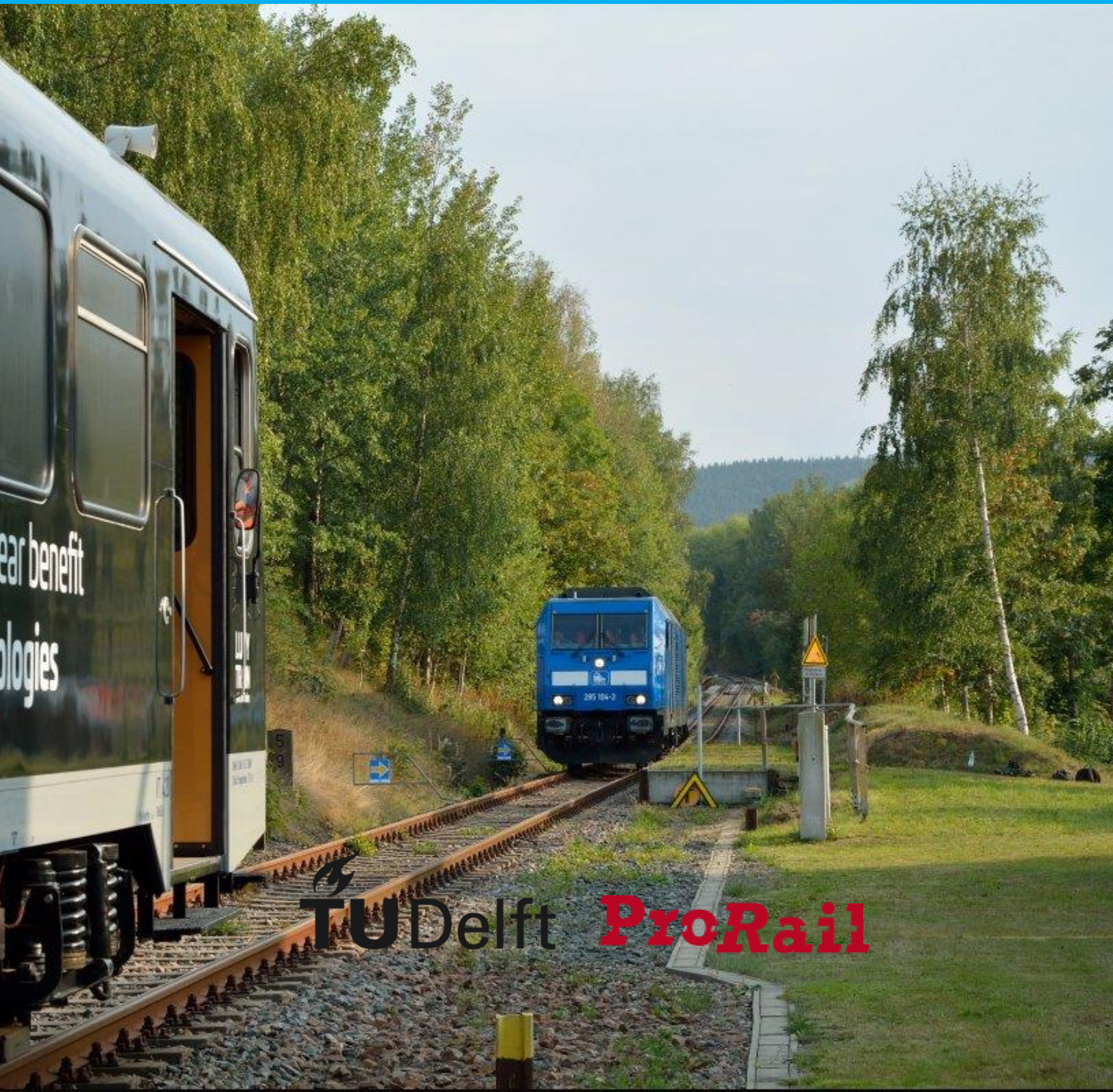
J.M. Jansen

ERTMS/ETCS Hybrid Level 3

a simulation-based impact assessment for the Dutch railway network



ERTMS/ETCS Hybrid Level 3

a simulation-based impact assessment for the Dutch railway network

a thesis submitted by

J.M. Jansen

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Final report
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Cover image: DB Netz AG, 2018
ERTMS/ETCS Level 3 test at the Deutsche Bahn Living Lab, Annaberg, Germany, September 6th 2018

Preface

The report in front of you is the final chapter of my period as student 4005201 at Delft University of Technology. Over the past years I obtained my bachelor's degree in Civil Engineering and studied on the programme to obtain the master's degree in Civil Engineering. It has been quite a journey.

The initial contact on the possibility for writing my masterthesis at ProRail started after an interesting lecture by Maarten Bartholomeus on the ERTMS/ETCS Hybrid Level 3 signalling concept. A thorough quantification of the impacts on both the railway capacity and possibilities for asset reduction was still lacking – my thesis was born.

During the course of this thesis I have had a lot of help and feedback from a few people. First, I would like to thank Egidio Quaglietta as my daily university supervisor. Thank you for your time and your critical view on my work. In the end we were always on the same page. In addition, I would like to thank professor Rob Goverde as the chair of the committee for his feedback and monitoring the process and quality of the work. Thirdly, I would like to express my gratitude to John Baggen for his role as second university supervisor.

Most of my time working on this thesis I spent at the Inktpot in Utrecht, the headquarters of ProRail. It was here where I had most meetings with both of my company supervisors. Therefore I would like to thank Maarten Bartholomeus and Alwin Pot for your almost everlasting time and critical detailed feedback on my work. Thank you for helping me around in the organization and sending me to the right persons elsewhere. A special thanks to Henri Olink for your support with the RailSys struggles. Furthermore I would like to thank the staff of the department AM/AT/Treinbeveiliging of ProRail, in particular the colleagues of room F2.02-06 for the coffee breaks and the social talks.

Lastly, I want to thank my parents, my sister and of course Merel for the ongoing support during my studies and my friends for the welcome distraction from the process, the coffee and the beers.

I hope you enjoy the read!

Joost Jansen
Delft, May 10th 2019

Summary

The combination of the mainline Dutch legacy signalling system (NS'54) and train protection system (ATB-EG) is functioning well, but has some drawbacks. Both systems are old and components will have to be replaced in the near future. Full brake supervision is lacking and the speed supervision functionality is limited to only five speed steps. Moreover, the Dutch railway network is about to reach the limit of its capacity with NS'54/ATB-EG. Expected demand growth from the year 2030 onwards cannot be matched by a service increment.

