example of this is the modelling of the different driver behaviours. This was achieved by manipulating a number of the braking curves. A feature could be added to the software where the braking behaviour (of individual trains) could be adapted without having to manipulate the signalling systems. This is an especially interesting option to have with studies where ATO and human drivers are compared. The simplified braking option within the model provides this feature but will not work properly with the ERTMS/ETCS systems as it influences the braking curves used by the system.

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Appendices

A. Timetable compression graphs

General note on the compression graphs

The compression graphs are for a one-hour period of the basic timetable pattern. These compression graphs contain the buffer times as discussed in chapter 8.2. The different train types shown in the compression graphs are the following:

- Sprinter trains shown in blue
- Intercity trains shown in green
- International/Highspeed trains shown in pink
- Freight trains shown in brown

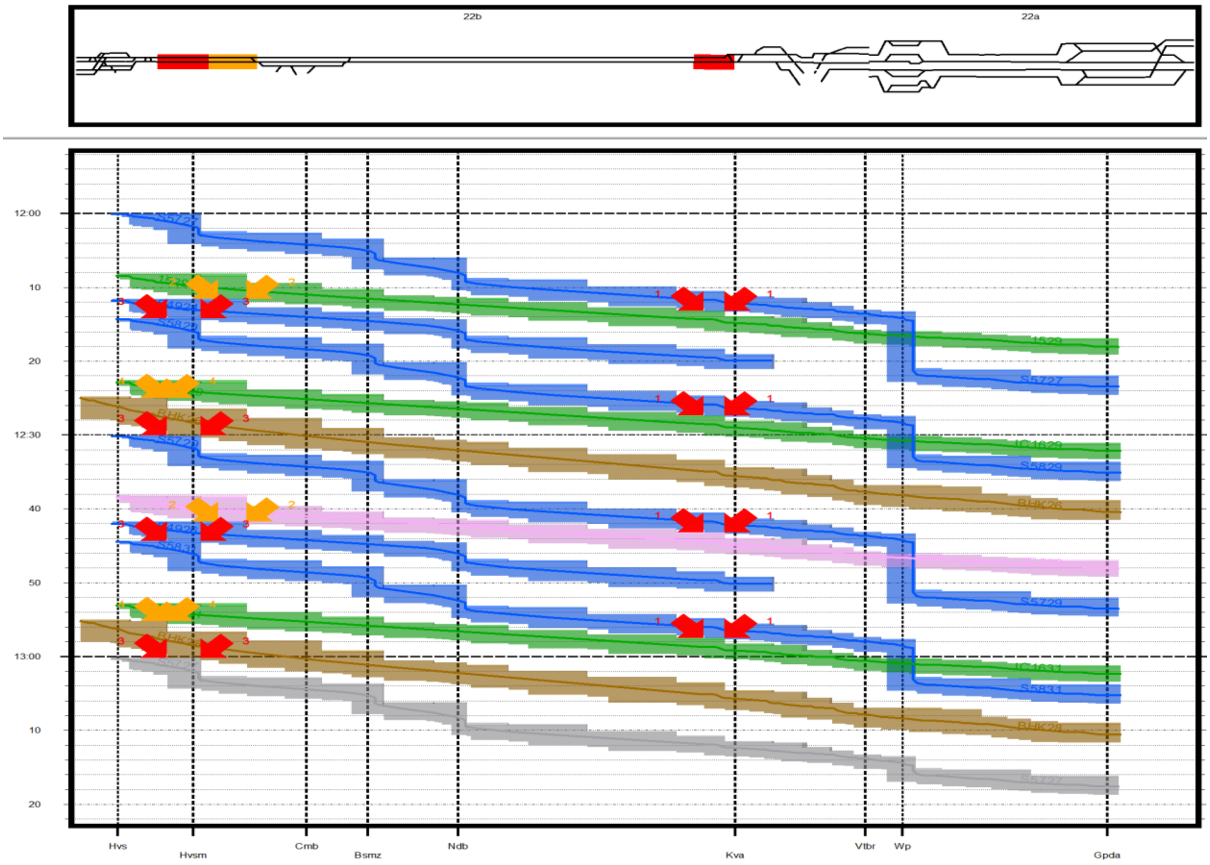
The first train from the next hour (i.e. first train to fall outside the compression) is marked in grey.

The arrows in the compression graphs indicate the critical sections (i.e. the location where train paths are compressed against each other). The colour of these arrows indicates the frequency these sections are marked as critical, going from yellow to red with increasing frequency.

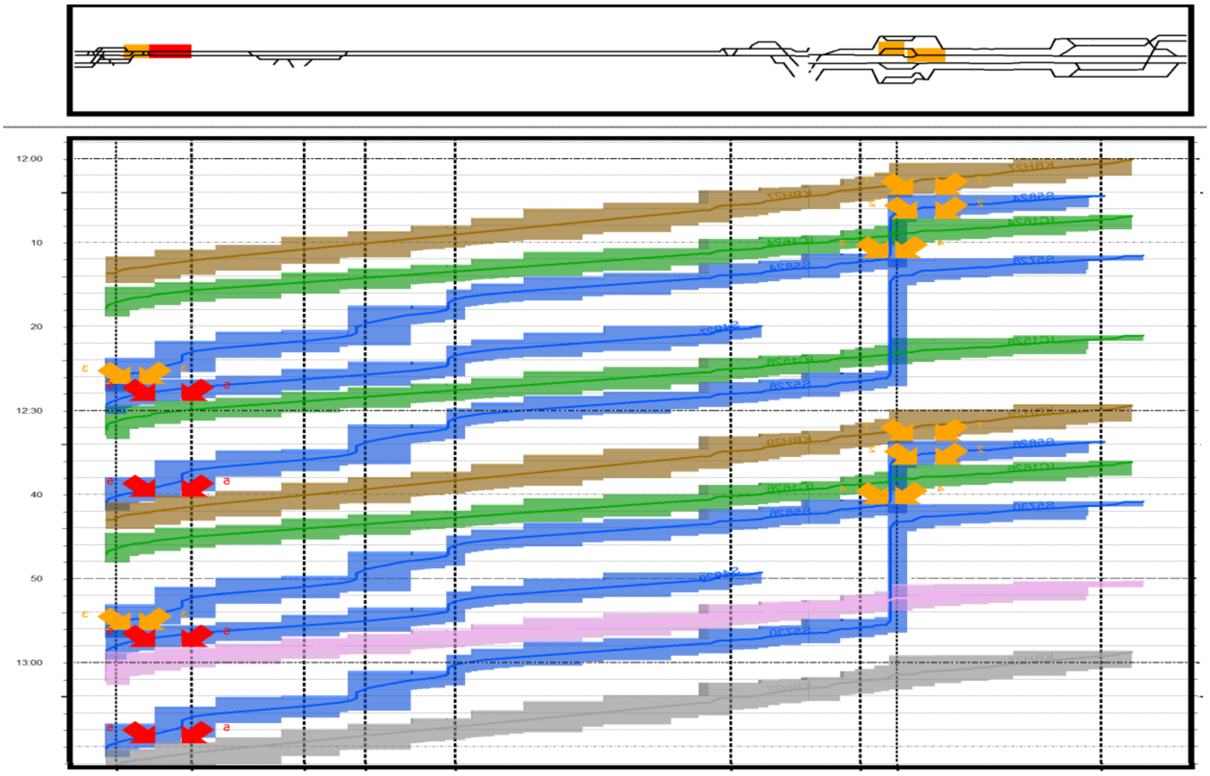
The compression graphs for the ATB/NS’54 and ERTMS/ETCS Level 2 and Hybrid Level 3 systems with and without ATO are provided in the same order as in the results in chapter 8.

A1. ATB/NS’54

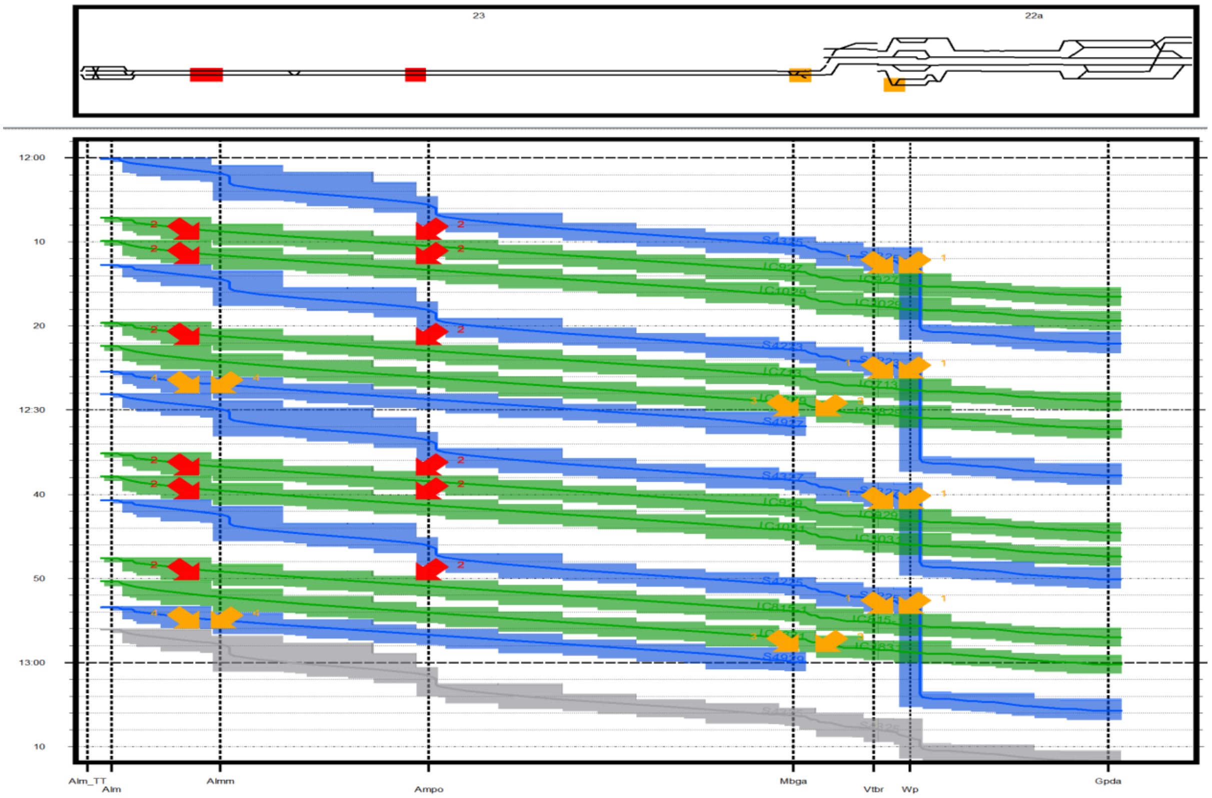
A1.1. ATB/NS’54 Hvs-Gpda



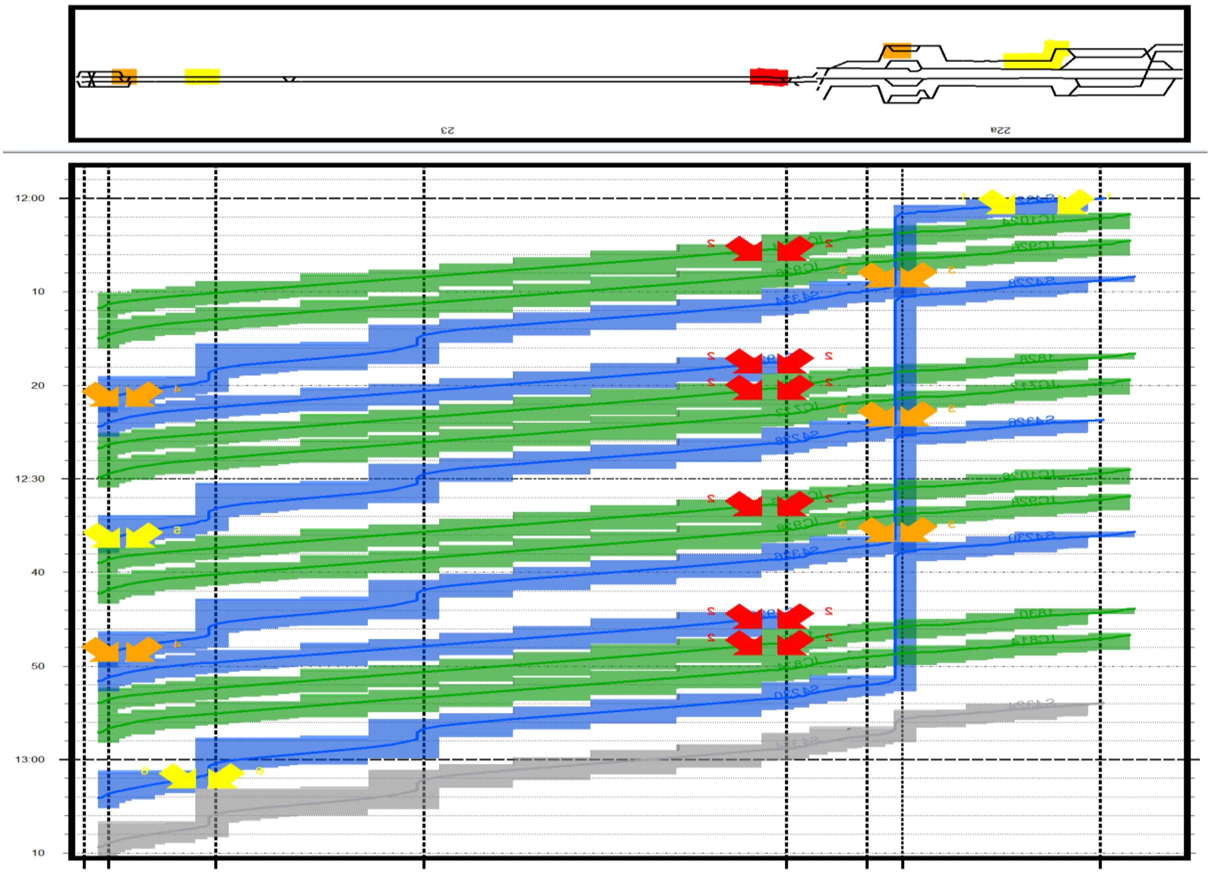
A1.2. ATB/NS’54 Gpda-Hvs



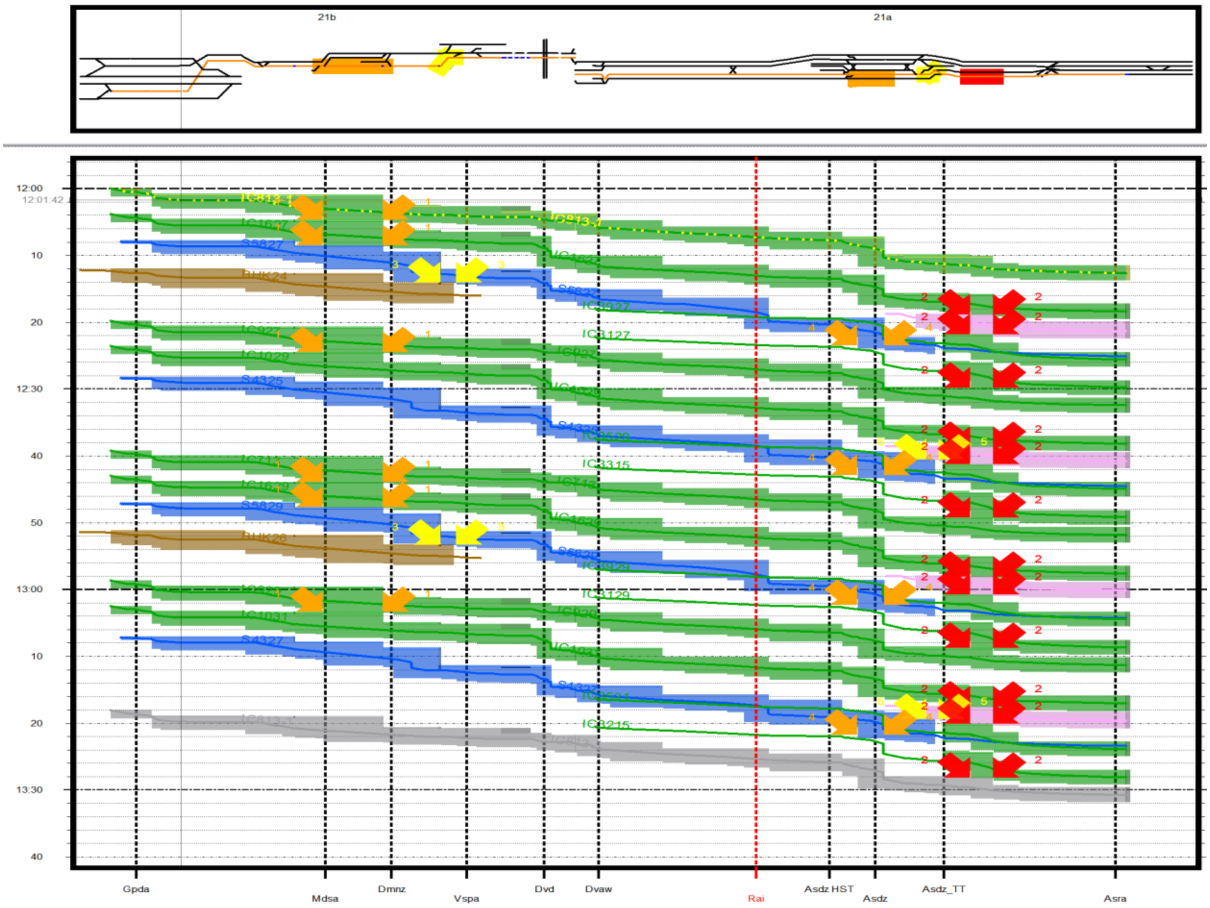
A1.3. ATB/NS’54 Alm-Gpda



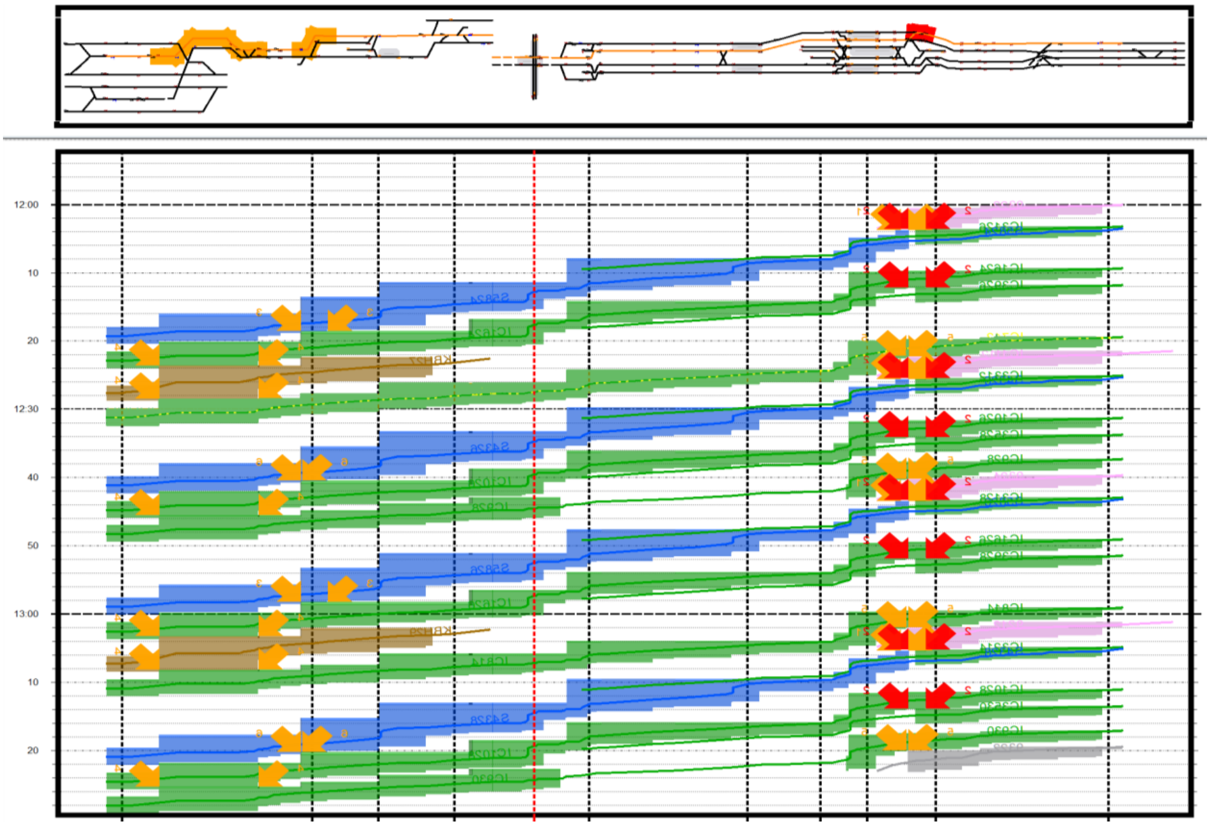
A1.4. ATB/NS’54 Gpda-Alm



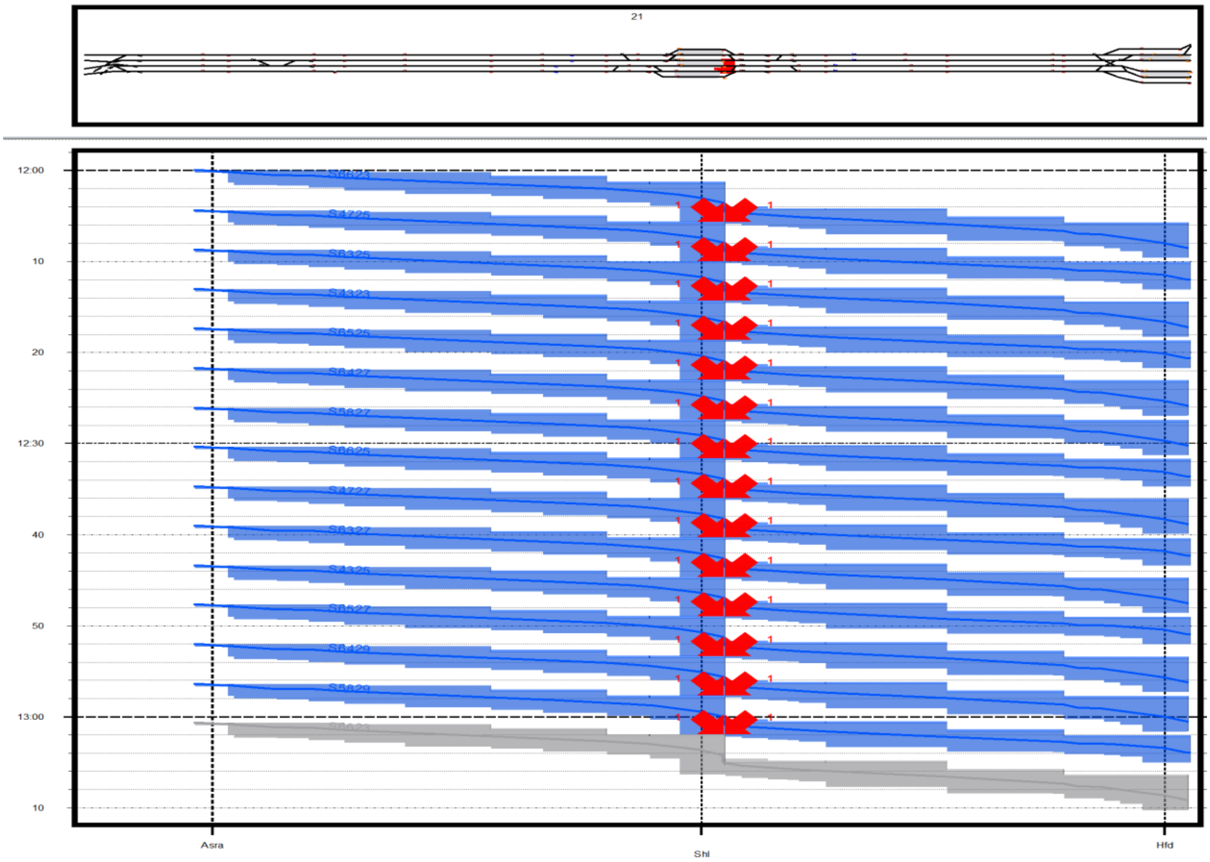
A1.5. ATB/NS’54 Gpda-Asra



A1.6. ATB/NS’54 Asra-Gpda

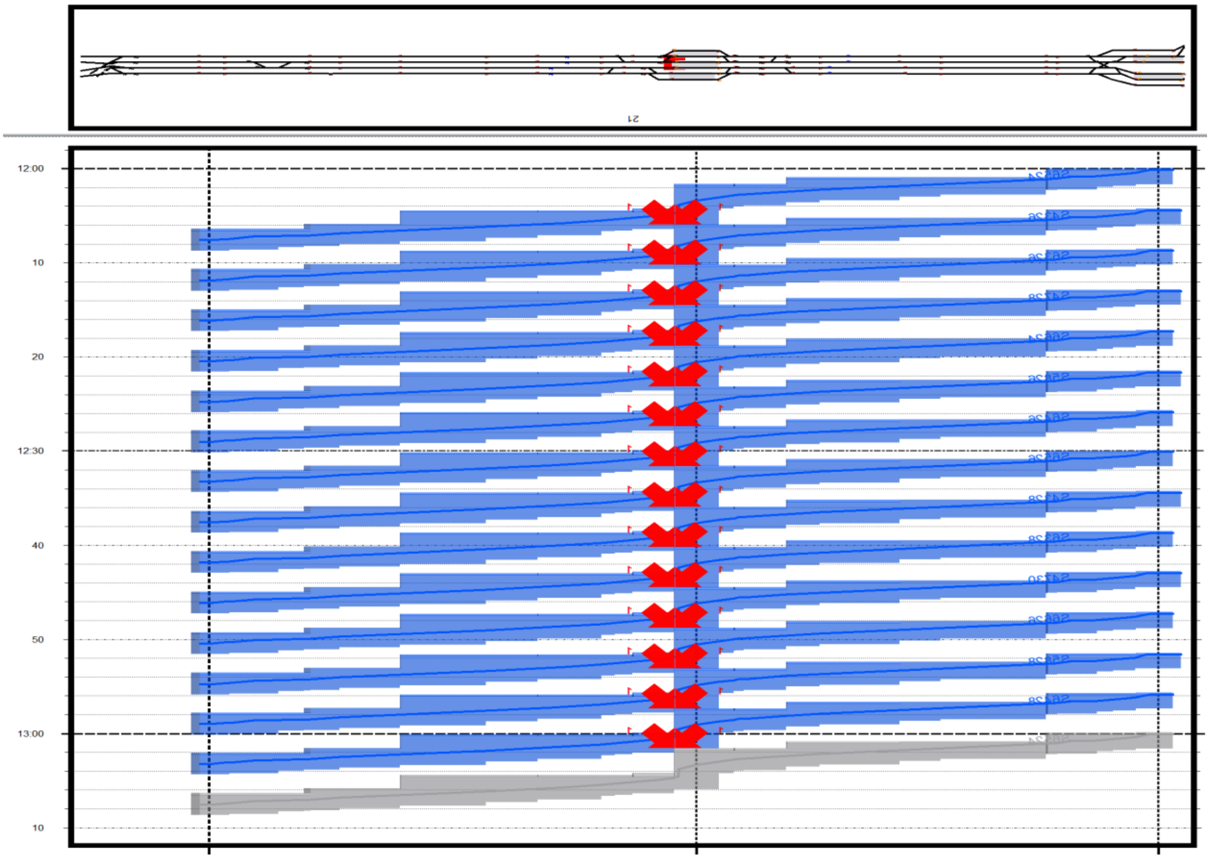


A1.7. ATB/NS’54 Asra-Hfd (S)



A1.8. ATB/NS’54 Asra-Hfd (IC)

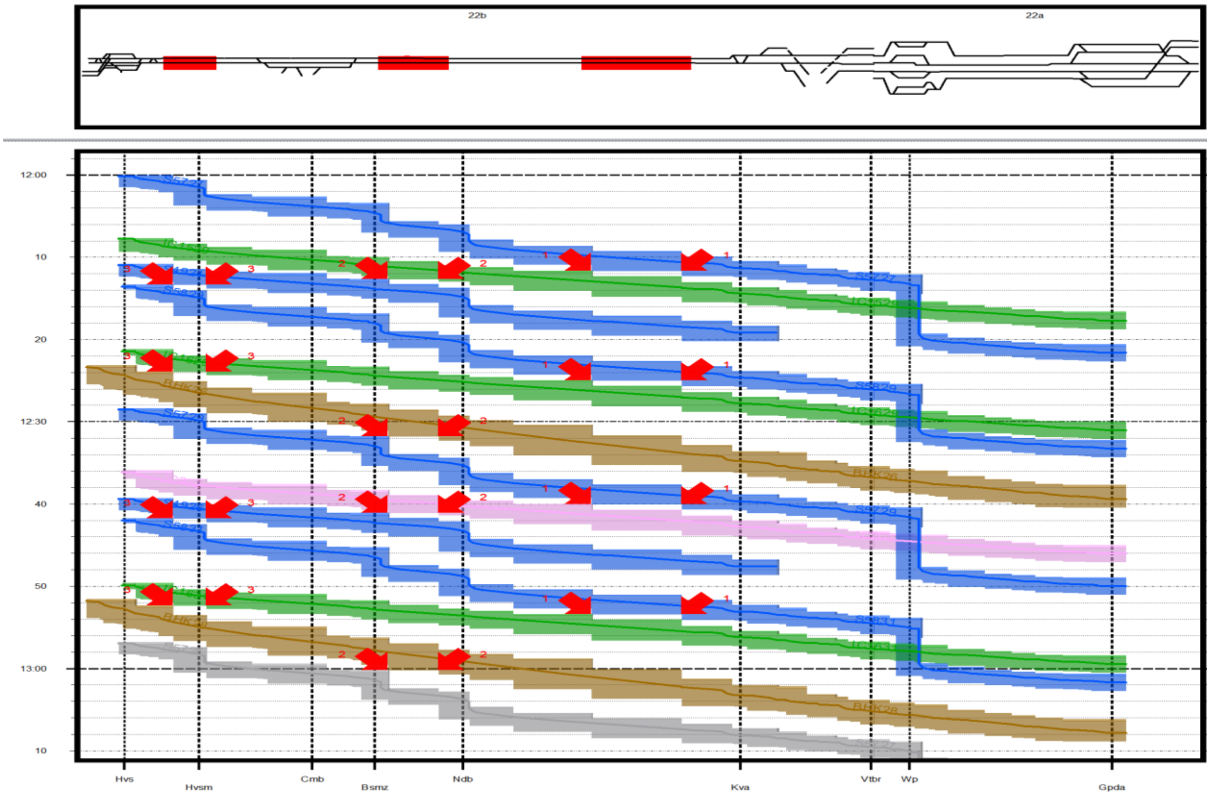
A1.9. ATB/NS’54 Hfd-Asra (S)



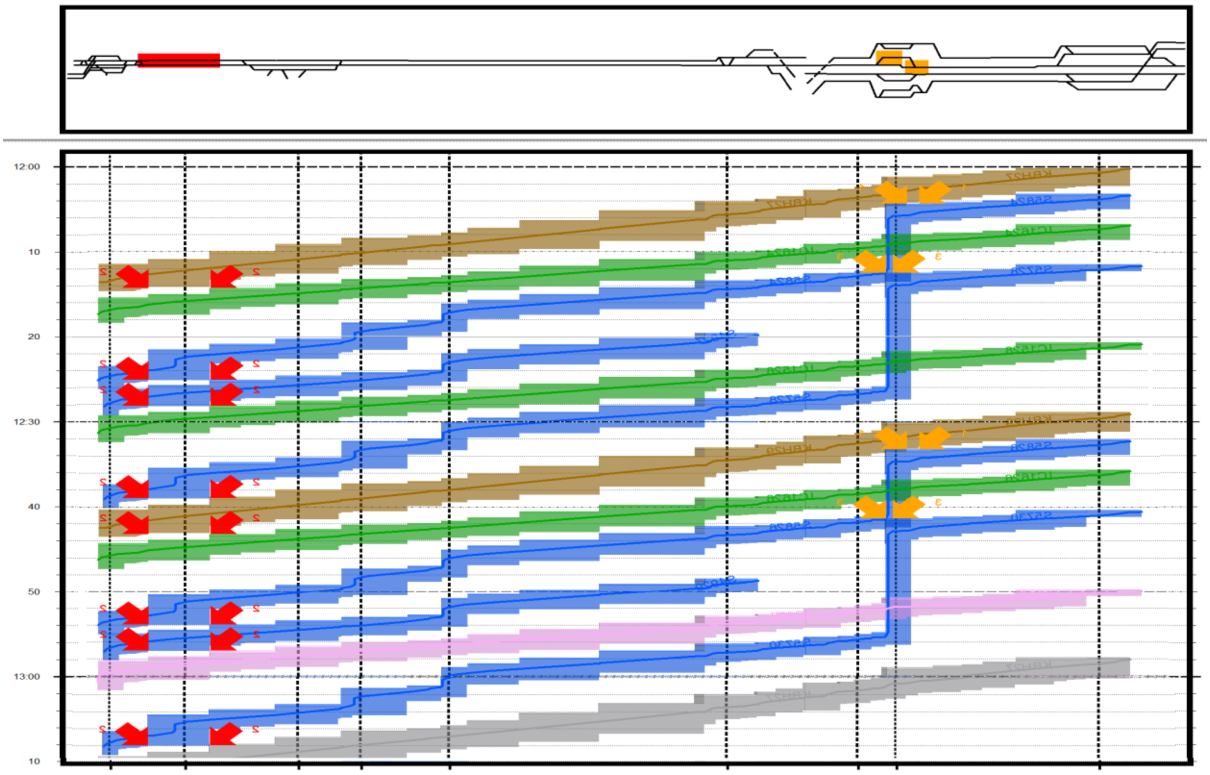
A1.10 ATB/NS’54 Hfd-Asra (IC)