Europe started to develop a new standard signalling and train protection system: the European Rail Traffic Management System (ERTMS). Part of this system are the European Train Control System (ETCS), a radio-communication protocol (GSM-R) and the non-developed European Traffic Management Layer (ETML). In the light of interoperability and enhanced safety Europe obliged the deployment of ERTMS/ETCS on several main rail corridors, connecting European cities and ports. Next to the interoperability and safety aspects, ERTMS/ETCS could also bring additional speed, railway capacity and/or system reliability.

Because of the Dutch replacement task of the legacy systems and the European TEN-t projects obliging the installation of ERTMS, the national government decided back in 2014 to install ERTMS/ETCS Level 2 on several mainline corridors by 2030. ERTMS/ETCS Level 3 technology allows for even more capacity while eliminating trackside train detection. However, this puts a high demand on the rolling stock, the remaining trackside equipment and operations. All trains need to be proven complete and the trackside needs to know the train positions any time to ensure safe railway operations. No practical solution exists to provide a safe, reliable and robust operation for a ERTMS/ETCS Level 3 system that solely relies on reported train positions. To overcome those issues, a new concept has been developed: ERTMS/ETCS Hybrid Level 3 (Furness, van Houten, Arenas & Bartholomeus, 2017). This concept is a combination of train position information, train integrity confirmation and trackside train detection.

As the signalling concept is still quite new, the impact of this concept on railway capacity and the possibilities for reducing trackside train detection has not yet been investigated thoroughly. Therefore the research question of this thesis is:

"What is the contribution of ERTMS/ETCS Hybrid Level 3 over ERTMS/ETCS Level 2 and the NS'54/ATB-EG legacy signalling system to the Dutch railway system in terms of capacity increase and reduction of trackside equipment?"

The research question is answered by implementing and modelling the different signalling systems on the corridor Utrecht – Den Bosch, and simulating the timetable. This is a corridor with relevant characteristics: mixed traffic (mainly Intercities and Sprinters, two additional freight paths per hour) and high infrastructure occupation rates.

ERTMS/ETCS Hybrid Level 3 implementation
The approach of ERTMS/ETCS Hybrid Level 3 with virtual subsections matches the operational principles of ERTMS/ETCS Level 2 technology. New is the infrastructure release mechanism based on position reports and integrity confirmation by the train. The location and layout of special track sections such as steep slopes, sections breaks, junctions and platforms could limit the optimal placement of Stop Marker Boards. These issues are not safety relevant, but can create operational risks that should be mitigated by e.g. solving in traffic control systems. Solutions could be found in flow dependent authorisation, train type dependent authorisation or the re-use of existing procedures and equipment.

Five infrastructure variants have been modelled and simulated for this study: (1) the legacy block signalling and train protection systems, (2) an ERTMS/ETCS Level 2 implementation on the current block layout, (3) a variant of ERTMS/ETCS Hybrid Level 3 with virtual subsections of approximately 500m and the existing amount of trackside train detection, (4) a variant of ERTMS/ETCS Hybrid Level 3 with small virtual subsections (up to 100m) and the existing amount of trackside detection and (5) a variant with small virtual subsections (up to 100m) and reduced trackside train detection.

Capacity assessment & system performance

The railway capacity of the variants is assessed on the basis of the Timetable Compression Method from UIC Leaflet 406. Table A.1 shows the infrastructure occupation and capacity consumption (including 60 seconds buffer time per train) of the different ERTMS/ETCS Hybrid Level 3 variants compared to NS'54/ATB-EG and ERTMS/ETCS Level 2. With small virtual subsections and leaving all trackside train detection in place, the infrastructure occupation can drop from 84,0% for the legacy signalling system to 66,7%. When reducing the trackside train detection to the minimum, the infrastructure occupation becomes 71,7%, which is still better than the ERTMS/ETCS Level 2 implementation. All ERTMS/ETCS implementations have an infrastructure occupation lower than 75%, which is the proposed maximum infrastructure occupation rate of mixed traffic lines with an acceptable quality of service according to UIC Leaflet 406.

Table A.1 | Infrastructure occupation and capacity consumption, timetable 2019

		Infrastructure occupation	Required buffer	Capacity consumption
NS'54/ATB-EG		84,0%	720 s	104,0%
ERTMS/ETCS L2		74,3%	600 s	90,9%
ERTMS/ETCS HL3	500m virtual subsections & existing trackside train detection	70,4%	606 s	87,2%
ERTMS/ETCS HL3	Virtual subsections up to 100m, existing trackside train detection	66,7%	564 s	82,4%
ERTMS/ETCS HL3	Virtual subsections up to 100m, reduced trackside train detection	71,7%	616 s	88,8%

The five variants have been examined for the sensitivity to changes of the braking parameters. By changing the ETCS Integrated Correction Factors for both gamma trains (trains with fixed composition and braking deceleration known) and lambda trains (trains with variable composition, braking percentage known) this sensitivity has been tested. The influence of the integrated correction factor K_dry on the gamma braking model is limited to an increase of the minimum runtime of a few seconds per train and an increase of up to 0,5% of the infrastructure occupation. The integrated correction factors for the lambda braking model Kr_int (train length dependent correction) and Kv_int (train speed dependent correction) individually lead to only minor changes in the minimum runtime of freight trains and the infrastructure occupation (runtime variations of maximum 7 seconds and infrastructure occupation variation up to 0,8%). The correction factor Kt_int for lambda trains (brake build-up time correction) leads to runtime variations of maximum 15 seconds and infrastructure occupation variation up to 1%.

To test the perturbation-resolving characteristics of the different infrastructure variants, a 10-minute and a 30-minute perturbation on the corridor have been implemented in the model. The short virtual subsections of ERTMS/ETCS Hybrid Level 3 can solve perturbations over 42% faster and the total delays can be reduced by almost 40% compared to the legacy signalling system.

The small virtual subsections in combination with the position report-based block release reduce the headways under ERTMS/ETCS Hybrid Level 3 by approximately a minute compared to ERTMS/ETCS Level 2 and the legacy block signalling system. The reduced headways and capacity benefits of ERTMS/ETCS Level 2 and the different Hybrid Level 3 infrastructure variants can be used to increase the average train speed, increase the service heterogeneity, increase the timetable stability and/or increase the train frequencies. In the light of the expected demand growth, this study increased the frequency by including a 7th and 8th hourly IC. The results of the new timetable compression are included in Table A.2. The infrastructure occupation of 3 out of 4 ERTMS/ETCS implementations exceeds the proposed rate of 75% by the UIC. The capacity consumption exceeds 100% depending on the variant. The existing timetable with the legacy signalling system shows that it is possible to run a timetable with a capacity consumption of 104% by bending the train paths at critical locations. However, this measure has an adverse effect on the running times of trains. This is partly mitigated by the ERTMS/ETCS braking curves and the improved technical minimum running times.