A2. L2 Permitted

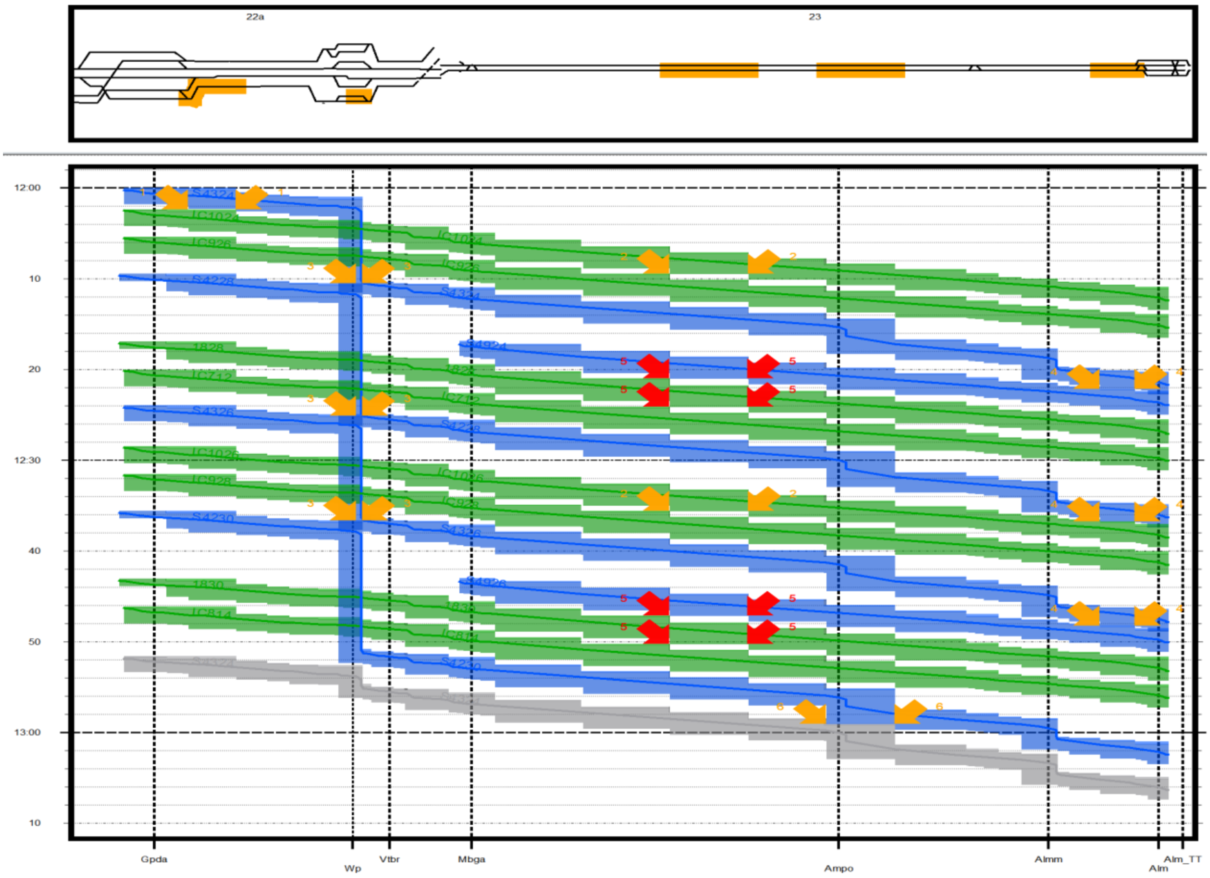
A2.1. L2 Permitted Hvs-Gpda



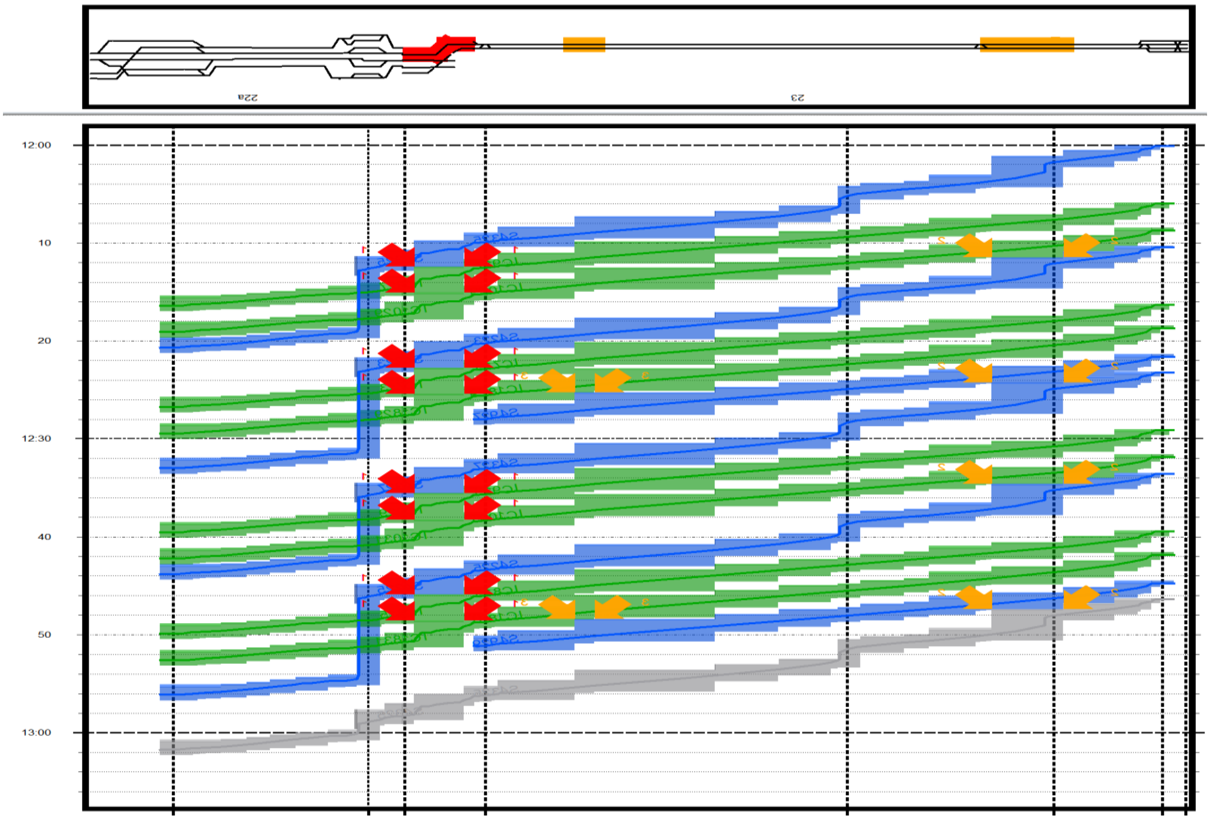
A2.2. L2 Permitted Gpda-Hvs



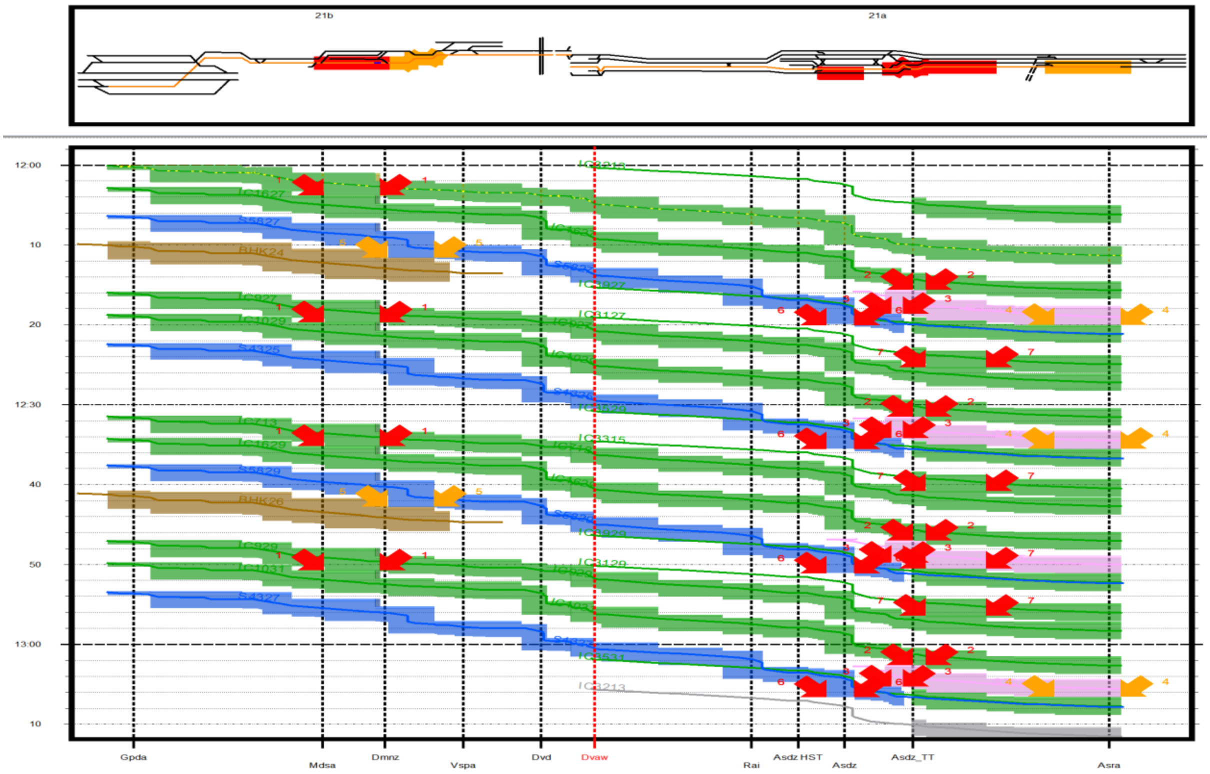
A2.3. L2 Permitted Alm-Gpda



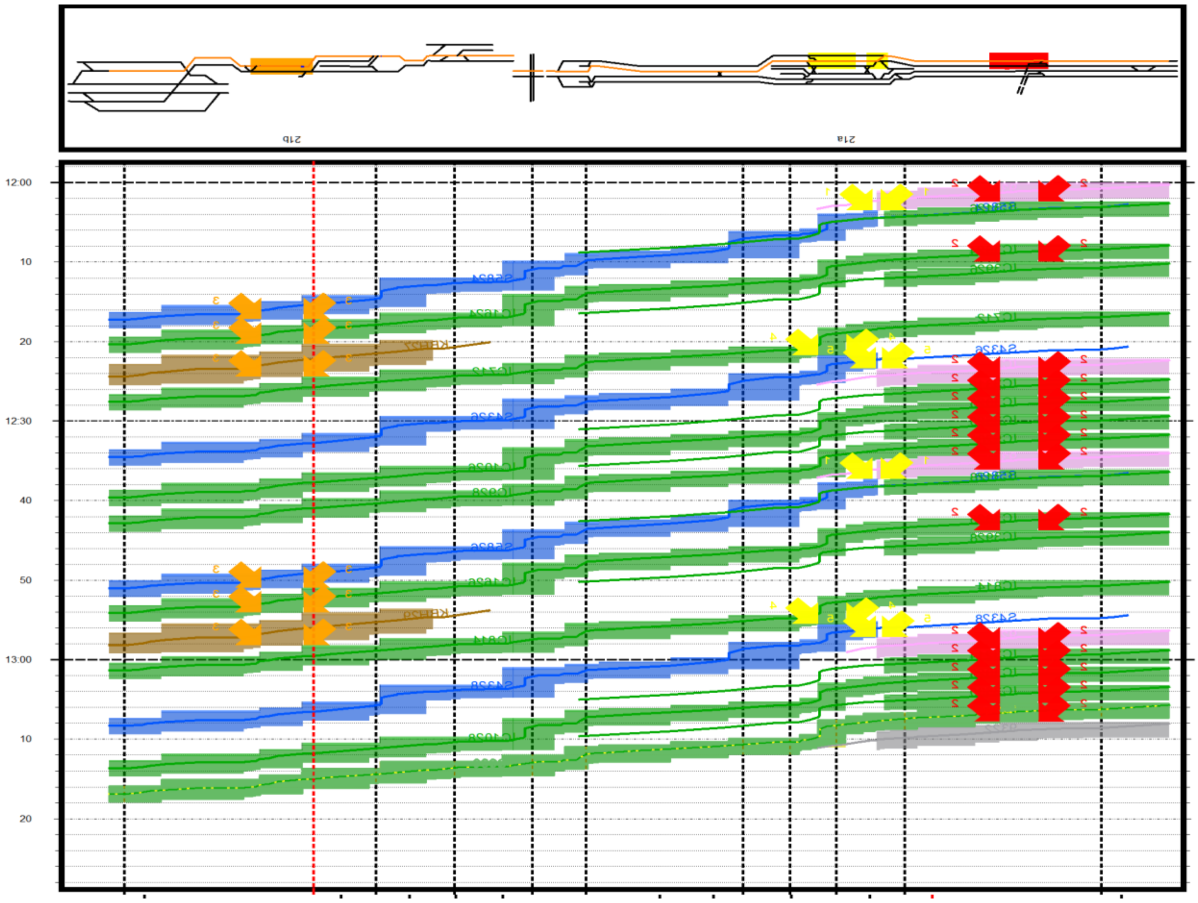
A2.4. L2 Permitted Gpda-Alm



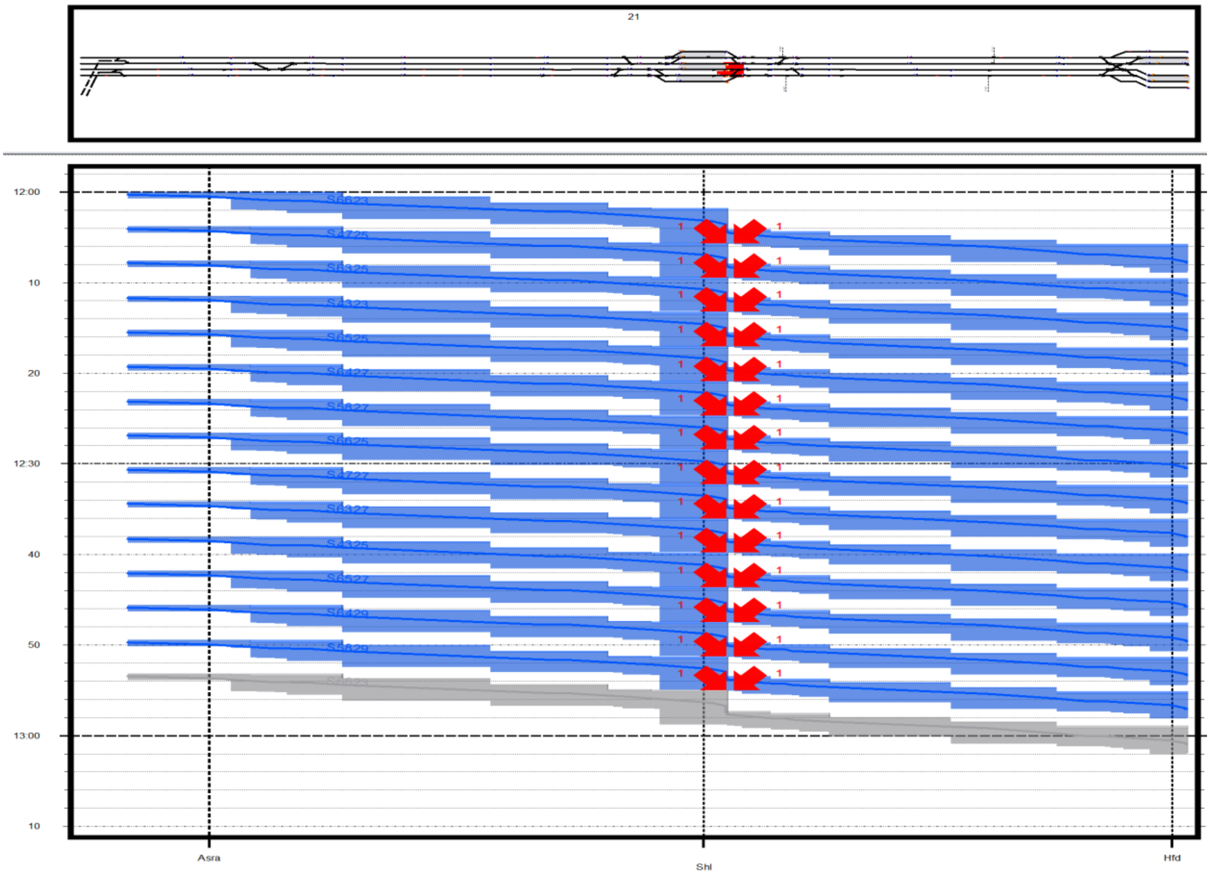
A2.5. L2 Permitted Gpda-Asra



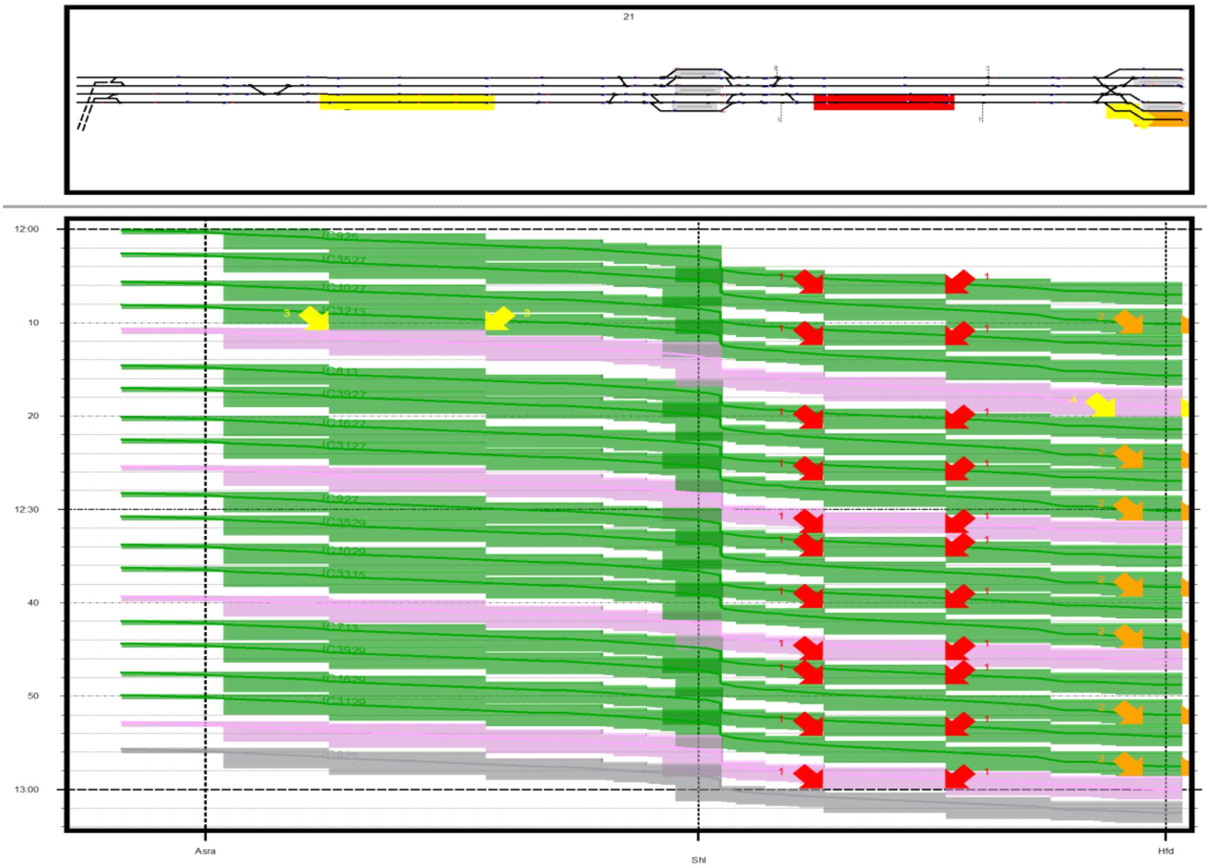
A2.6. L2 Permitted Asra-Gpda



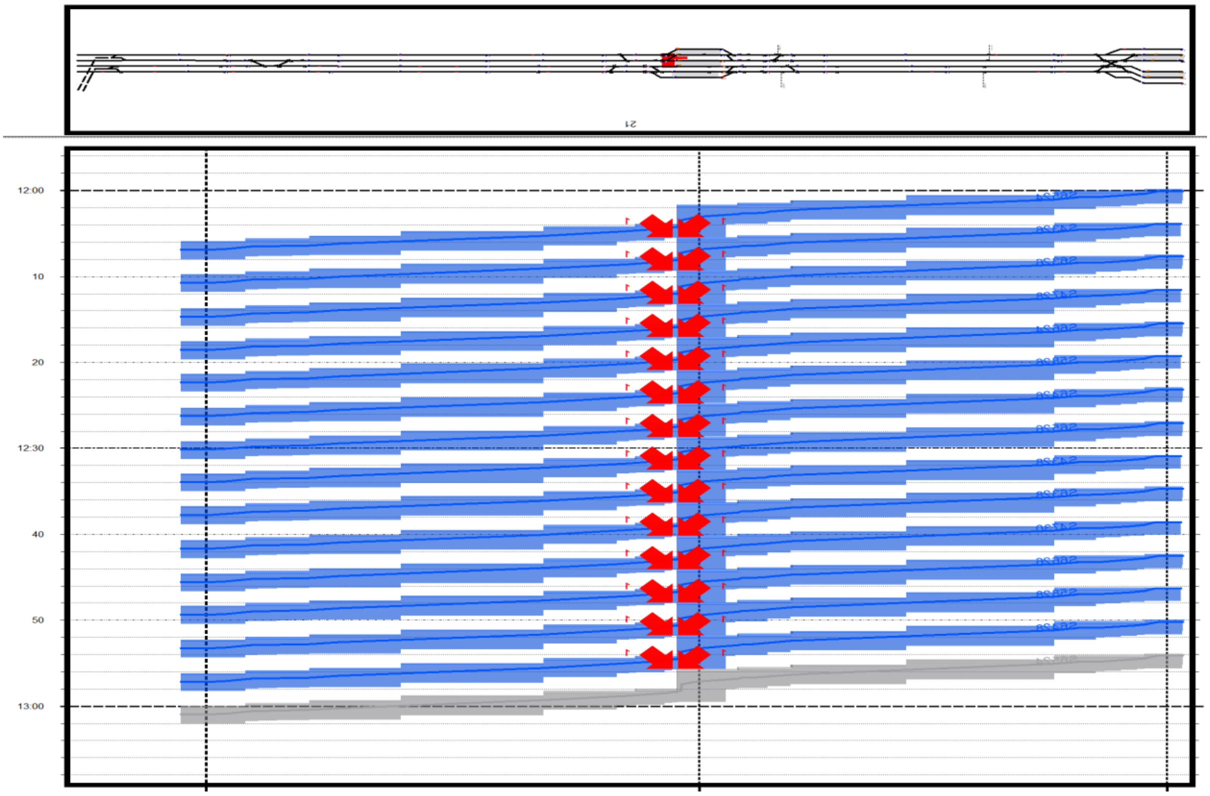
A2.7. L2 Permitted Asra-Hfd (S)



A2.8. L2 Permitted Asra-Hfd (IC)



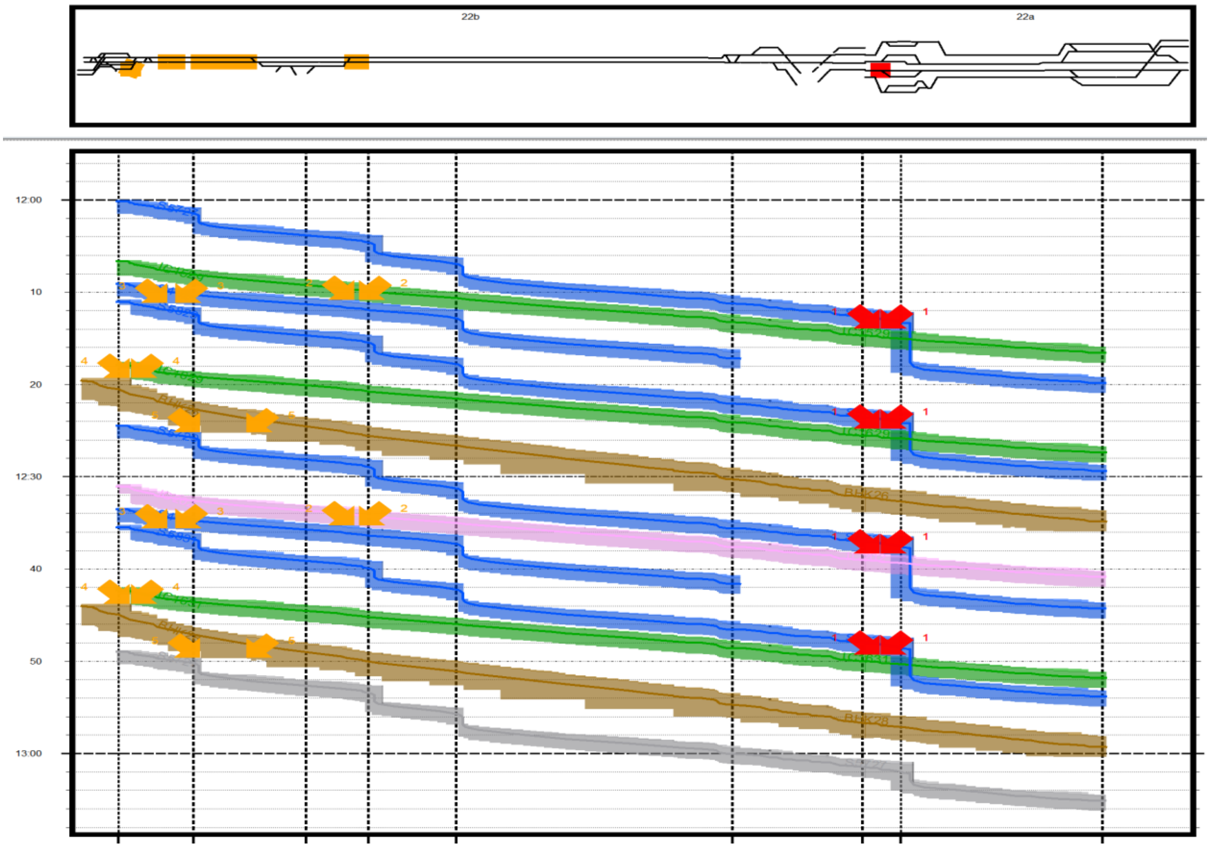
A2.9. L2 Permitted Hfd-Asra (S)