Table A.2 | Infrastructure occupation and capacity consumption, extended timetable

		Infrastructure occupation	Required buffer	Capacity consumption
ERTMS/ETCS L2		82,6%	840 s	105,9%
ERTMS/ETCS HL3	500m virtual subsections & existing trackside train detection	77,6%	840 s	100,9%
ERTMS/ETCS HL3	Virtual subsections up to 100m, existing trackside train detection	73,1%	840 s	96,4%
ERTMS/ETCS HL3	Virtual subsections up to 100m, reduced trackside train detection	79,1%	840 s	102,4%

Reduction of trackside equipment
The impact of changes in trackside equipment is assessed based on the expected track (un)availability. In the year 2018, over 10.000 Train Depleting Irregularities have been counted on the Dutch railway network. 2.198 of those irregularities were related to the signalling and train protection systems, of which 78,6% had a technical cause or was triggered by a process error. Both causes could have been influenced and should have been prevented by the infrastructure manager.

By changing the type of trackside train detection from GRS track circuits to axle counters, the track unavailability related to block signalling and train protection systems on the corridor Utrecht – Den Bosch can be reduced by approximately 10 irregularities per year. This is an improvement of 20% compared to track circuits. The change of NS'54/ATB-EG equipment to ERTMS/ETCS equipment results in almost 5% less track unavailability. The precise impact of increasing the amount of virtual subsections in the ERTMS/ETCS Hybrid Level 3 variants is unknown as no comparable components are in use as of 2019. Increasing the number of virtual subsections is assumed to increase track unavailability. This is a conservative approach, as it is actually only a software configuration.

Reducing the trackside train detection to the bare minimum requires axle counters because of the limited maximum section length of GRS track circuits. This ERTMS/ETCS Hybrid Level 3 solution could result in a decrease of track unavailability of over 40% compared to the legacy signalling & train detection systems and a decrease of more than 20% compared to ERTMS/ETCS Level 2 with axle counters. Figure A.1 shows the yearly Train Depleting Irregularities on the corridor Utrecht – Den Bosch for the different infrastructural variants.

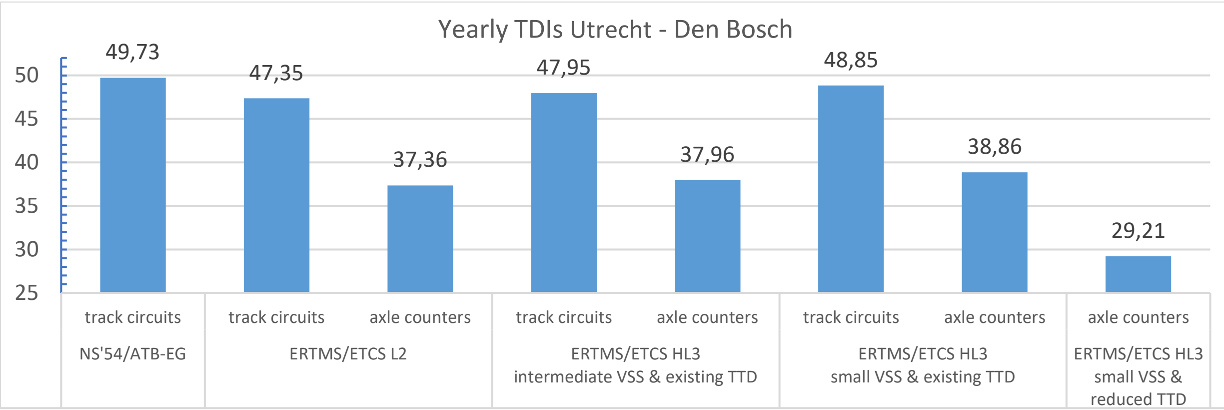


Figure A.1 | Yearly TDIs related to signalling and train protection systems, corridor Utrecht - Den Bosch

Conclusions
ERTMS/ETCS Hybrid Level 3 is a new and promising signalling concept which fits the existing Engineering Rules ERTMS with only minor modifications. By creating short blocks and using both onboard train integrity monitoring and trackside train detection, ERTMS/ETCS Hybrid Level 3 delivers optimal performance and mitigates operational risks in degraded scenarios. The systems allows for large capacity benefits as well as possibilities for reduction of trackside train detection. This results in the possibility to increase train frequencies to meet future demand as well as the possibility to reduce track unavailability significantly. The balance between capacity and reduction of trackside train detection will be made by ProRail project specific as the balance can differ from corridor to corridor.

Altogether, ERTMS/ETCS Hybrid Level 3 offers a capacity improvement and a reduction of track assets and unavailability compared to both NS'54/ATB-EG and ERTMS/ETCS Level 2.

Samenvatting

De combinatie van het Nederlandse seinstelsel NS’54 en het treinbeveiligingssysteem ATB-EG functioneert naar behoren, maar heeft enkele nadelen. De systemen zijn relatief oud en componenten zullen op termijn moeten worden vervangen. Het bestaande systeem kent geen volledige remcurve-bewaking en de snelheidsbewaking is gelimiteerd tot een vijftal stappen. Bovendien zit het Nederlandse spoorwegnetwerk vrijwel op de capaciteitslimiet van de huidige beveiliging. De voorspelde groei van het aantal toekomstige treinreizigers kan daardoor niet worden gefaciliteerd met extra treinbewegingen.

Vanaf de jaren ’90 wordt in Europa gewerkt aan de ontwikkeling en uitrol van een nieuw treinbeveilings-systeem: het European Rail Traffic Management System (ERTMS). ERTMS bestaat uit drie onderdelen: seingeving en treinbeïnvloeding via het European Train Control System (ETCS), een rail-specifiek radiocommunicatie protocol (GSM-R) en een standaard voor railverkeersleiding, European Traffic Management Layer (ETML). Vanwege verbeterde interoperabiliteit en veiligheid heeft Europa het gebruik van ERTMS/ETCS verplicht gesteld op enkele internationale corridors. Daarnaast kan ERTMS/ETCS ook voordelen bieden op het gebied van snelheid, capaciteit en/of betrouwbaarheid van het railsysteem.