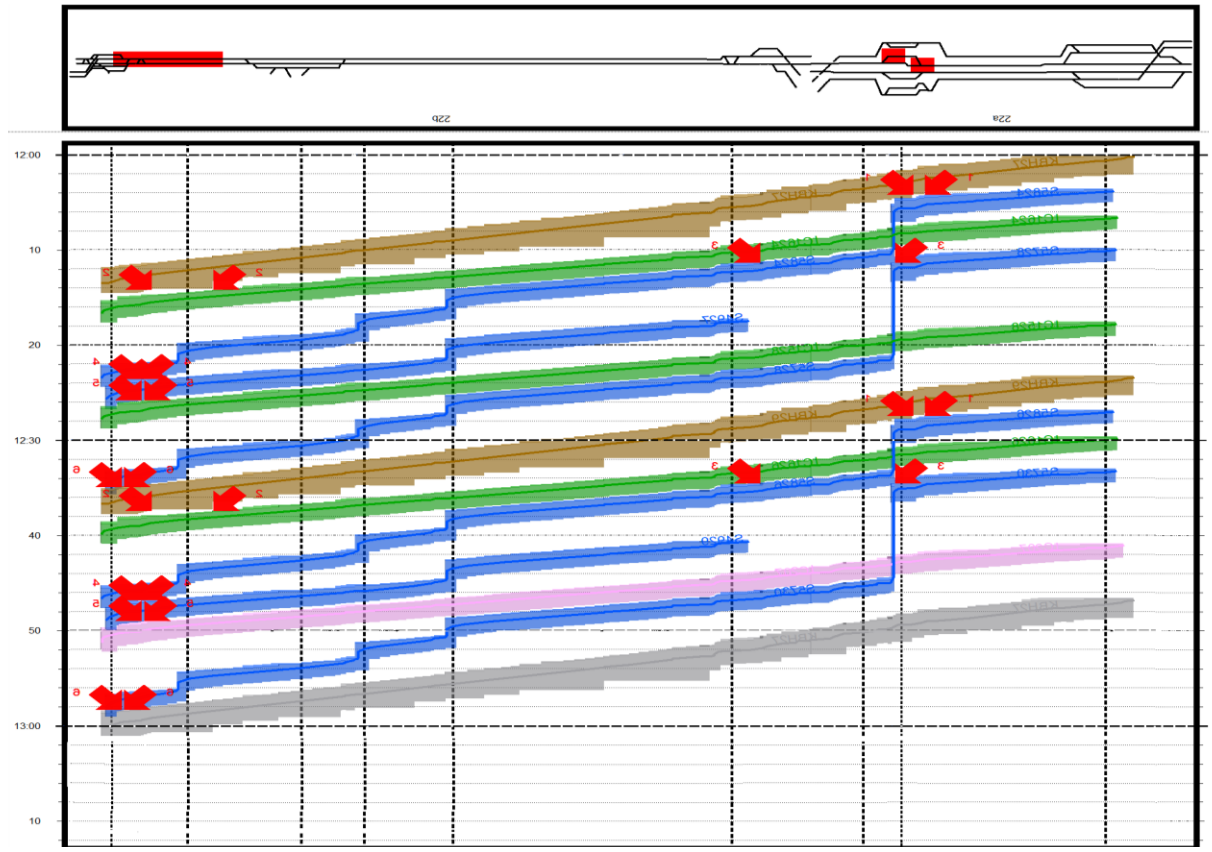
A2.10. L2 Permitted Hfd-Asra (IC)