Vanwege de Nederlandse vervangingsopgave ten aanzien van NS’54 en ATB-EG alsmede de Europese verplichting voor de aanleg van ERTMS heeft de overheid in 2014 besloten tot de aanleg van ERTMS/ETCS Level 2 op diverse lijnen van het hoofdrailnetwerk. De techniek van ERTMS/ETCS Level 3 biedt meer capaciteit en elimineert de baangebonden treindetectie. Echter verhoogt dit systeem de druk op het materieel, de overgebleven baangebonden componenten en de operationele processen. Om veilig spoorgebruik te kunnen waarborgen moet van elke trein de compleetheid aangetoond worden en moet de baan op elk moment op de hoogte zijn van de locatie van alle treinen. Tot op heden bestaat er nog geen praktische oplossing om een veilige, betrouwbare en robuuste ERTMS/ETCS Level 3 implementatie mogelijk te maken. Om de tekortkomingen te mitigeren is het treinbeveiligingsconcept ERTMS/ETCS Hybrid Level 3 ontwikkeld (Furness, van Houten, Arenas & Bartholomeus, 2017). Dit concept integreert de treinposities, meldingen van compleetheid en de meldingen van de baangebonden treindetectie.

Het concept van ERTMS/ETCS Hybrid Level 3 is nog relatief nieuw en er is nog geen grondig onderzoek verricht naar de impact op spoorcapaciteit en de mogelijkheden tot reductie van baangebonden treindetectie. De onderzoeksvraag van deze masterscriptie luidt dan ook:

“Wat is de bijdrage van ERTMS/ETCS Hybrid Level 3 ten opzichte van ERTMS/ETCS Level 2 en NS’54/ATB-EG voor het Nederlandse spoornetwerk, ten aanzien van een capaciteitstoename en de mogelijkheid tot het reduceren van baangebonden componenten?”

Deze onderzoeksvraag wordt beantwoord door middel van het ontwerpen en modelleren van de infrastructurele systemen en het simuleren van de dienstregeling op de spoorcorridor Utrecht – Den Bosch. Deze corridor heeft relevante karakteristieken voor een goede vergelijking, waaronder een gemixt treinbeeld en een hoge spoorbezetting.

Implementatie van ERTMS/ETCS Hybrid Level 3
Het principe van ERTMS/ETCS Hybrid Level 3 met virtuele blokken komt overeen met de operationele principe van ERTMS/ETCS Level 2. Nieuw aan het concept is de vrijgave van infrastructuur op basis van positierapporten en bevestiging van de compleetheid van de trein. Specifieke baangebonden elementen zoals steile hellingen, geïsoleerde lassen, wissels en perrons kunnen de optimale plaatsing van virtuele blokken in de weg staan. Dit resulteert niet in veiligheidsrisico’s maar kan wel operationele risico’s met zich meebrengen die het treinverkeer hinderen. Oplossingen hiervoor kunnen gezocht worden in de verkeersleidingssystemen. Hierbij kan gedacht worden aan doorstromingsafhankelijke autorisaties, treintype-afhankelijke autorisaties of hergebruik van bestaande processen en componenten.

Voor dit onderzoek zijn vijf varianten van de infrastructuur gemodelleerd: (1) NS’54/ATB-EG, de bestaande systemen, (2) ERTMS/ETCS Level 2 op basis van de bestaande blokindeling, (3) een variant van ERTMS/ETCS Hybrid Level 3 met virtuele blokken van ca. 500m en de bestaande baangebonden treindetectie, (4) een variant van ERTMS/ETCS Hybrid Level 3 met virtuele blokken tot ca. 100m lengte en de bestaande baangebonden treindetectie en (5) een variant van ERTMS/ETCS Hybrid Level 3 met

korte virtuele blokken van minimaal ca. 100m lengte waarin de baangebonden treindetectie tot het minimum is gereduceerd.

Capaciteitsbeoordeling & prestaties

De spoorcapaciteit van de verschillende varianten wordt beoordeeld op basis van de methode van gecomprimeerde dienstregelingen (UIC Leaflet 406). Tabel B.1 laat zien wat de bezetting van de infrastructuur en de spoorcapaciteit (inclusief een buffer van 60s tussen alle treinen) is voor de verschillende varianten. Onder ERTMS/ETCS Hybrid Level 3 met kleine virtuele blokken en alle bestaande baangebonden treindetectie zakt de infrastructuur bezetting van 84,0% naar 66,7%. Als de baangebonden treindetectie tot het minimum wordt gereduceerd, komt de bezetting uit op 71,7%. Dit is nog altijd een gunstiger bezettingsgraad dan de ERTMS/ETCS Level 2 implementatie. Elke implementatie van ERTMS/ETCS resulteert in een bezettingsgraad lager dan 75% en voldoet daarmee aan de richtlijnen uit UIC Leaflet 406 voor wat betreft de maximale bezettingsgraad.

Tabel B.1 | Infrastructuurbezetting en capaciteitsbenutting, dienstregeling 2019

		Infrastructuur bezetting	Benodigde buffer	Capaciteits-benutting
NS'54/ATB-EG		84,0%	720 s	104,0%
ERTMS/ETCS L2		74,3%	600 s	90,9%
ERTMS/ETCS HL3	Virtuele blokken van 500m & bestaande baangebonden treindetectie	70,4%	606 s	87,2%
ERTMS/ETCS HL3	Virtuele blokken tot 100m, bestaande baangebonden treindetectie	66,7%	564 s	82,4%
ERTMS/ETCS HL3	Virtuele blokken tot 100m, gereduceerde baangebonden treindetectie	71,7%	616 s	88,8%

De vijf varianten zijn vervolgens geanalyseerd voor de gevoeligheid voor veranderingen in het remmodel. Door de geïntegreerde ETCS-correctiefactoren te variëren voor zowel gamma-treinen (treinen met een vaste samenstelling en een bekende remvertraging) als voor lambda-treinen (treinen met een wisselende samenstelling en een bekend rempercentage) is deze gevoeligheid getest. Variatie van de parameter K_dry voor gamma-treinen resulteert in een verandering van de minimale rijtijd van slechts enkele seconden. De infrastructuurbezetting varieert tot maximaal 0,5% afwijking. De parameters voor gamma-treinen Kr_int (treinlengte afhankelijke correctie) en Kv_int (snelheidsafhankelijke correctie) leiden tot kleine afwijkingen in de rijtijd en infrastructuurbezetting. De rijtijden variëren maximaal 7 seconden, de infrastructuurbezetting wijkt tot 0,8% af. De correctie op de rem-opbouwtijd van lambda-treinen heeft meer impact: de rijtijd wijkt tot 15 seconden af, terwijl de infrastructuurbezettingsgraad tot 1% afwijkt.