A3. HL3 Permitted

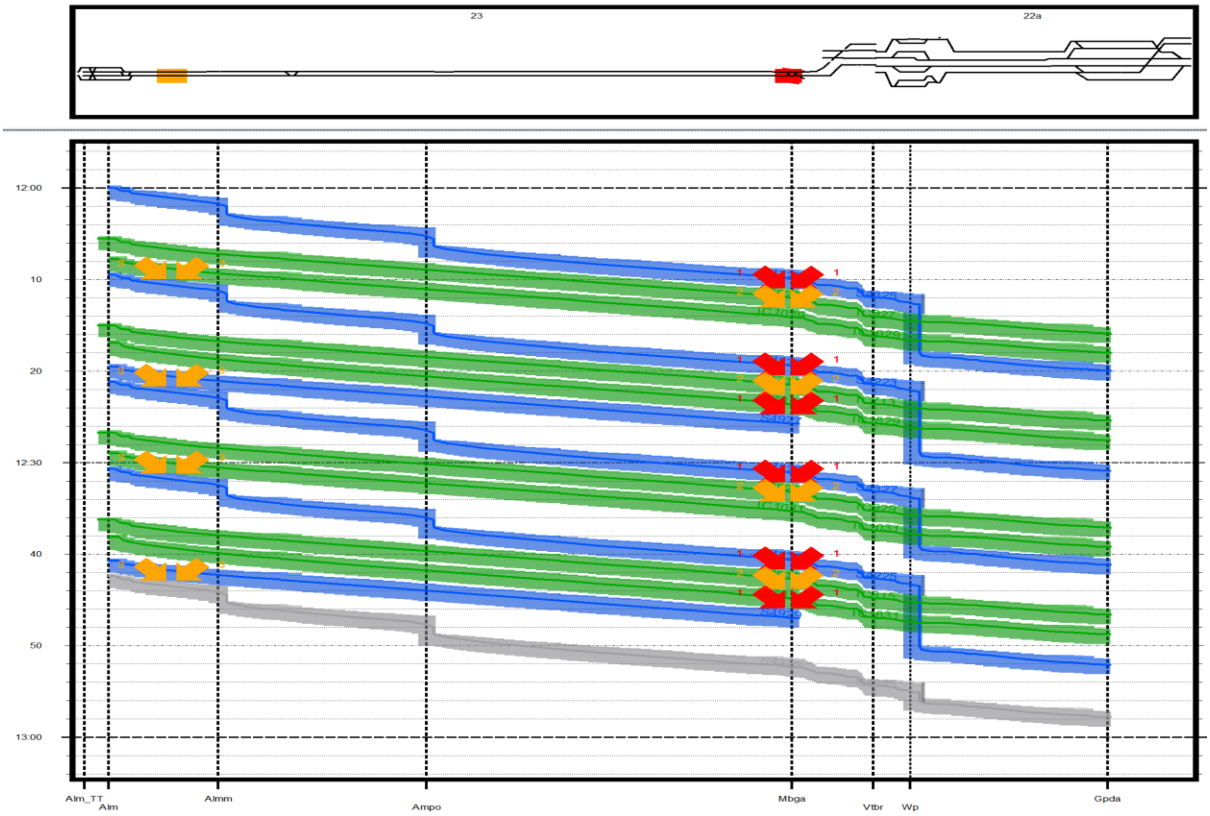
A3.1. HL3 Permitted Hvs-Gpda



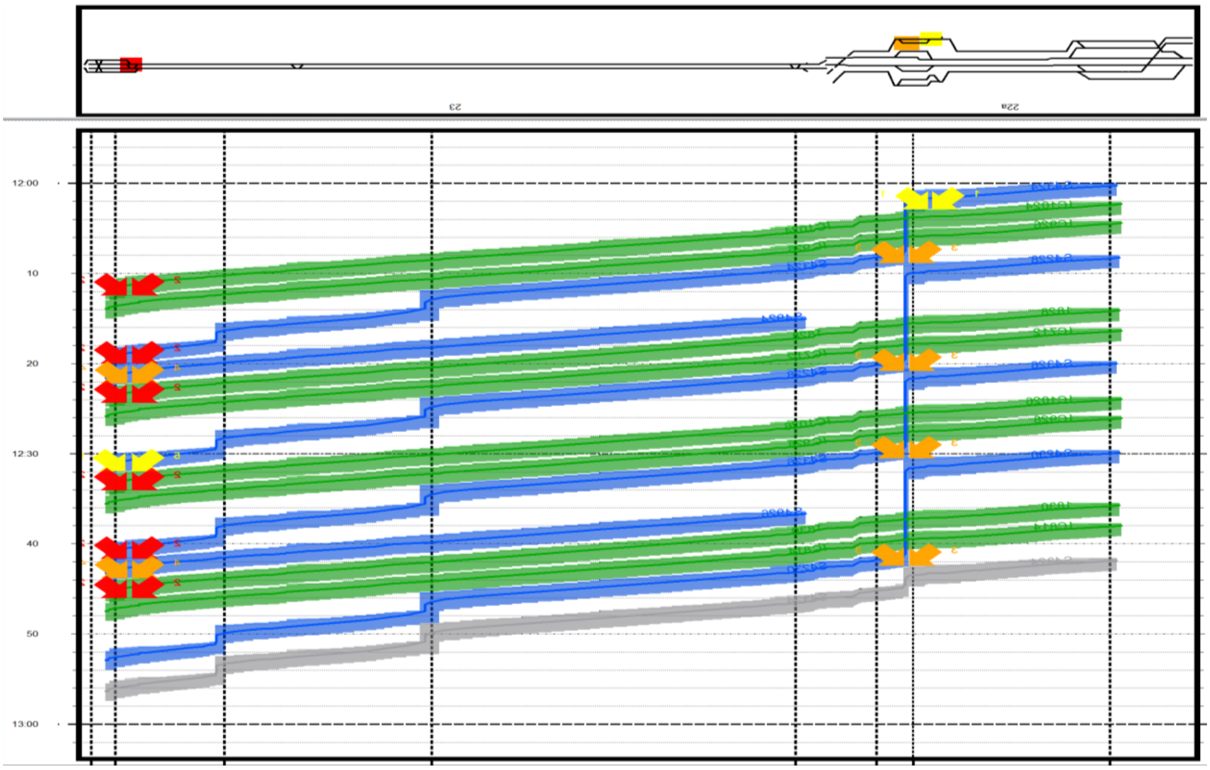
A3.2. HL3 Permitted Gpda-Hvs



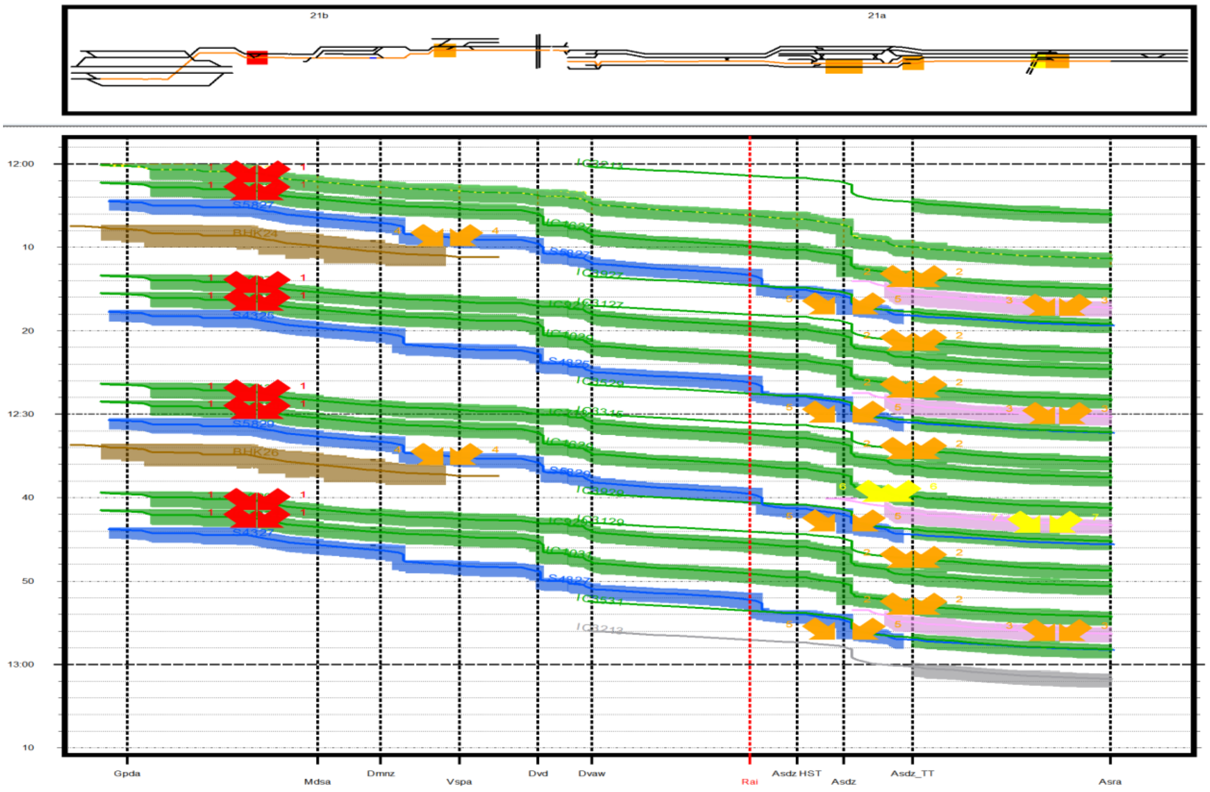
A3.3. HL3 Permitted Alm-Gpda



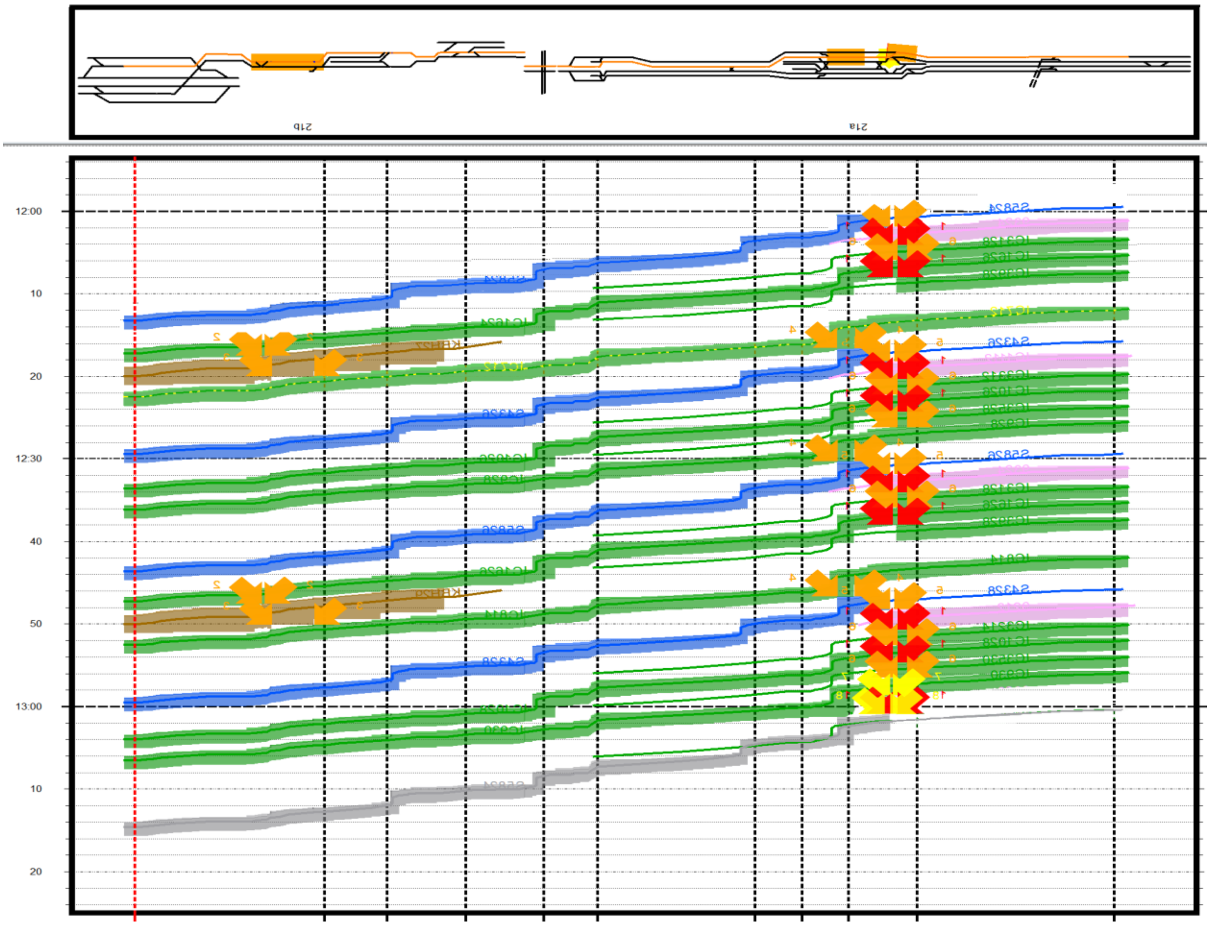
A3.4. HL3 Permitted Gpda-Alm



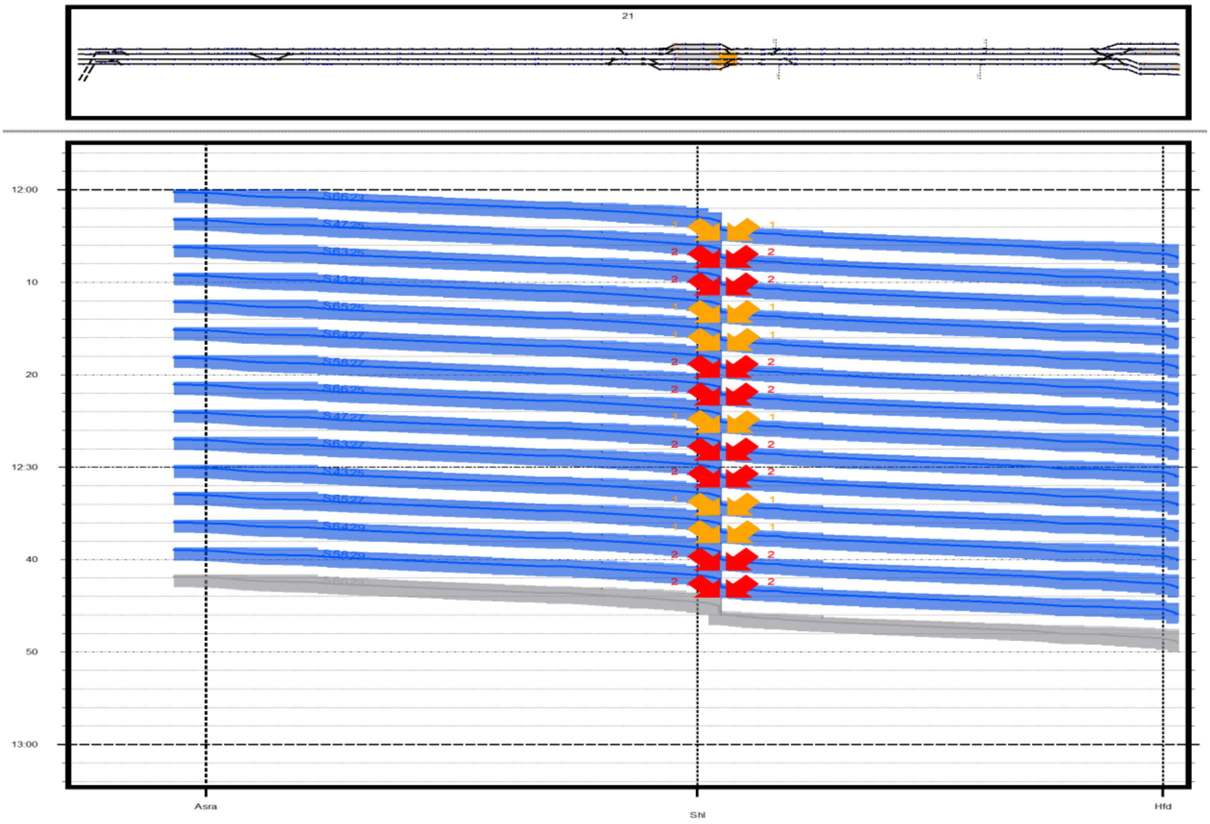
A3.5. HL3 Permitted Gpda-Asra



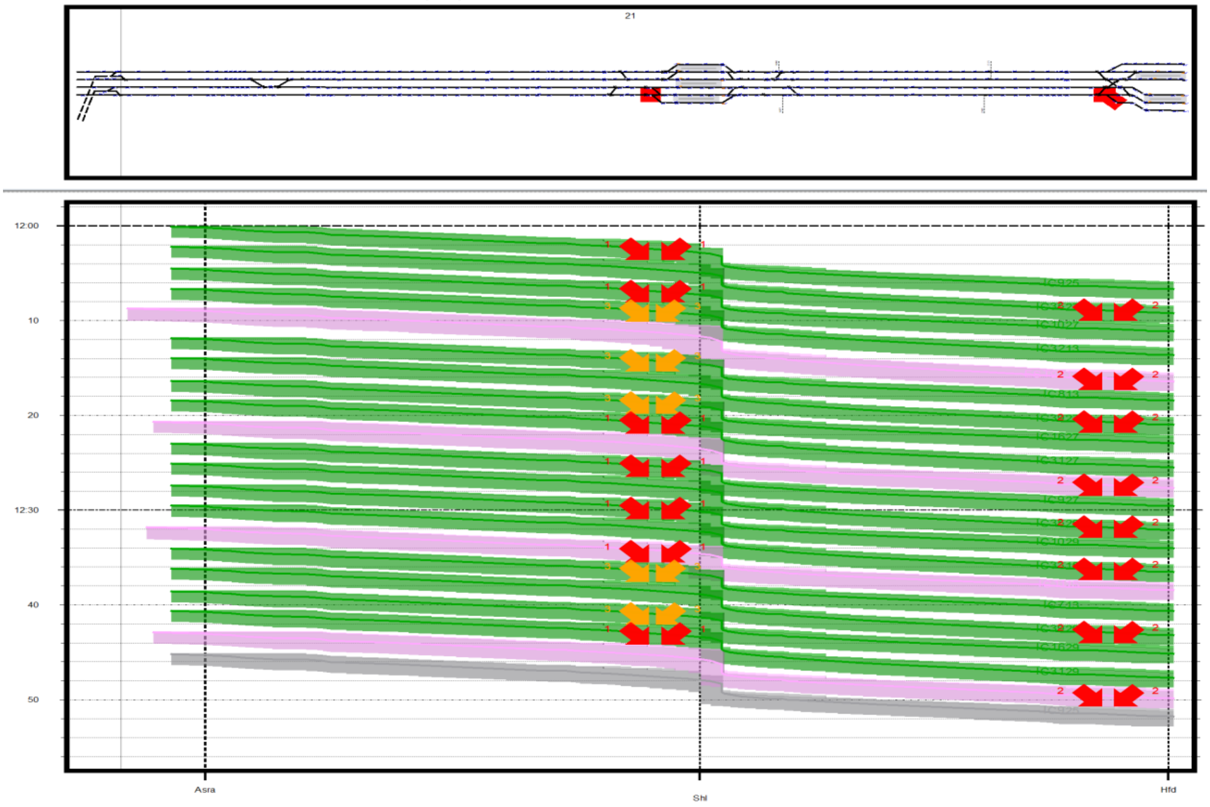
A3.6. HL3 Permitted Asra-Gpda



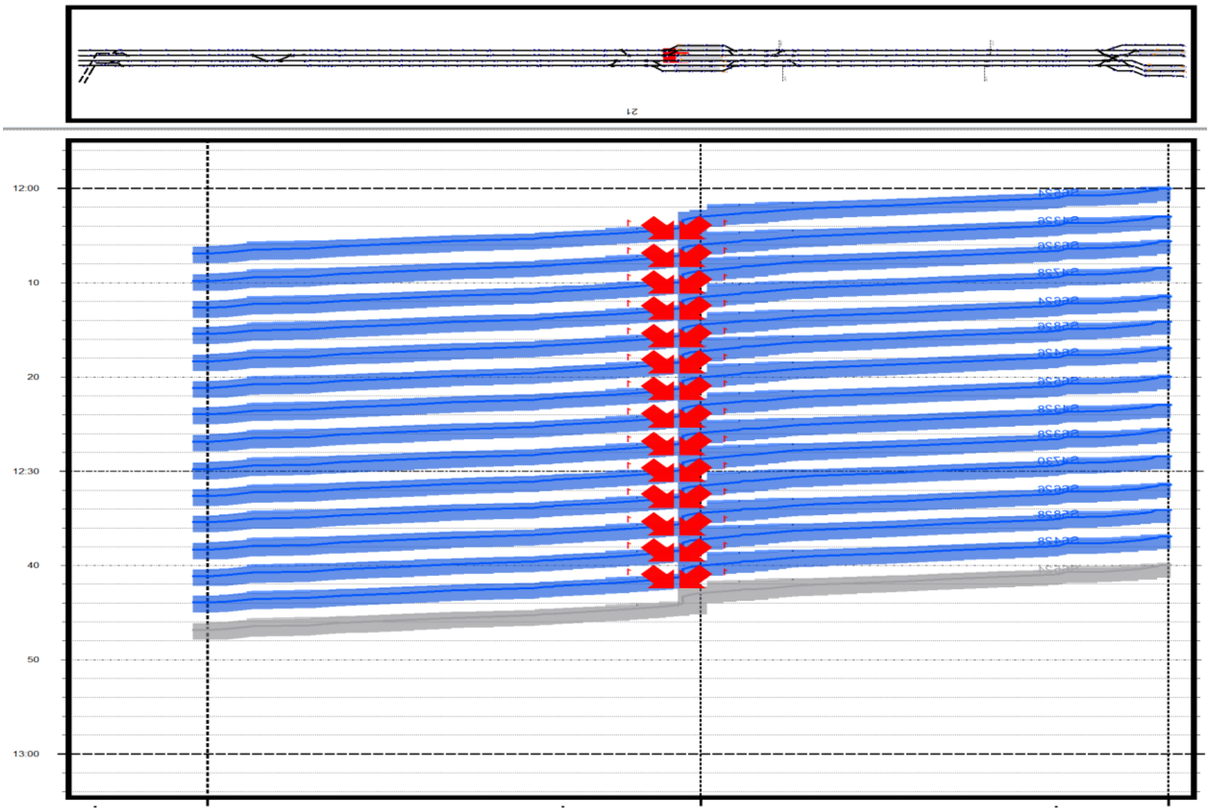
A3.7. HL3 Permitted Asra-Hfd (S)



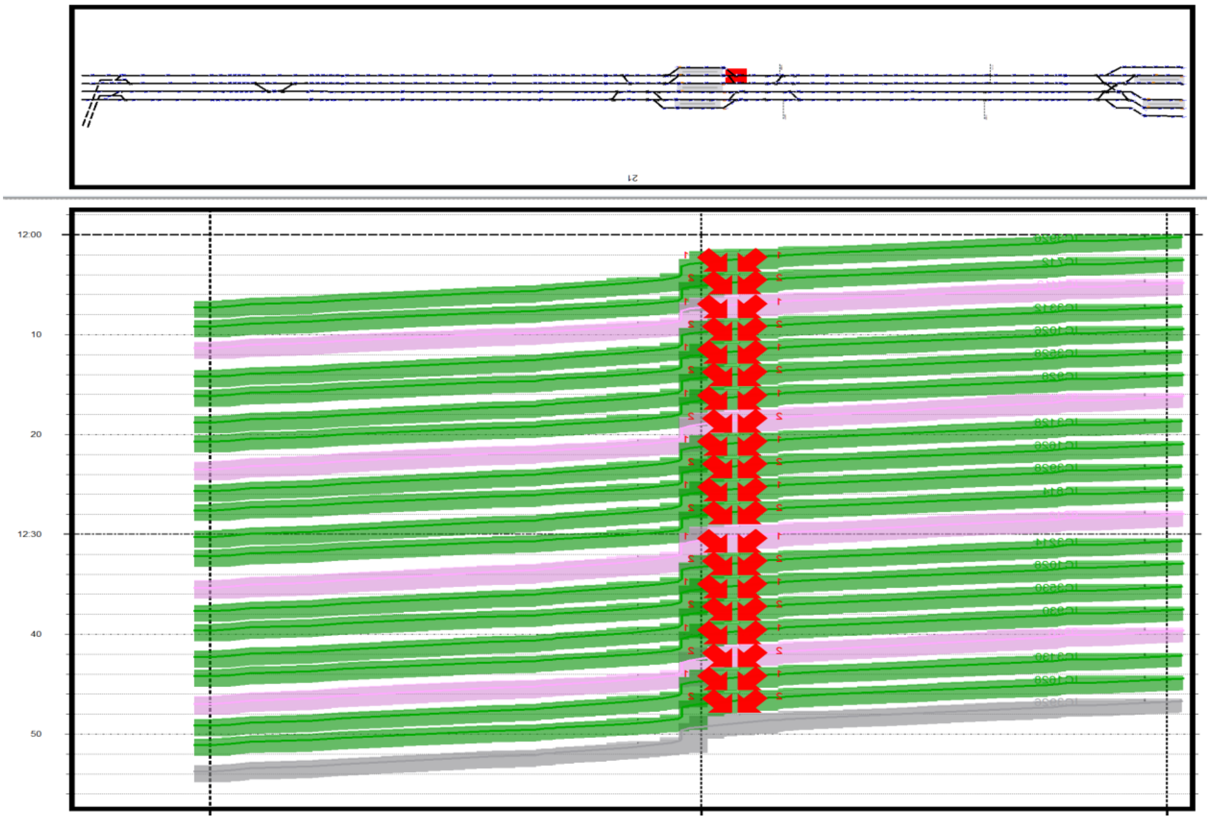
A3.8. HL3 Permitted Asra-Hfd (IC)



A3.9. HL3 Permitted Hfd-Asra (S)

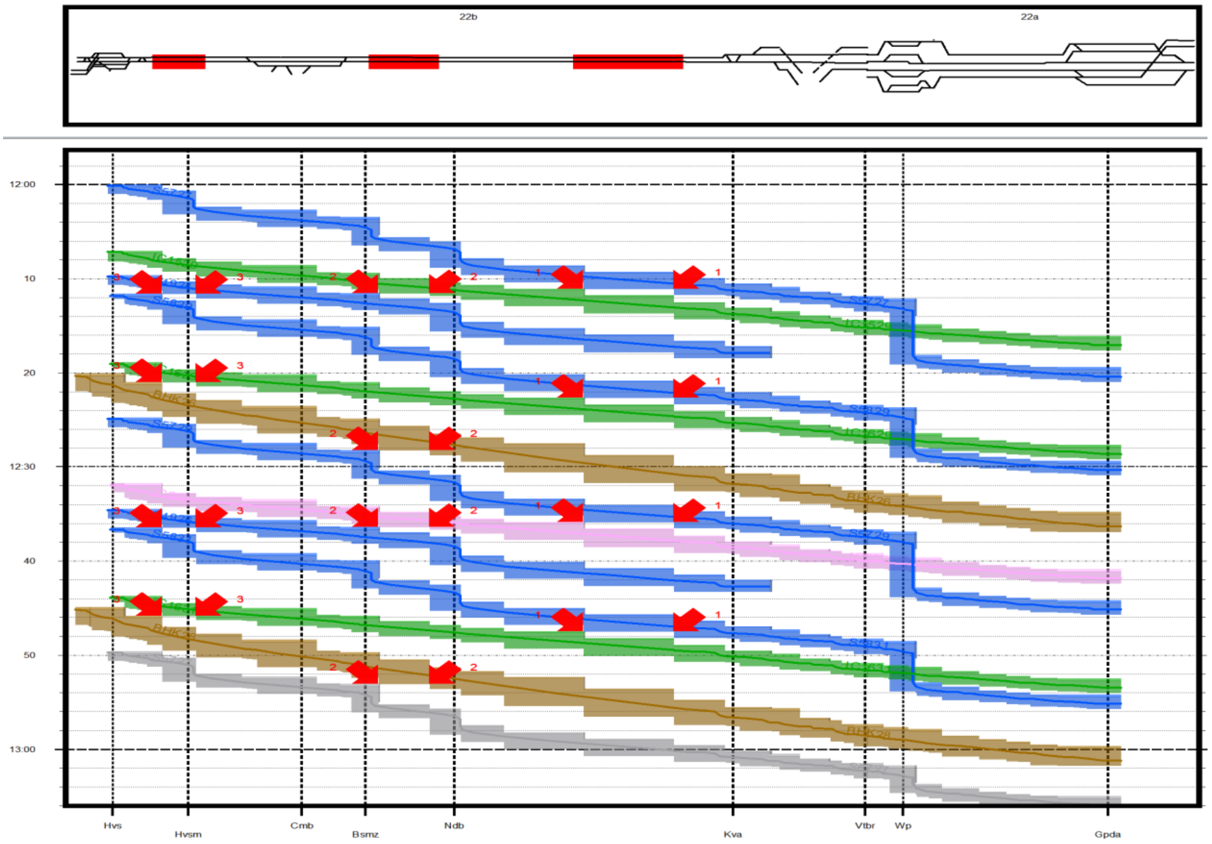


A3.10. HL3 Permitted Hfd-Asra (IC)

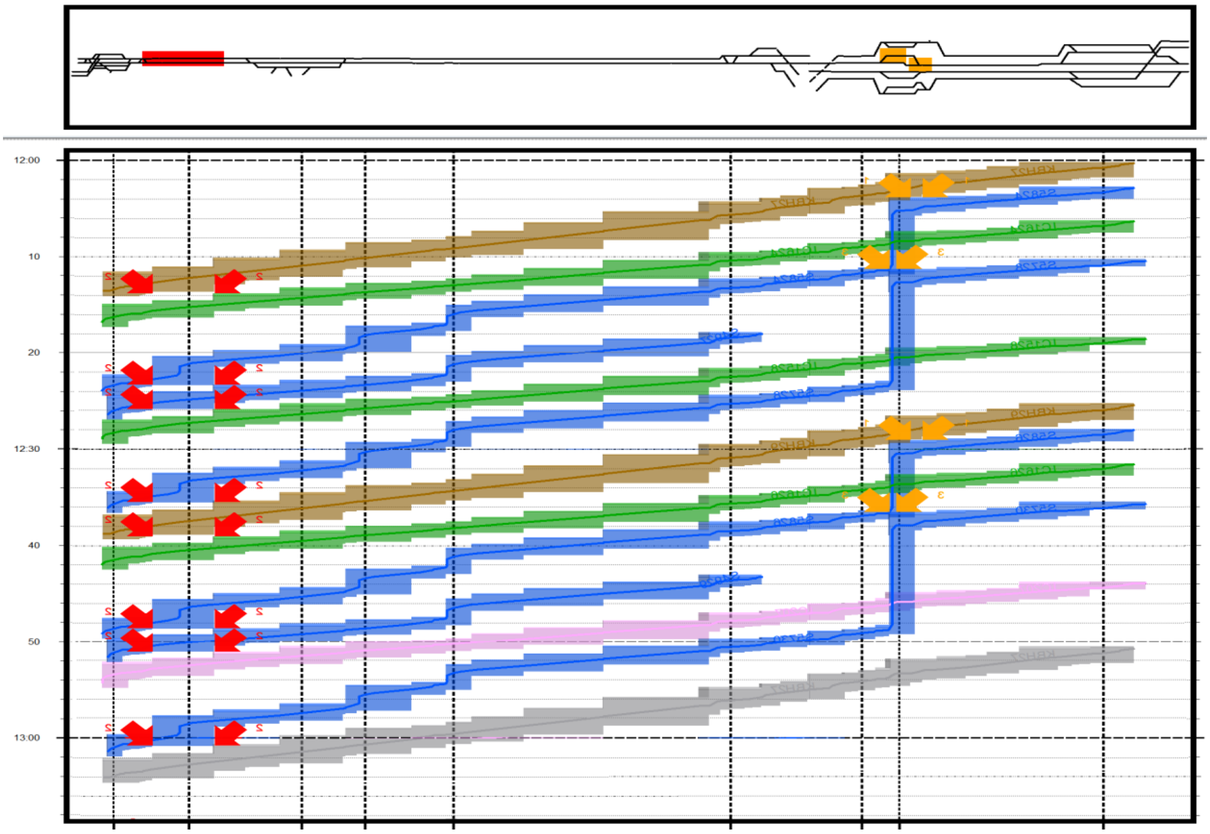


A4. L2 ATO (30s buffer)