Om het oplossend vermogen van de verschillende implementaties te beoordelen zijn een verstoring van 10 en een verstoring van 30 minuten gemodelleerd. Door de korte virtuele blokken en daardoor de mogelijkheid op korte afstand van elkaar te volgen kan ERTMS/ETCS Hybrid Level 3 verstoringen tot 42% sneller oplossen. De totale opgelopen vertragingen kunnen tot bijna 40% worden beperkt in vergelijking met NS'54/ATB-EG.

De korte virtuele blokken in combinatie met vrijgave van infrastructuur op basis van positie-verklaringen en bevestiging van de compleetheid van de treinen van ERTMS/ETCS Hybrid Level 3 leiden tot een verkorting van de opvolgtijden tot ca. 1 minuut ten opzichte van ERTMS/ETCS Level 2 en NS'54/ATB-EG. Deze kortere opvolgtijden en de capaciteitsvoordelen van ERTMS/ETCS Hybrid Level 3 kunnen worden gebruikt om de snelheden te verhogen, de heterogeniteit te verhogen, het verbeteren van de stabiliteit van de dienstuitvoering en/of het verhogen van de treinfrequenties. Met het oog op de verwachte reizigersgroei is in deze studie onderzocht of een 7^{e} en 8^{e} Intercity per uur kan worden ingepast op het baanvak. De resultaten zijn toegevoegd in Tabel B.2. Alhoewel drie van de vier ERTMS/ETCS implementaties leiden tot een bezettingsgraad hoger dan 75% en een capaciteitsbenutting van meer dan 100%, betekent dit niet dat uitvoering van een dienstregeling met een 7^{e} en 8^{e} Intercity onmogelijk is. Door het uitbuigen van het de treinpaden kan dit worden bewerkstelligt. Dit is ook het geval in de huidige dienstregeling onder NS'54/ATB-EG. Deze maatregel gaat ten koste van de minimale rijtijd van de treinen, maar wordt door de snelheidsafhankelijke remcurve van ERTMS/ETCS gemitigeerd.

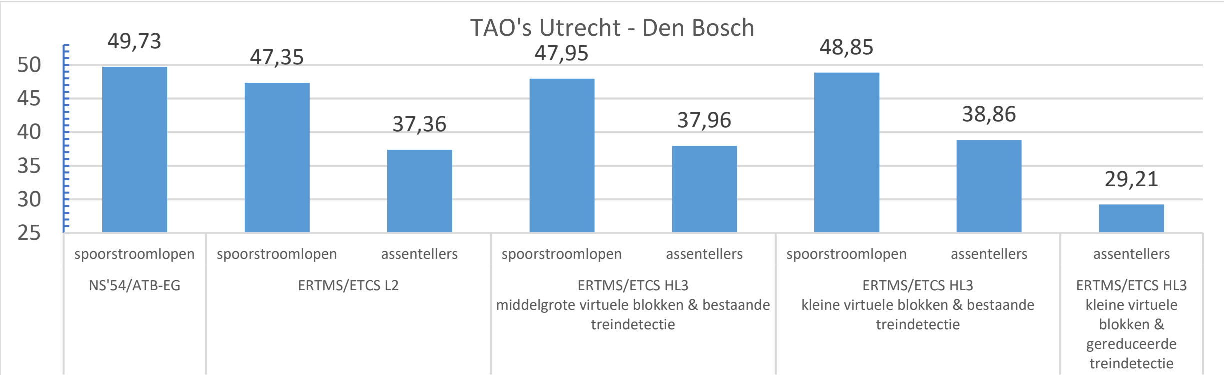
Tabel B.2 | Infrastructuurbezetting en capaciteitsbenutting, aangepaste dienstregeling met extra treinen

		Infrastructuur bezetting	Benodigde buffer	Capaciteits-benutting
ERTMS/ETCS L2		82,6%	840 s	105,9%
ERTMS/ETCS HL3	Virtuele blokken van 500m & bestaande baangebonden treindetectie	77,6%	840 s	100,9%
ERTMS/ETCS HL3	Virtuele blokken tot 100m, bestaande baangebonden treindetectie	73,1%	840 s	96,4%
ERTMS/ETCS HL3	Virtuele blokken tot 100m, gereduceerde baangebonden treindetectie	79,1%	840 s	102,4%

Reductie van baangebonden componenten
De impact van verandering aan baangebonden componenten wordt beoordeeld aan de hand van de te verwachten (on)beschikbaarheid van het systeem. In 2018 kwamen op het gehele Nederlandse spoornetwerk meer dan 10.000 gevallen van een Treindienst Aantastende Onregelmatigheid (TAO) voor. 2.198 van deze TAO's zijn gerelateerd aan het seinwezen en de treinbeveiligingssystemen, waarvan 78,6% een technische oorzaak had of werd veroorzaakt door een procesfout. TAO's met deze typen oorzaken kunnen worden beïnvloed en hadden moeten worden voorkomen door de infrastructuurmanager.

Door het veranderen van het type baangebonden treindetectie van GRS spoorstroomlopen naar assentellers kan de onbeschikbaarheid op de corridor Utrecht – Den Bosch met circa 10 TAO's per jaar afnemen. Dit is een verbetering van circa 20% in vergelijking met spoorstroomlopen. De implementatie van ERTMS/ETCS Level 2 vergeleken met NS'54/ATB-EG levert een reductie van circa 5% onbeschikbaarheid op. De impact van een toename van het aantal virtuele blokken is onbekend. Aangenomen is dat dit leidt tot een toename van de onbeschikbaarheid. Dit is een conservatieve aanpak, aangezien het feitelijk alleen een aanpassing van de software configuratie betreft.

Het reduceren van de baangebonden treindetectie impliceert de overgang van spoorstroomlopen naar assentellers, gezien de beperkingen in sectielengte bij spoorstroomlopen. Deze ERTMS/ETCS Hybrid Level 3 oplossing resulteert in een afname van meer dan 40% onbeschikbaarheid in vergelijking met NS'54/ATB-EG en een afname van meer dan 20% onbeschikbaarheid ten opzichte van ERTMS/ETCS Level 2 met assentellers. Figuur B.1 presenteert de te verwachten jaarlijkse TAO's uit de categorie Seinwezen & Treinbeveiligingssystemen voor de corridor Utrecht – Den Bosch.