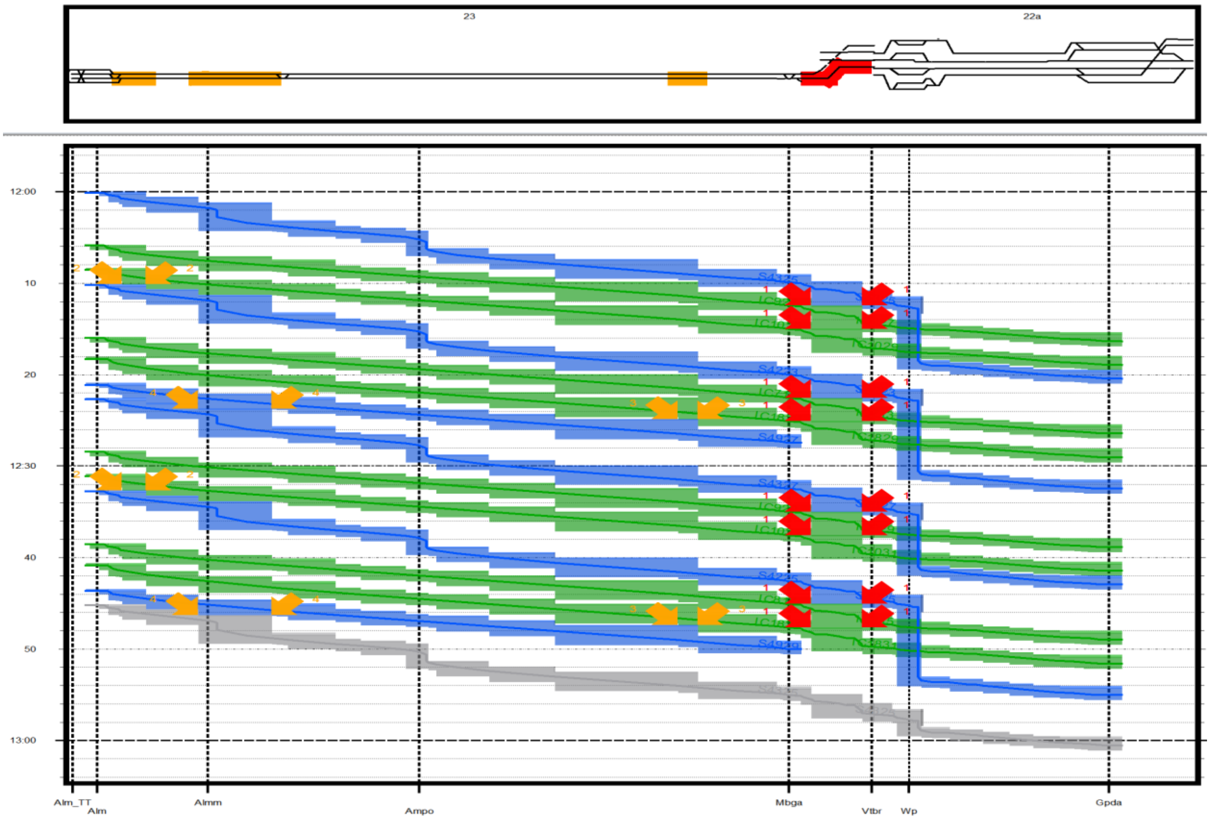
A4.1. L2 ATO Hvs-Gpda



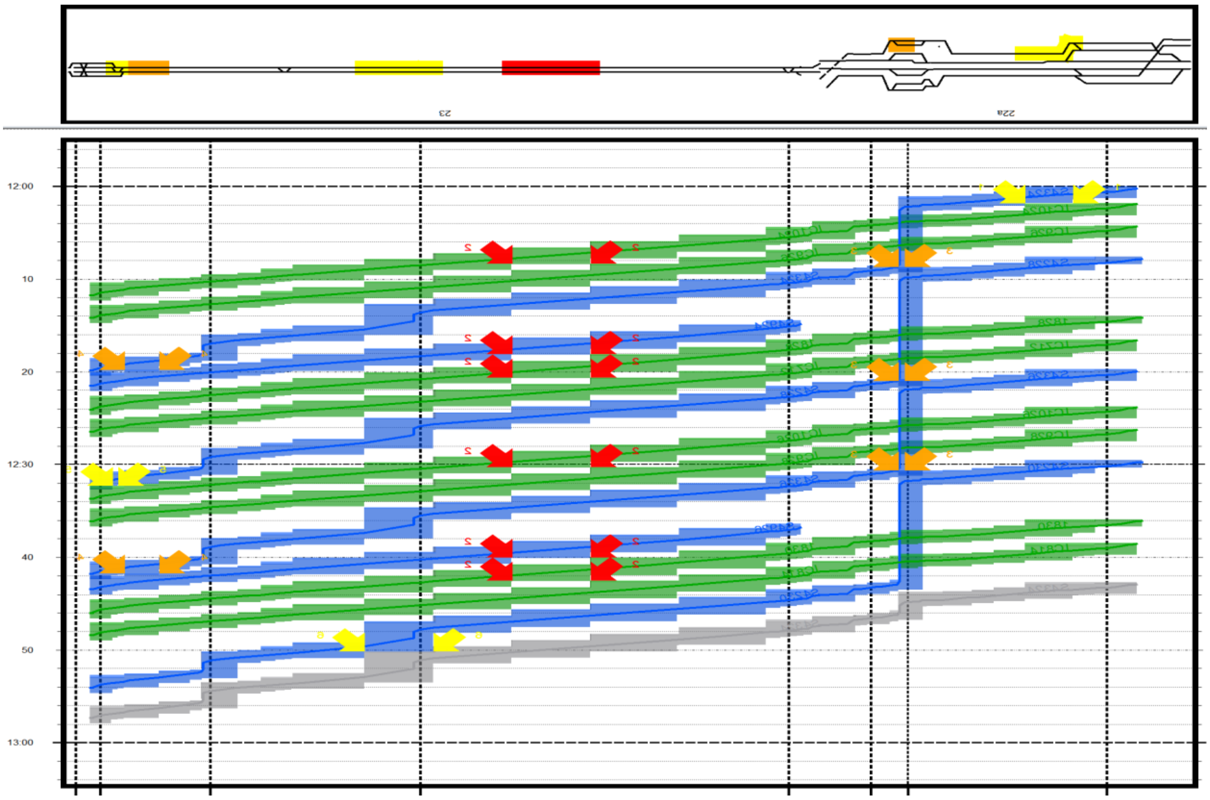
A4.2. L2 ATO Gpda-Hvs



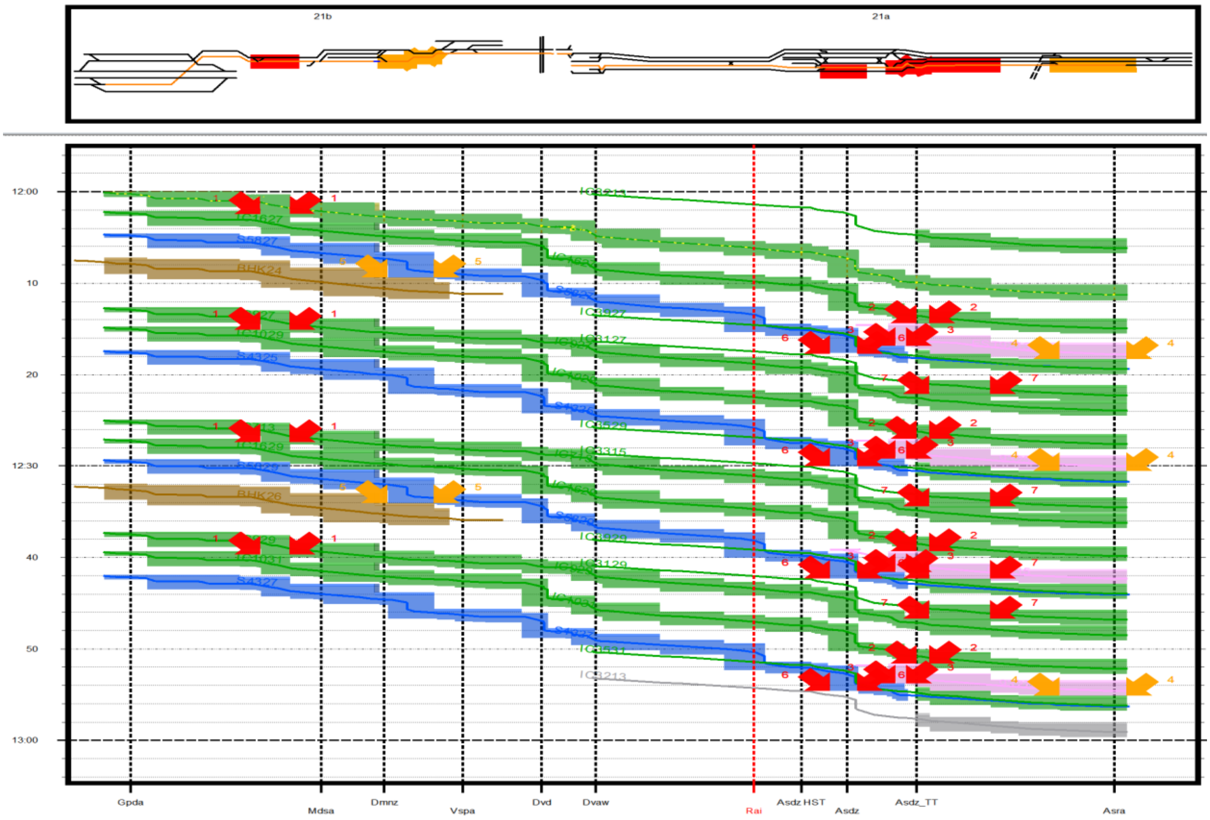
A4.3. L2 ATO Alm-Gpda



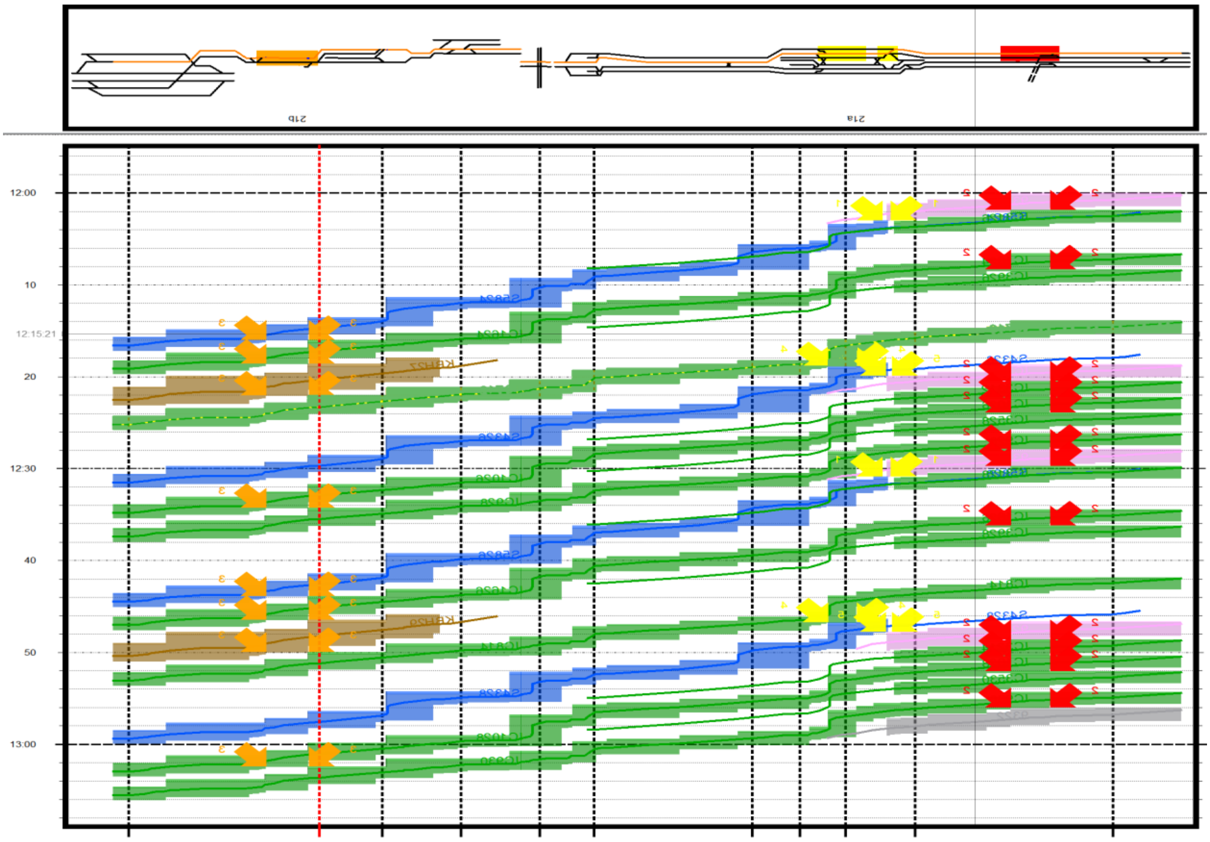
A4.4. L2 ATO Gpda-Alm



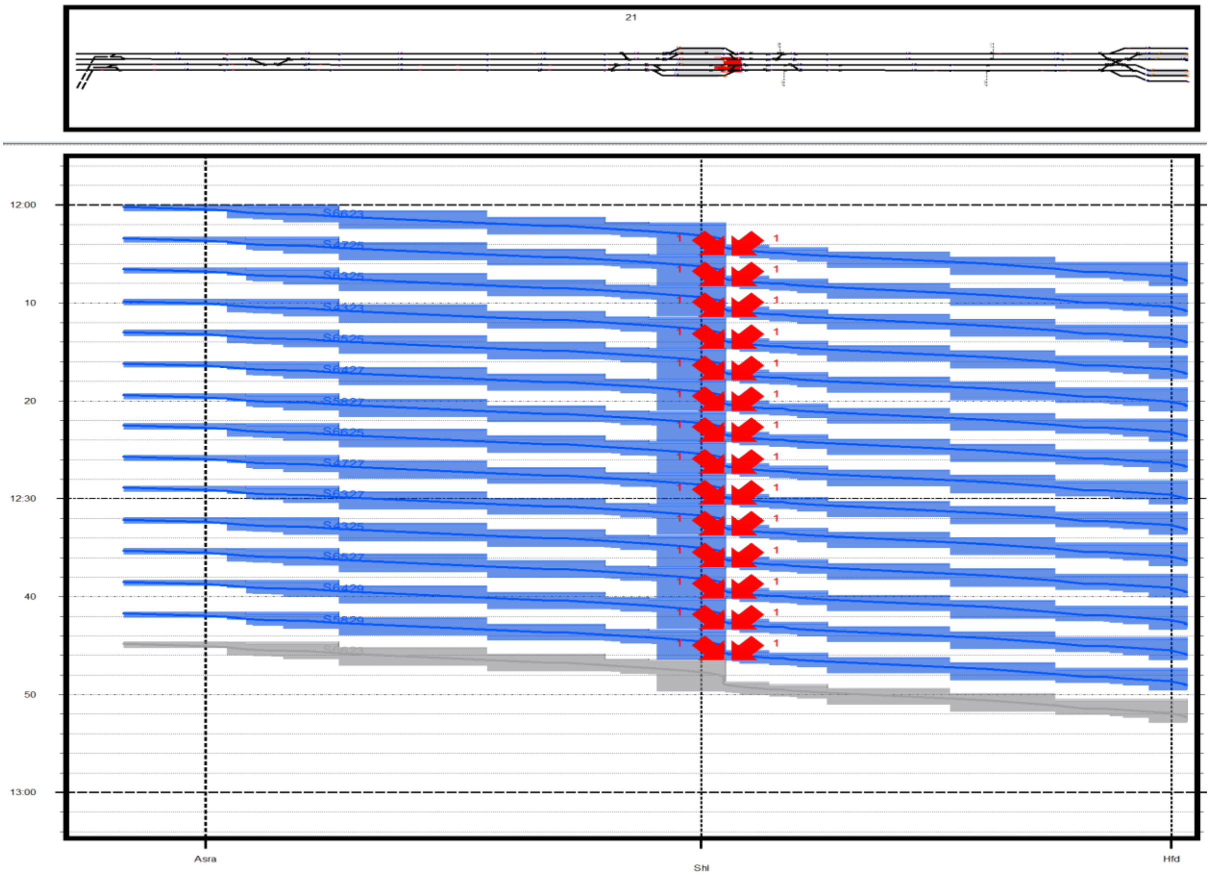
A4.5. L2 ATO Gpda-Asra



A4.6. L2 ATO Asra-Gpda

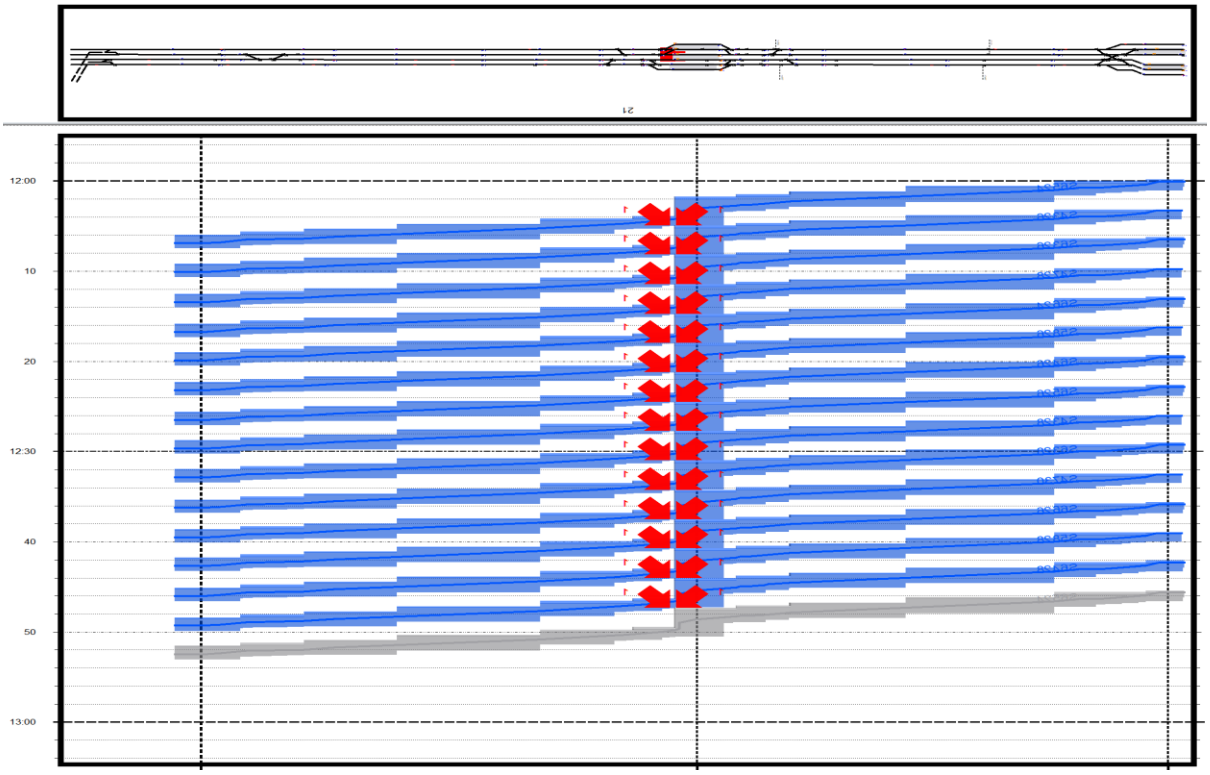


A4.7. L2 ATO Asra-Hfd (S)



A4.8. L2 ATO Asra-Hfd (IC)

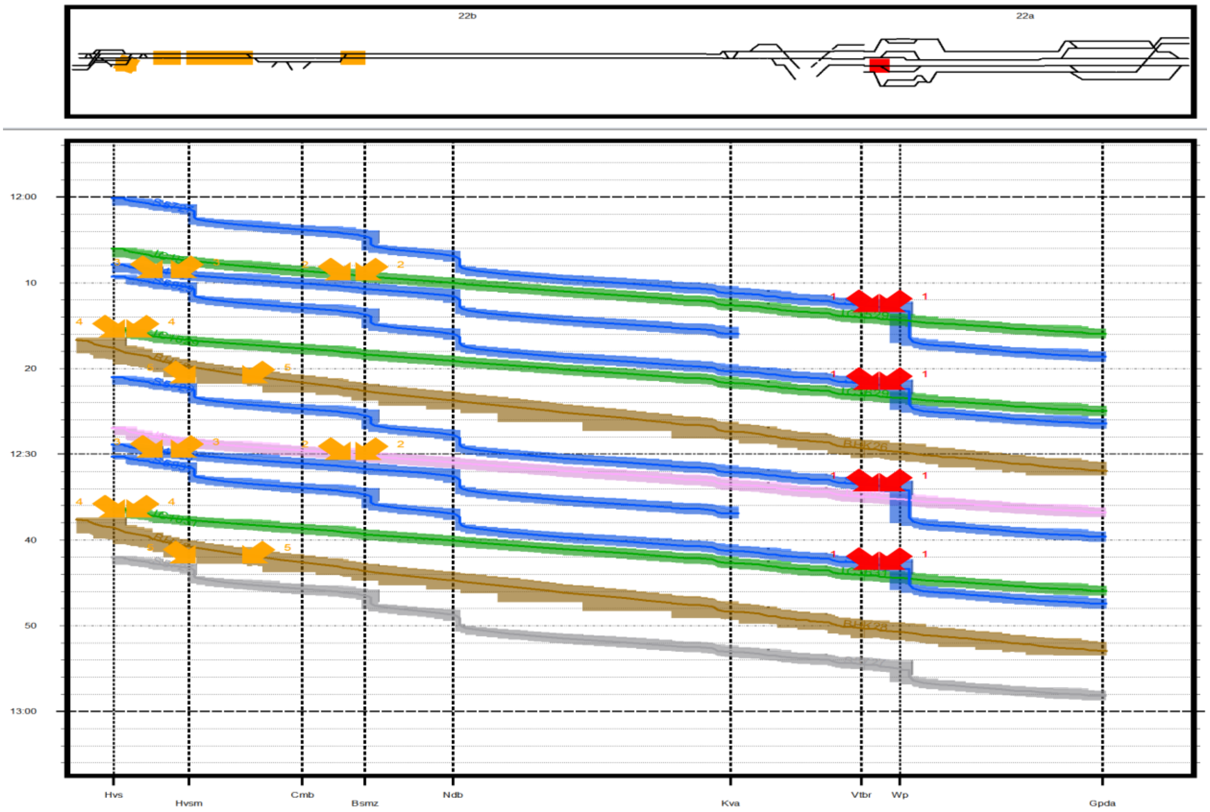
A4.9. L2 ATO Hfd-Asra (S)



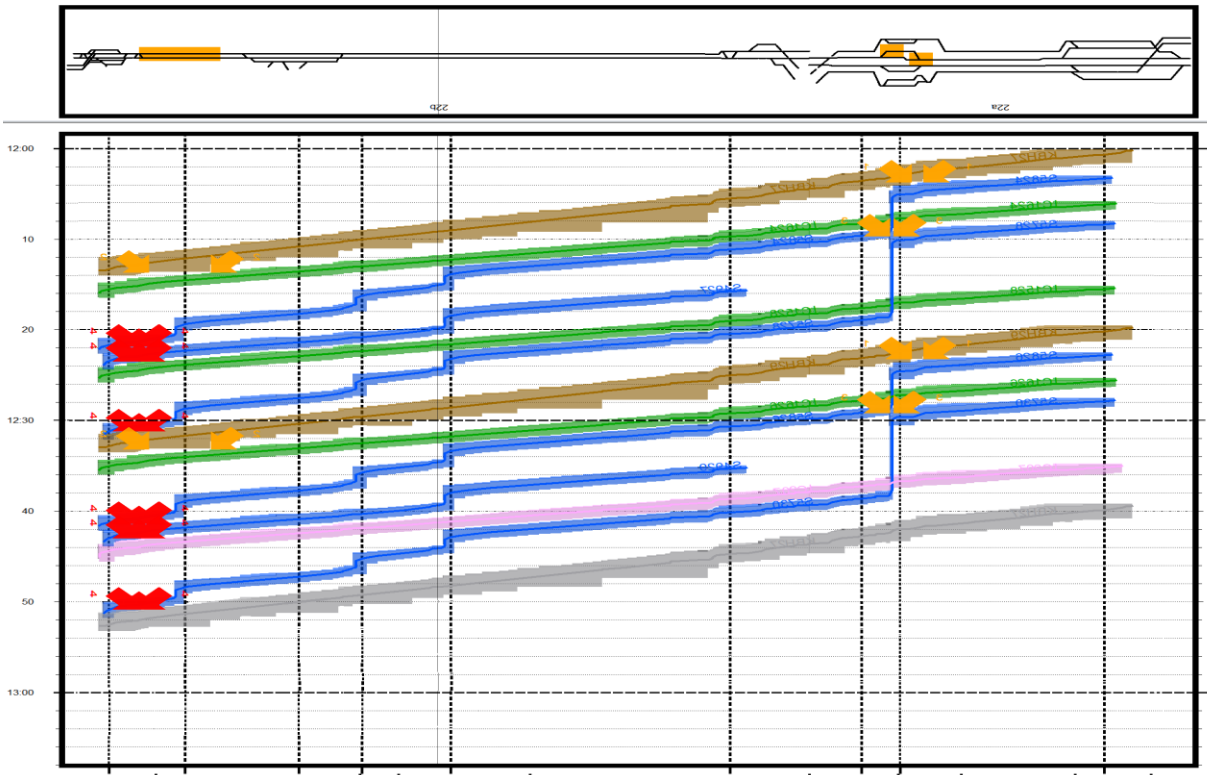
A4.10. L2 ATO Hfd-Asra (IC)

A5. HL3 ATO (30s buffer)

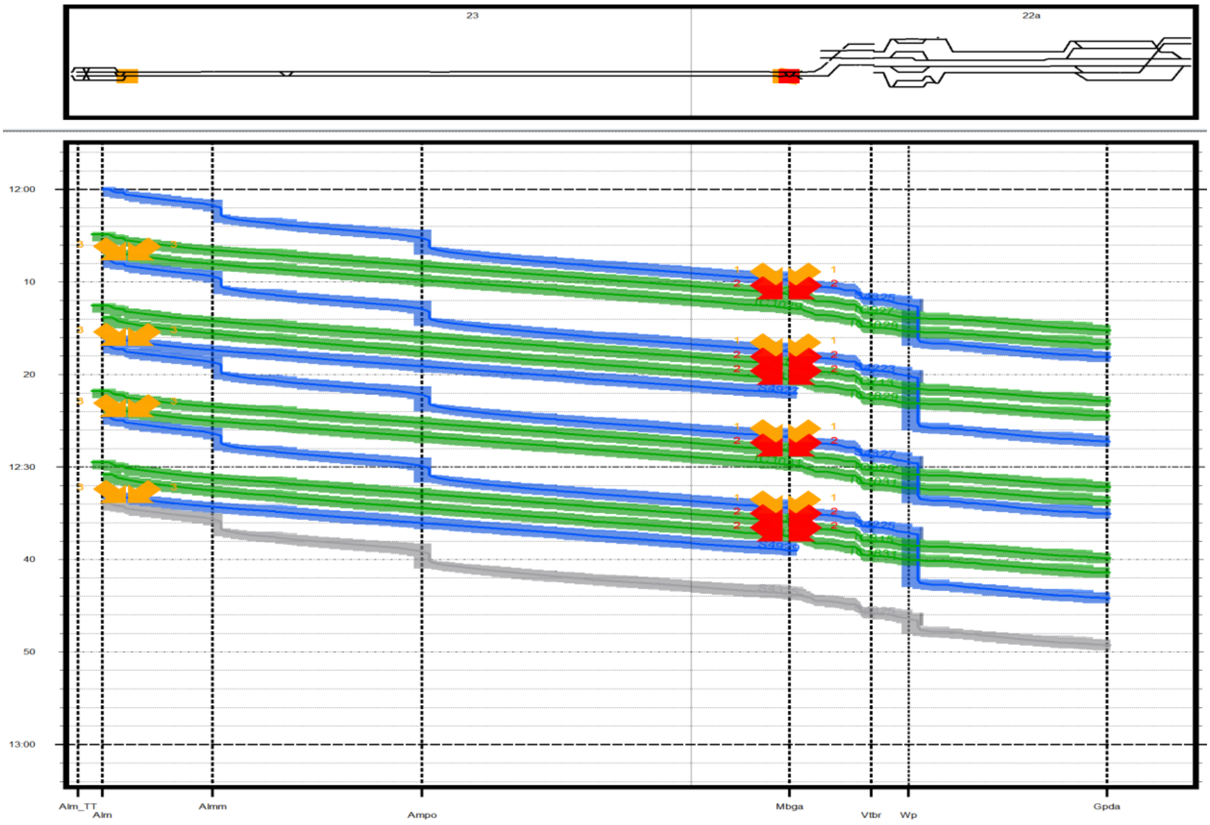
A5.1. HL3 ATO Hvs-Gpda



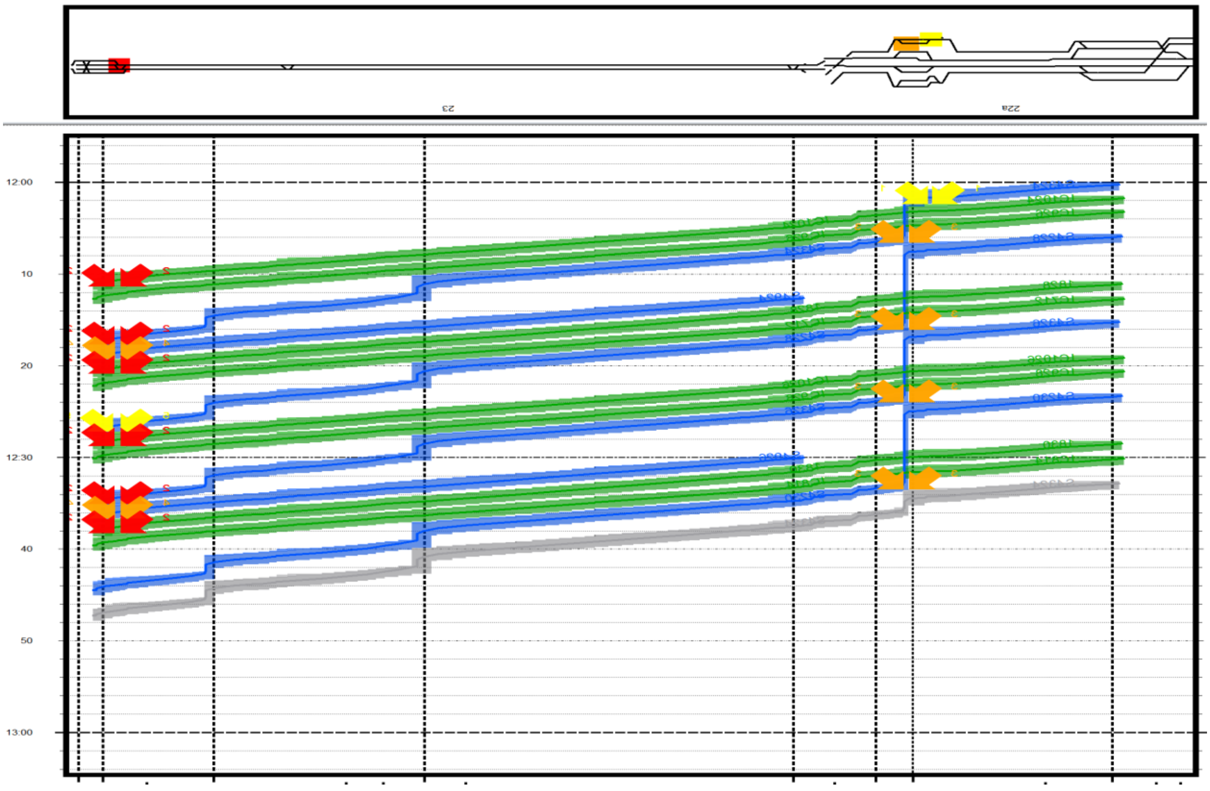
A5.2. HL3 ATO Gpda-Hvs



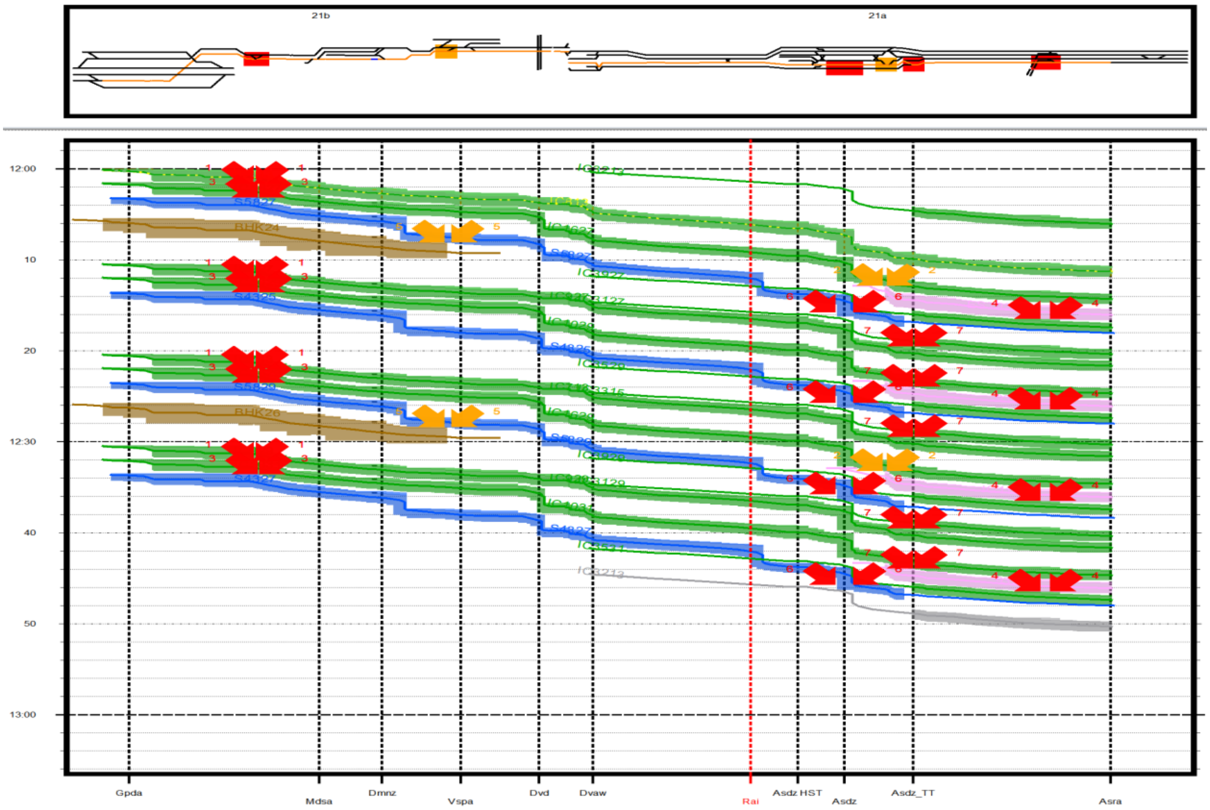
A5.3. HL3 ATO Alm-Gpda



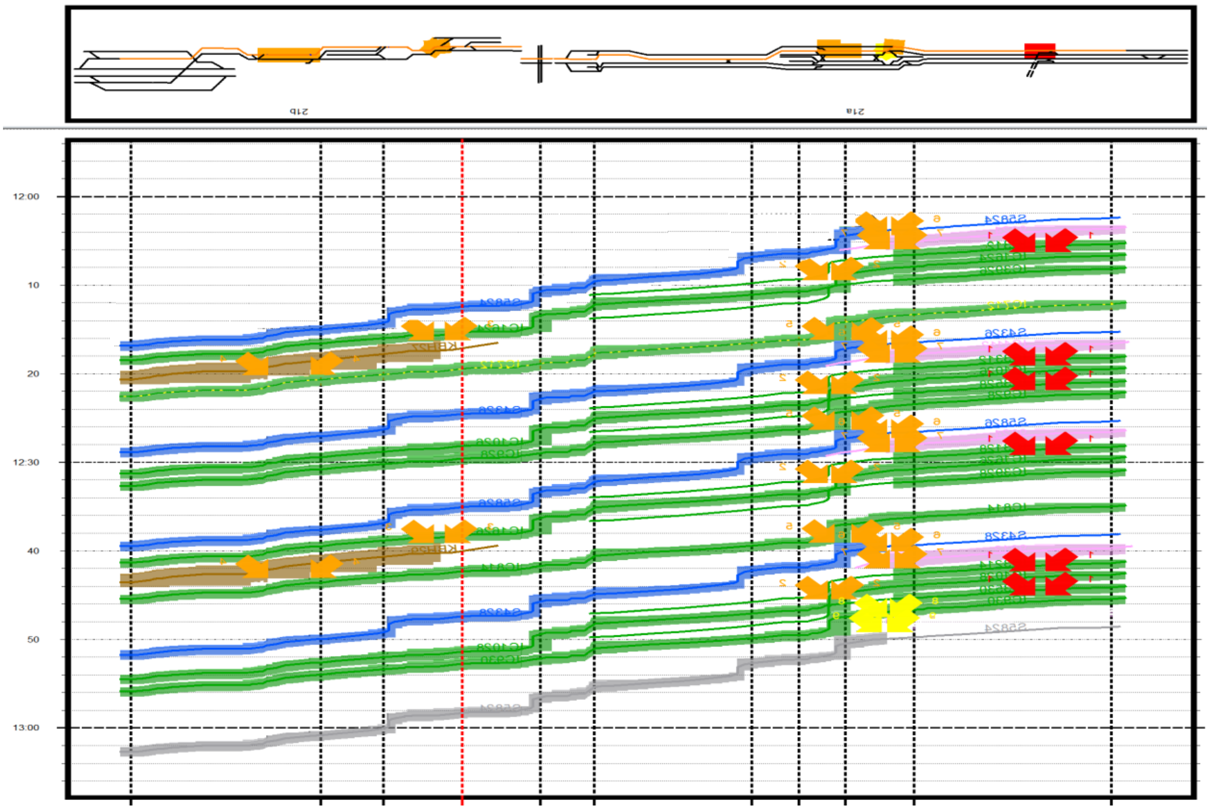
A5.4. HL3 ATO Gpda-Alm



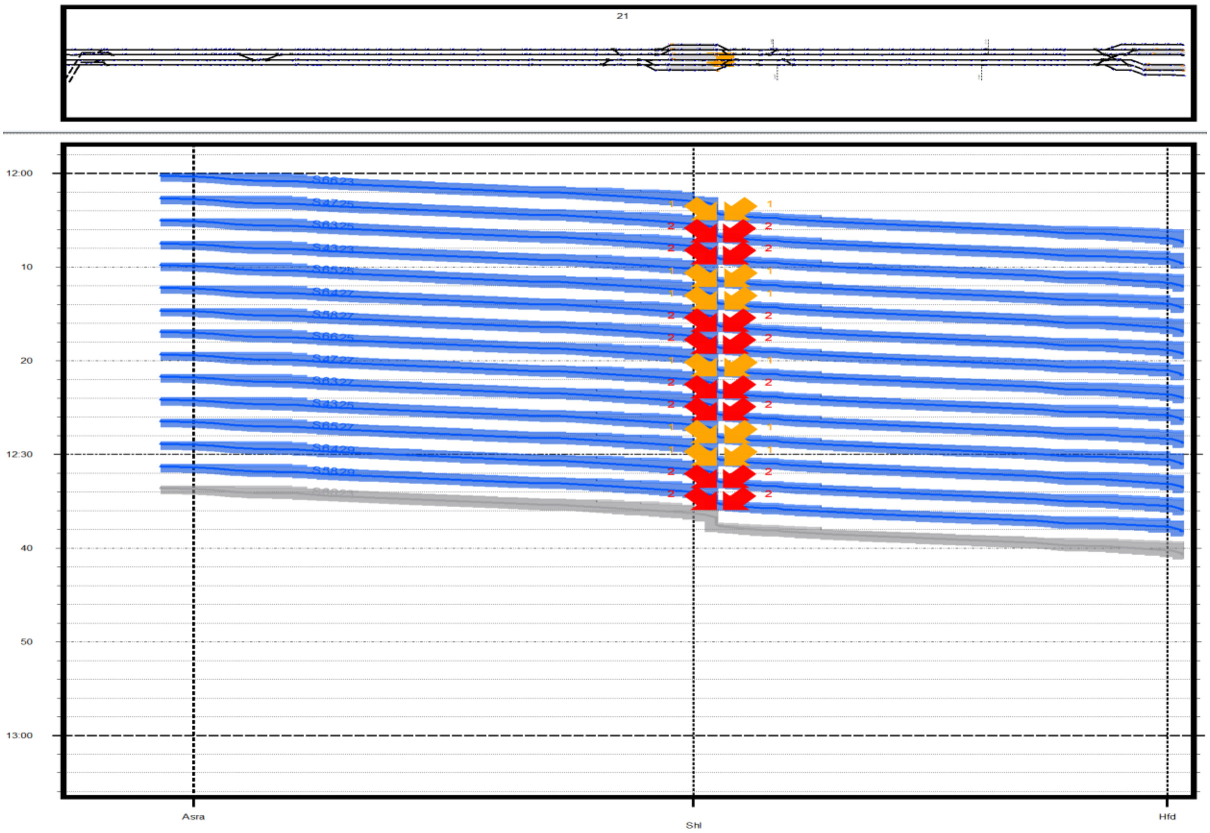
A5.5. HL3 ATO Gpda-Asra



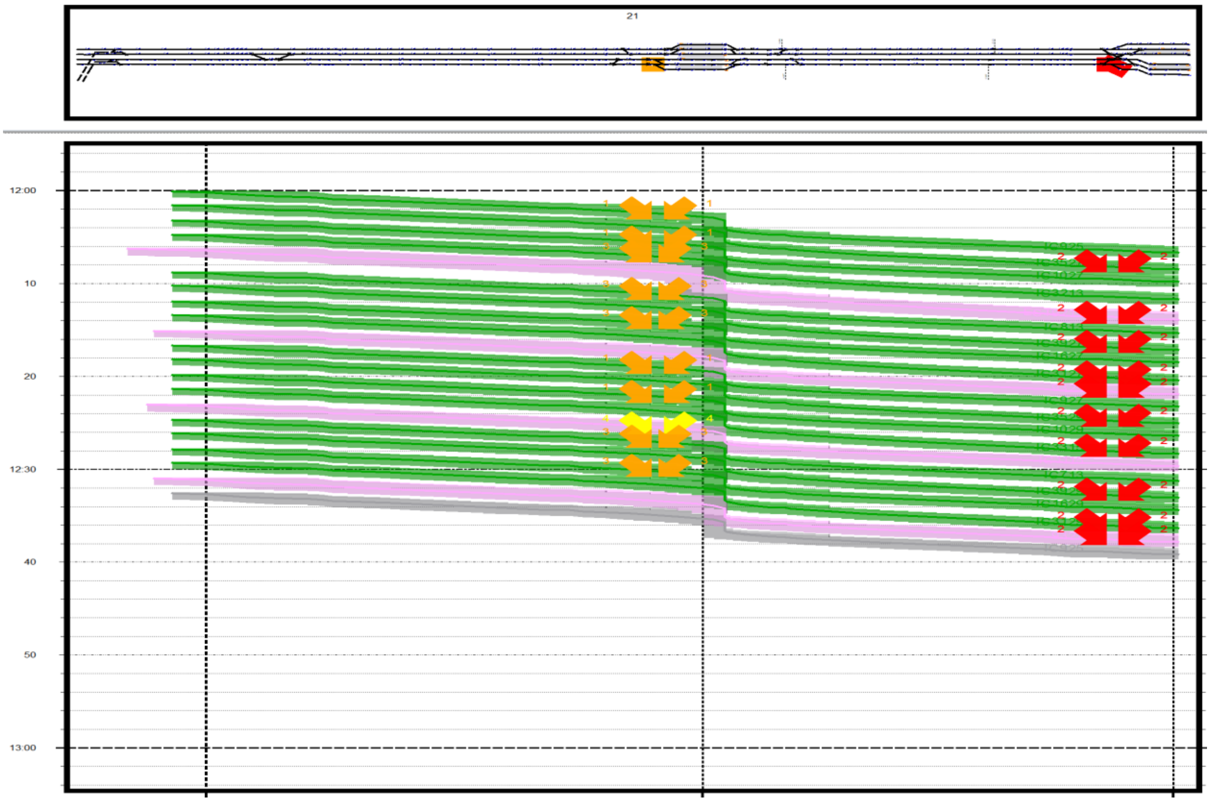
A5.6. HL3 ATO Asra-Gpda



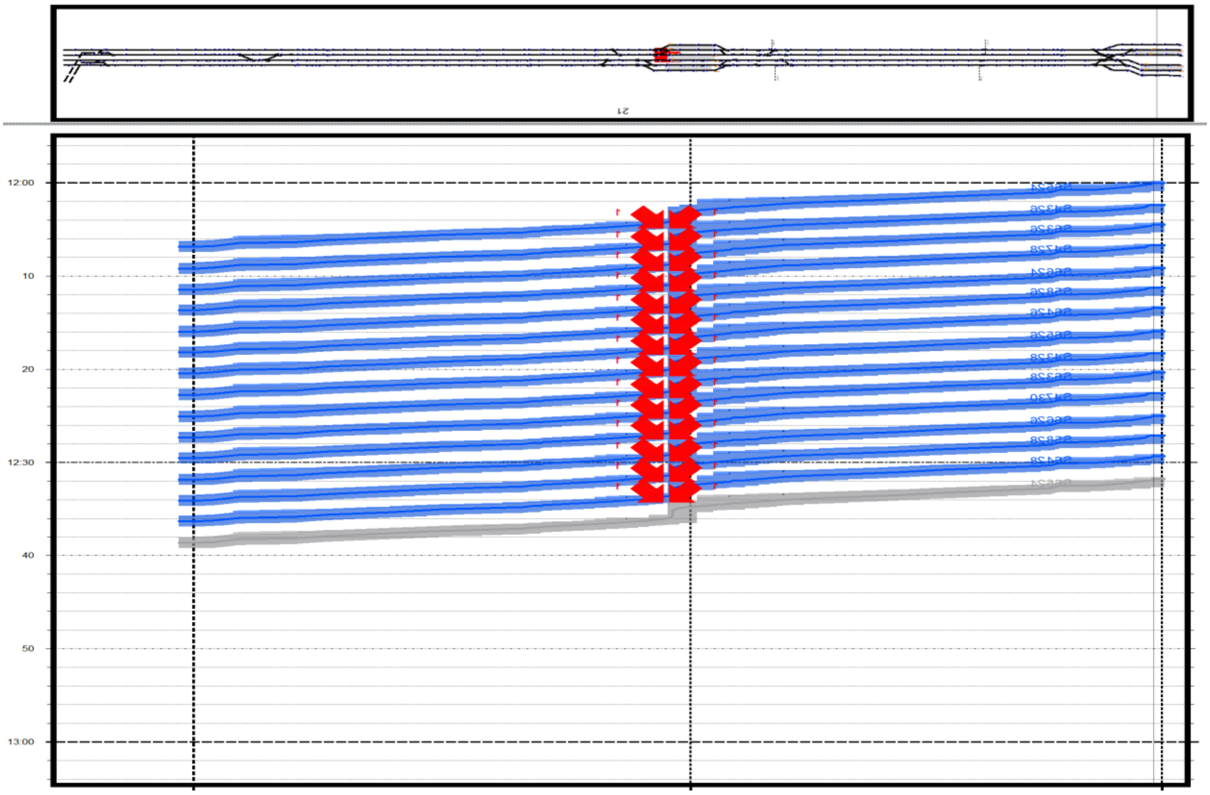
A5.7. HL3 ATO Asra-Hfd (S)