Figuur B.1 | Verwacht aantal jaarlijkse TAO's gerelateerd aan het seinwezen en treinbeveiling, Utrecht – Den Bosch

Conclusies
ERTMS/ETCS Hybrid Level 3 is een nieuw en veelbelovend treinbeveiligingssysteem. Het past vrijwel naadloos in de geldende ontwerpvoorschriften ERTMS. De korte virtuele blokken in combinatie met rapportage van treinpositie en compleetheid en de baangebonden treindetectie resulteert in hoge prestaties en vermindert de impact van storingen aan trein en infrastructuur. Dit biedt de mogelijkheid om de treinfrequentie aan te passen aan de voorspelde reizigersgroei en tegelijkertijd de onbeschikbaarheid van de infrastructuur significant te verminderen. Het is aan ProRail om de precieze balans tussen capaciteitsgroei en reductie van baangebonden treindetectie op projectbasis te bepalen. De balans kan verschillen van corridor tot corridor.

ERTMS/ETCS Hybrid Level 3 levert een verbetering van de spoorcapaciteit en vermindering van baangebonden treindetectie en onbeschikbaarheid ten opzichte van zowel NS'54/ATB-EG alsmede ERTMS/ETCS Level 2.

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Glossary

A	Brake deceleration of train
ATB-EG	Automatische Trein Beïnvloeding Eerste Generatie, Dutch legacy Automatic Train Protection system
ATB Vv	Automatische Trein Beïnvloeding Verbeterde versie, improved Dutch ATP-system
ATP	Automatic Train Protection system
ATO	Automatic Train Operation
BG	Balisegroup: set of eurobalises for static transmission of trackside data and positioning referencing
CL	Confidence Level of the ETCS braking model
D_bec	Distance compensation in the ETCS braking model
DMI	Driver Machine Interface in the rolling stock
EBD-curve	Emergency Brake Deceleration braking-curve in the ETCS braking model
EBI	Emergency Brake Intervention (limit)
ED-brake	Electrodynamic brake of rolling stock
EoA	End of Authority
ERA	European Railway Agency
ERTMS	European Rail Traffic Management System, consisting of subsystems ETCS, GSM-R & ETML
ETCS	European Train Control System, part of ERTMS
ETML	European Traffic Management Layer, part of ERTMS
EVC	European Vital Computer, onboard system controlling movement authorities
G	Rolling stock brake setting for freight trains. Slow brake build-up and brake release
GRS	Train detection system based on track circuits, developed by General Railway Systems
GSM-R	International standard for wireless railway communication, part of ERTMS
HL3	ERTMS/ETCS Hybrid Level 3
I-curve	Indication braking-curve in the ETCS braking model
IC	Intercity
IM	Infrastructure Manager
IXL	Interlockings
K_dry	Integrated correction factor for the EBD-performance on dry rails
K_wet	Integrated correction factor for the EBD-performance on wet rails
Kr_int	Integrated correction factor to the EBD-performance, based on train length
Kt_int	Integrated correction factor to the brake build-up time
Kv_int	Integrated correction factor to the EBD-performance, based on train speed
L2	ERTMS/ETCS Level 2
L3	ERTMS/ETCS Level 3
L/H	Additional safety and TC regime for heavy freight trains on steep slopes for bridges
λ	Lambda, the braked weight percentage of lambda trains. Lambda trains require the use of the conversion model to calculate deceleration values
LoA	Limit of Authority
MA	Movement Authority
MB	Moving Blocks
Mg-brake	Electromagnetic rail brake of rolling stock
NS	Nederlandse Spoorwegen, main Dutch railway undertaking
NS'54	Dutch Legacy signalling system, seinstelsel 1955
NV	National Values
OBE-drawing	Overzicht Baan en Emplacement, schematic drawings of the track layout and components
OVS	Ontwerpvoorschriften, Dutch railway Engineering Rules

P	Rolling stock brake setting for passenger trains. Fast brake build-up and brake release
P-curve	Permitted braking-curve in the ETCS braking model
RLN	Richtlijn, directive
RU	Railway Undertaking, operator
SBI	Service Brake Intervention limit
SGM	StadsGewestelijk Materieel, old type of rolling stock for Sprinter-services
SLT	Sprinter Light Train, common type of rolling stock for Sprinter-services
SMB	Stop Marker Board
SvL	Supervised Location
T_be	Brake build-up time in the ETCS braking model
T_traction	Traction cut-off time in the ETCS braking model
TAO	Treindienst Aantastende Onregelmatigheid, English: TDI
TC	Traffic Control
TDI	Train Depleting Irregularity, Dutch: TAO
TIMS	Train Integrity Monitoring System
TTD	Trackside train detection, GRS track circuits or axle counters
UIC	Union Internationale des Chemins de Fer, the international union of railways
V_bec	Speed build-up compensation in the ETCS braking model
VIRM	Verlengd Inter Regio Materieel, common type of rolling stock for IC-services
VPT	Vervoer Per Trein, information and communication systems for TC
VSS	Virtual subsection
W-curve	Warning braking-curve in the ETCS braking model
X/G	Additional safety and TC regime for trains near steep slopes in tunnels

1. Introduction

Block signalling and automatic train protection are two of the railway safety systems to control the risk of train accidents. The existing Dutch block signalling system NS’54 in combination with the automatic train protection (ATP) system Automatische TreinBeïnvloeding Eerste Generatie (ATB-EG) on the main lines is functioning well, but this combination has some drawbacks. Both systems have been designed more than 60 years ago with proven technology. Components are old and will have to be replaced in the future. The speed supervision functionality of ATB-EG is limited to only five speed steps and full brake supervision is lacking.

Moreover, the capacity of the Dutch railway network is almost fully used, but the number of train passengers and the amount of rail-transported freight is still growing rapidly. The ambitions of the national and regional governments, the operators and ProRail to facilitate this growth are combined in OV Toekomstbeeld 2040 / ‘Future of Public Transport 2040’ (Programma Toekomstbeeld OV, 2019). Infrastructure related solutions to facilitate this growth are thought to be a new safety system (ERTMS/ETCS), Automatic Train Operation (ATO), increased voltage of the catenary system (3kV) and unbundling of trains (ProRail, 2019a).

1.1. European Rail Traffic Management System

The European Rail Traffic Management System (ERTMS) is proposed to be the new standard European safety system. Train control is included in the European Train Control System (ETCS). Back in 2014, the Dutch government decided to invest in ERTMS/ETCS Level 2 (L2): Seven main line corridors should be upgraded to ERTMS/ETCS L2 technology by 2030.

The integrated cab signalling and automatic train protection system offers benefits in the form of interoperability, increased safety, speed, capacity and/or reliability over the legacy NS’54 block signalling system and the existing automatic train protection system ATB-EG. To fully benefit from all opportunities that ERTMS/ETCS L2 offers, corridors have to be divided in short block sections, requiring a substantial amount of trackside train detection.

The concept of ERTMS/ETCS Level 3 (L3) allows for even more capacity while eliminating trackside train detection (TTD). The main advantages of ERTMS/ETCS L3 over ERTMS/ETCS L2 are the increased capacity by further reduced headways, reduced cost by removing trackside train detection and an improved infrastructure reliability, as the amount of equipment that could possibly break down is reduced. Both ERTMS/ETCS L2 and ERTMS/ETCS L3 increase railway safety and partly facilitate a further growth of the railway capacity.

1.2. Problem description

ERTM/ETCS L3 has some disadvantages over ERTMS/ETCS L2 (Furness, 2017). The trackside signalling system needs to know the locations of all trains within its area at any given time and it needs to be sure that all trains are integer. Not knowing the location or integrity of a train directly leads to a deadlock: the system is unable to safely release infrastructure because of the absence of trackside train detection.

ERTMS/ETCS L3 sets requirements to the remaining track side equipment as well. The trackside signalling system is linking the train movements to the infrastructure occupation at any given time. The radio connection via GSM-R between track and train should be available for all trains at any given time. A big issue is the recovery of the trackside signalling system from an (un)intentional shutdown. The location of the trains on the tracks is completely unclear with ERTMS/ETCS L3 technology when trains are not reporting and the trackside signalling system cannot supervise the tracks safely until the locations of all trains is known again. Last but not least is the issue of moving non-reporting trains outside the original reserved authorisation. The trackside signalling system is completely blind for those trains. The tracks might have to be swept manually. This requires cumbersome operational procedures for safety reasons.

To summarise, ERTMS/ETCS L3 sets a high demand on both track and train:

- Each train needs to be equipped with a positive Train Integrity Monitoring System (TIMS), no tolerance accepted;
- Communication between track and train relies for 100% on GSM-R, to transmit train integrity, train position and Movement Authorities (MAs);
- The trackside signalling system needs to be available at any time and needs to know the characteristics (position and integrity) of all trains. Cumbersome operational procedures are required for sweeping sections in case of (un)intentional recovery of the trackside signalling system and moving non-reporting trains;
- Accuracy of position reports needs to be very high to prevent locks of critical infrastructure, while it is physically free.

These issues need to be addressed before ERTMS/ETCS L3 can be introduced as a safety system on the European railway network. Critically, a proven and standardized off-the-shelf solution for train integrity monitoring is not readily available, but solutions for monitoring train integrity are being developed and are already in use outside Europe. Therefore, the proven technique of ERTMS/ETCS L2 was thought to be the ERTMS solution for the future.

However, to overcome the reported issues of ERTMS/ETCS L3 technology a solution is available: a Hybrid Level 3 (HL3) signalling system (Furness, 2017). Several implementations of this hybrid ERTMS/ETCS L3 can be thought of: a hybrid version of L3 with fixed virtual subsections (VSS) could be introduced with limited remaining trackside train detection of ERTMS/ETCS L2 or a hybrid version of ERTMS/ETCS L3 with moving blocks (MB) and limited remaining trackside train detection can be introduced.

The concept of ERTMS/ETCS HL3 offers most of the benefits of ERTMS/ETCS L3: a higher capacity and lower asset cost by reducing trackside train detection compared to ERTMS/ETCS L2 technology. The four challenges of ERTMS/ETCS L3 are dealt with by leaving limited trackside train detection in place. Trains without position report, unknown integrity status, loss of GSM-R connection or failure of the trackside signalling system are not completely lost and can be dealt with by the ERTMS/ETCS HL3 system (ERTMS User Group, 2018).

Real-life tests of ERTMS/ETCS L3 and HL3 have been conducted over the past few years in the Netherlands (SpoorPro, 2017), England (ENIF, 2018) and Germany (Deutsche Bahn, 2018). The first test in Lelystad back in 2013 was a collaboration between ProRail, Arcadis, Alstom and Bombardier. The test in England was a collaboration between Network Rail and ProRail. In Germany, Deutsche Bahn conducted a ERTMS/ETCS L3 test at the 'Living Lab' near Annaberg.

1.3. Objective

This leads to the objective of this master thesis. Despite real-life tests and proof of concept, the effects of the ERTMS/ETCS HL3 signalling system on track capacity and asset reduction for the Dutch railway network are not yet fully quantified.

The objective of this thesis is to investigate the impacts of ERTMS/ETCS HL3 and advantages in terms of capacity consumption and asset costs with respect to ERTMS/ETCS L2 and NS'54/ATB-EG for the Dutch railway network.

1.4. Research questions

The main research question for this master thesis is:

"What is the contribution of ERTMS/ETCS Hybrid Level 3 over ERTMS/ETCS Level 2 and the NS'54/ATB-EG legacy signalling system to the Dutch railway system in terms of capacity increase and reduction of trackside equipment?"

To obtain the objectives of this thesis, the following set of sub-questions has to be answered:

1. What are the theoretical advantages in terms of capacity and trackside equipment reduction of ERTMS/ETCS Hybrid Level 3 over ERTMS/ETCS Level 2 and NS'54/ATB-EG?
2. How can ERTMS/ETCS Hybrid Level 3 be implemented on the Dutch railway network in terms of infrastructure and operations according to the Engineering Rules ERTMS, or how should the Engineer Rules ERTMS be adjusted to match the infrastructural and operational requirements for ERTMS/ETCS Hybrid Level 3 implementation?
3. What is the impact of ERTMS/ETCS Hybrid Level 3 on the capacity consumption of the Dutch railway network and how is this affected by non-integer trains?
4. What is the impact from ERTMS/ETCS Hybrid Level 3 on the signalling system by reducing trackside equipment along the Dutch railway network?

1.5. Methodology

This master thesis analyses potential impacts of a ERTMS/ETCS HL3 implementation on the Dutch railway network. On one hand, it will investigate the effects of ERTMS/ETCS HL3 on the capacity consumption. On the other hand, it will assess a possible reduction of trackside train detection whilst enhancing track availability.

To assess the effects of ERTMS/ETCS HL3 over ERTMS/ETCS L2 and the legacy NS'54/ATB-EG system, a more extensive literature study will be the first part of this master thesis. It will outline characteristics of the different systems and their limitations. The valid engineering rules ERTMS (OVS60040) are studied to find the possibilities of implementing ERTMS/ETCS HL3 given the present regulations.

Microscopic simulation of the railway system will support the research, to answer the main research questions and the set of sub-questions. The railway planning and operations simulation programme RailSys will be used to test the ERTMS/ETCS HL3 principles, model the infrastructure and signalling systems and simulate the timetable. As simulating the complete Dutch railway network would comprise a very broad simulation, the simulation will be limited to a few representative corridors of the Dutch railway network. The selected corridors are representative in terms of track layout, intermediate stops and stations, type of railway traffic (mixed ICs, Sprinter and freight trains) and timetable. Results from the simulation are used to address the research questions and to achieve the objectives of this thesis.