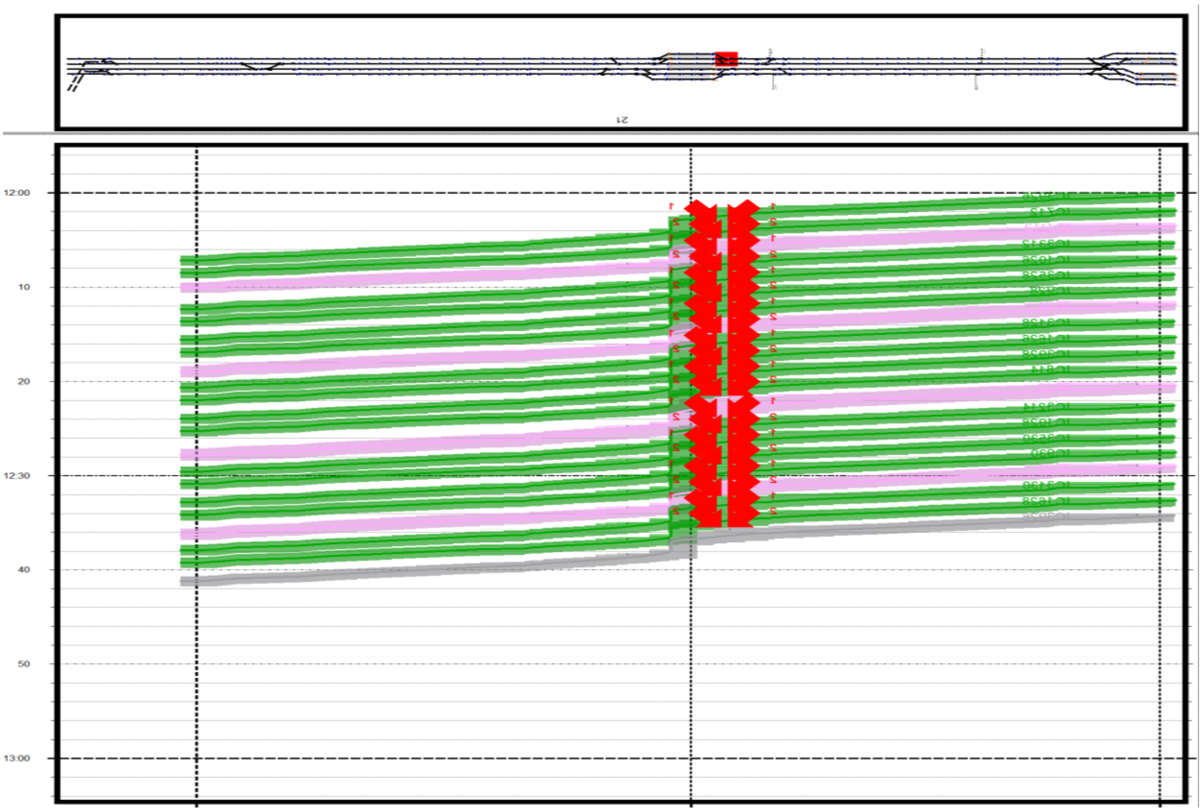
A5.8. HL3 ATO Asra-Hfd (IC)



A5.9. HL3 ATO Hfd-Asra (S)

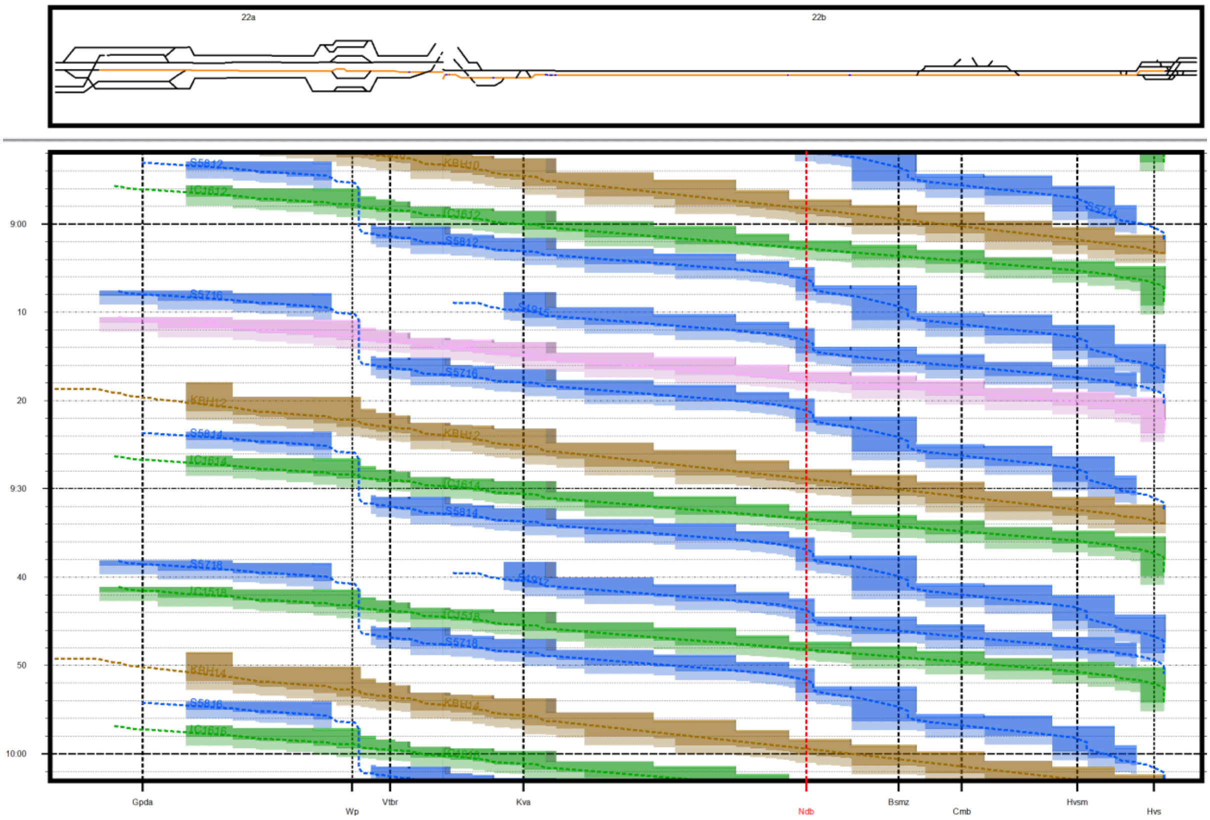


A5.10. HL3 ATO Hfd-Asra (IC)

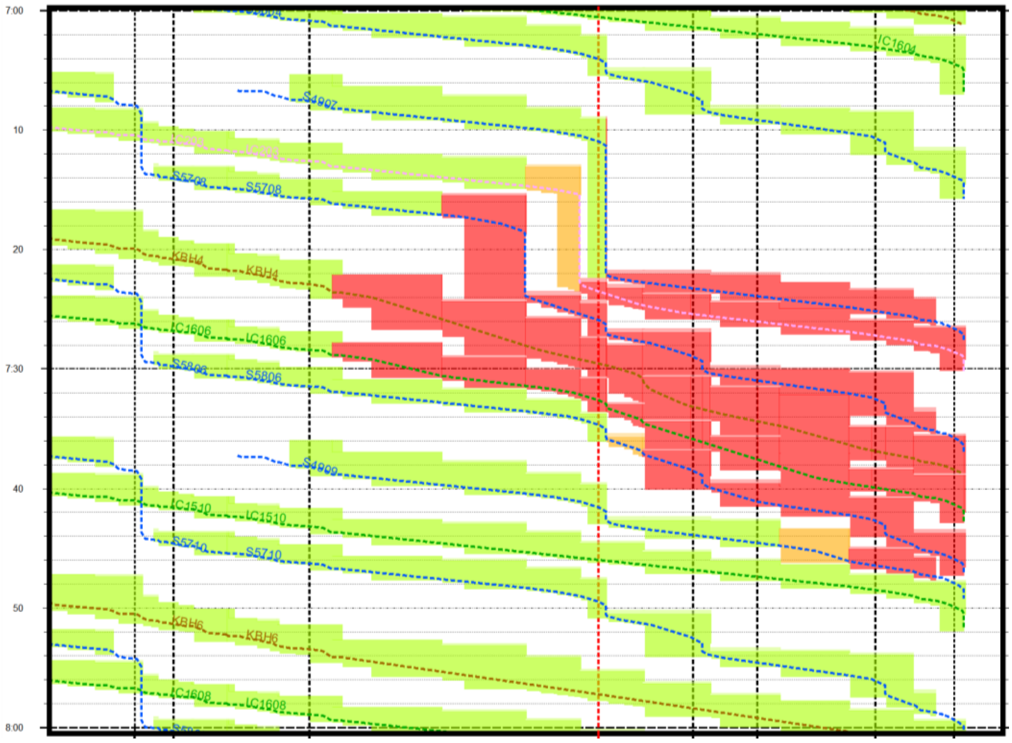


B. Figures perturbed system performance

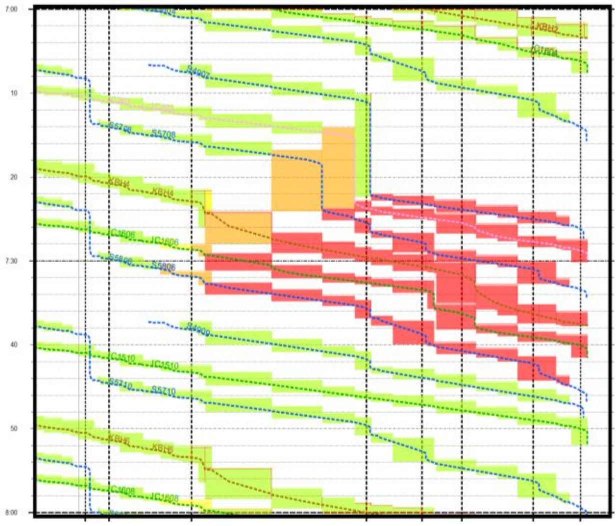
B1. Timetable pattern perturbed performance test (optimised for ATB/NS'54)



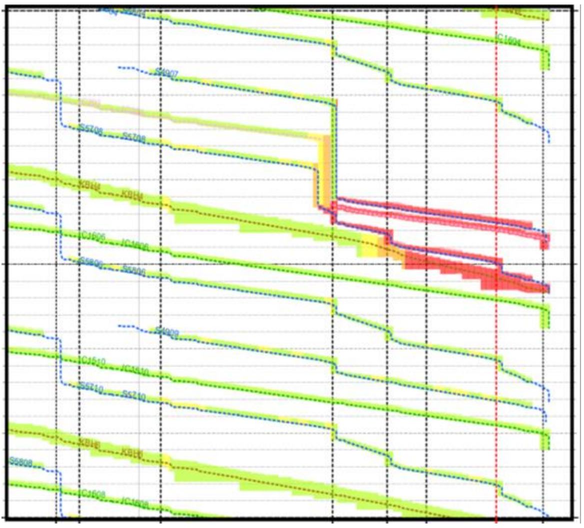
B.2 Performance test ATB/NS'54



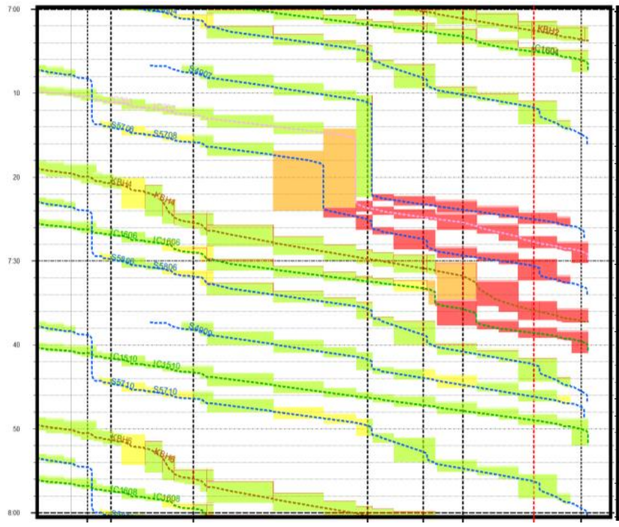
B3. Performance test with constant timetable



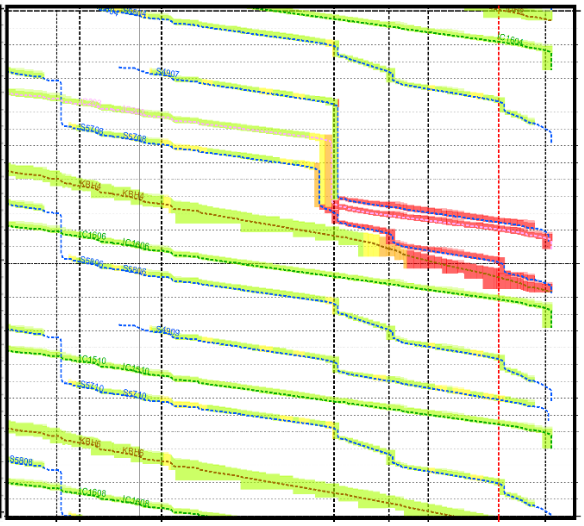
Level 2



Hybrid Level 3

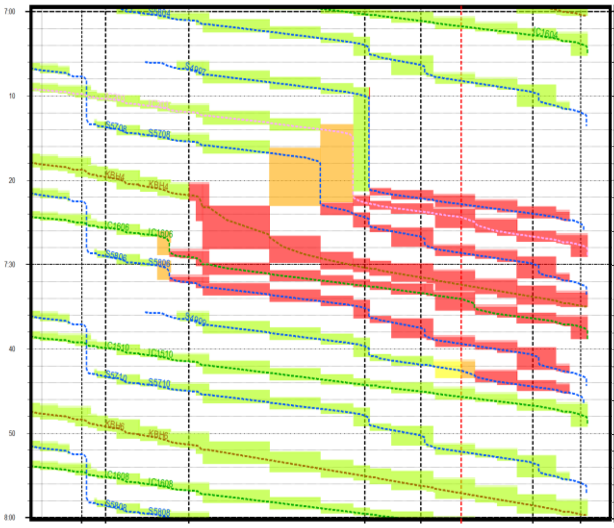


Level 2 ATO

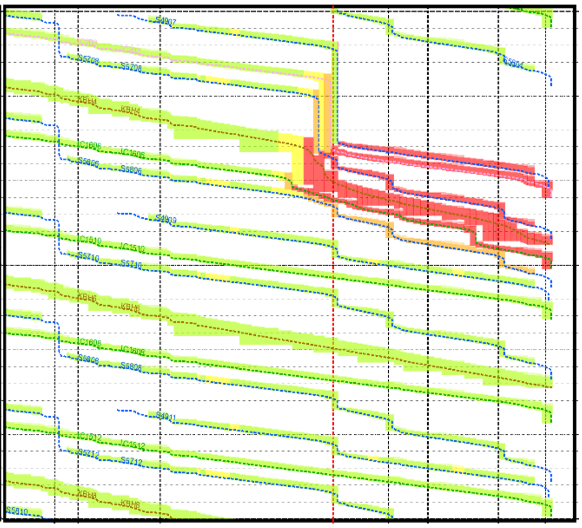


Hybrid Level 3 ATO

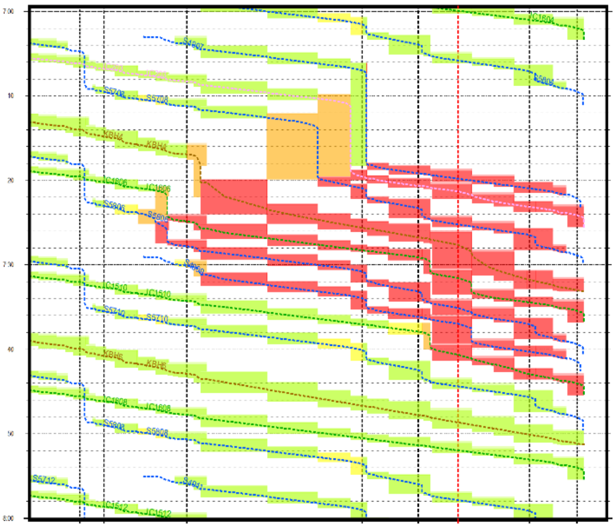
B4. Performance test with optimised timetable (shorter headways)



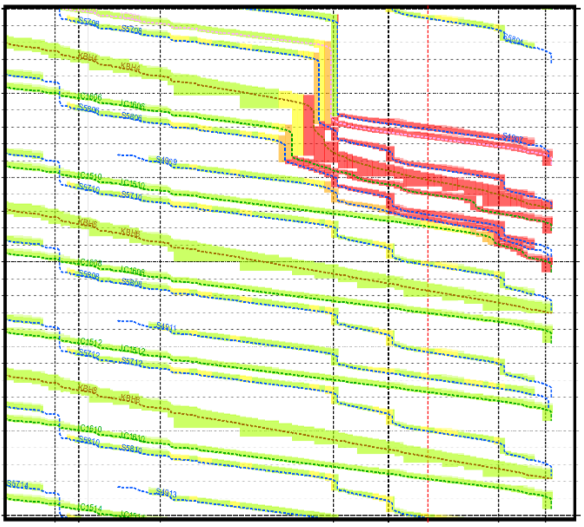
Level 2



Hybrid Level 3



Level 2 ATO



Hybrid Level 3 ATO