The analysis of the impact of reduced trackside train detection is based on available relevant data of the reliability and availability of different infrastructure components. This data is available in-house.

1.6. Limitations

Not included in this study are the following sideways related topics:

- Quantification of traction energy reduction;
- Upgrading track sections to track speeds of 160 km/h, maximum track speeds remain as-is;
- Replacement of GSM-R by FRMCS (Future Railway Mobile Communication System);
- Satellite localisation for train localisation is not considered;
- ATO capacity benefits.

1.7. Structure of the document

Chapter 2 contains a more extensive description of the background of the problem. The why of railway signalling is explained, as well as the different signalling systems to address the safety issues. The Dutch legacy signalling system is described here, as well as the proposed European railway signalling system ERTMS/ETCS and its different implementations. The end of chapter 2 describes the proposed assessment tools for both the railway capacity and reduction of trackside train detection.

The third chapter analyses the different studies that have already been performed on the capacity effects and reduction of trackside equipment of ERTMS/ETCS L2 and (H)L3 over the legacy system NS'54/ATB-

EG. This chapter also contains an analysis of the ERTMS/ETCS brake models and couples the brake characteristics and brake models to the infrastructure occupation of trains.

Chapter 4 analyses the possibilities for the implementation of ERTMS/ETCS HL3 to the Dutch railway system, under the current engineering rules on ERTMS: OVS60040. The impact of the engineering rules on implementation has a place in this chapter as well.

Chapter 5 goes into detail of the setup of the simulation cases. It describes the tooling, corridor selection, required input for the simulation model (infrastructure, timetable and rolling stock) and output of the simulation runs. Required assumptions for modelling and simulation are included in this chapter.

The sixth chapter will examine the results of the case study on the minimum run times, the capacity assessment. The results are used to answer the third sub-question.

Chapter 7 describes the impact of the reduction of trackside equipment and the relevant components on the infrastructure (un)availability. Data of the year 2018 has been studied to come up with conclusion on the impact of an asset reduction.

Chapter 8 is the final chapter in which the research questions will be answered and where conclusions and recommendations regarding the benefits and implementation of ERTMS/ETCS HL3 find a place.

2. Background

This chapter provides relevant background information on safe and efficient railway operations, the related safety systems, in particular the block signalling systems and automatic train protection systems, and lastly an introduction of the used assessment methods for railway capacity and the reduction of trackside equipment.

2.1. Principles for safe and efficient railway operations

To ensure safe and efficient railway operations, railway systems are equipped with several safety systems on the railway track. Railway safety includes danger for passengers and freight, other traffic, personnel and the environment. A safe system is a system that is free from danger.

But how safe is safe? In the railway sector, the safety systems need to comply to Safety Integrity Level 4 (SIL4) (CENELEC, 2018). This mean that for each of the systems the probability of failure is smaller than 10^{-9} per hour. Human operations are much less safe, with failure probabilities of 10^{-3} to 10^{-1} per action.

The railway safety systems are largely based on past events. The systems aim for removing the causes of accidents, reducing the probability of occurring of accidents and reducing the consequences of accidents. Safety critical signalling systems must be fail-safe: at failures, the systems go to a safe state (e.g. when the coded track circuit of ATB-EG fails, the maximum speed a train can drive is the lowest of the supervised speeds, 40 km/h).

To reduce the risk of train accidents from collisions with other trains (rear-on, head-on and flank), at level-crossings, with external objects and people and to reduce the risk of derailment, four rail signalling principles are introduced (Theeg, 2009). The four signalling principles and the way they work are the following:

1. Exclusive authorization: Only one user (train) gets authorization to move within a certain track section;
2. Guarantee of authorization: The authorized section is locked and the authorization is maintained until it has been assured that the authorized section is no longer used;
3. Requirements for safe usage must be clear and followed: Clear and timely information, no entry without permission, and no violation of boundaries as time, speed and distance limits;
4. Guarantee of authorization monitoring: If one of the requirements is no longer met, the user has to be warned.

The four railway signalling principles can be translated into a functional description for the railway safety systems. The main functionality of the safety systems are:

- Set up a safe route for each train over the track;
- Prevent conflicting routes of other trains;
- Provide authority to the relevant train;
- Hold the safe route during the train movement;
- Supervise the train to stay within the authority;
- Release the route after train passage.

2.2. Railway safety systems

The railway safety systems that provide this functionality are the interlocking system, interacting with the track free detection, block signalling and automatic train protection systems. They are to be considered in detail in this subsection.

2.2.1. Interlockings

Interlocking (IXL) systems guarantee that a signal is released if and only if the route to the next signal is safe. The system checks if the switches are correctly set and locked, if there are no conflicting routes and whether the tracks are free before the new route is set and locked. New routes can only be set once the track has been detected free: the system uses the output of the track free detection to set or extend the routes.

Two general used interlocking systems include relay interlockings and computer interlockings. Relay interlocking have been developed since the 1920s to replace the manual lever operations of mechanical interlocking systems. Electric point operation allowed for the control of larger areas, whilst panel operation enabled the remote control over larger areas. Relay interlocking are being replaced by computer interlockings since the 1980s. Panels are replaced by computer consoles and the points and signals are now interlocked by software. Control of large areas is possible over large areas by a centralized traffic control. Several implementations of electronic interlockings are present on the Dutch network.

2.2.2. Block signalling

Block signalling systems can be seen as a simple and automatic form of interlocking systems for the open track. Blocks are used to physically separate trains on the same track from each other. The signals at the end of the blocks only have to guard against following and opposing train movements. The signals react to information from the track free detection. In general only one train is allowed to be in a certain track section. Only when that first train has left the section, a second following train can enter the block.

In general the length of a block must exceed the braking distance of a train. The braking distance depends on the initial speed and the brake rate. When a corridor handles mixed traffic, the length of a block section depends on the brake characteristics of the worst-case braking distance.

2.2.3. Track free detection

The track free detection detects whether the track is free or occupied by a train. It monitors the occupation of track sections, which are electrically insulated sections. Devices that are currently often used for track free detection are track circuits and axle counters.

The basic principle behind the track circuits lies in the electrical connection of the two rails via the wheelset of a train to short out an electrical circuit (Figure 1). This circuit is monitored by a system to detect the presence of a train on a section. Sections are separated by insulated joints to monitor the presence of rolling stock on individual sections.

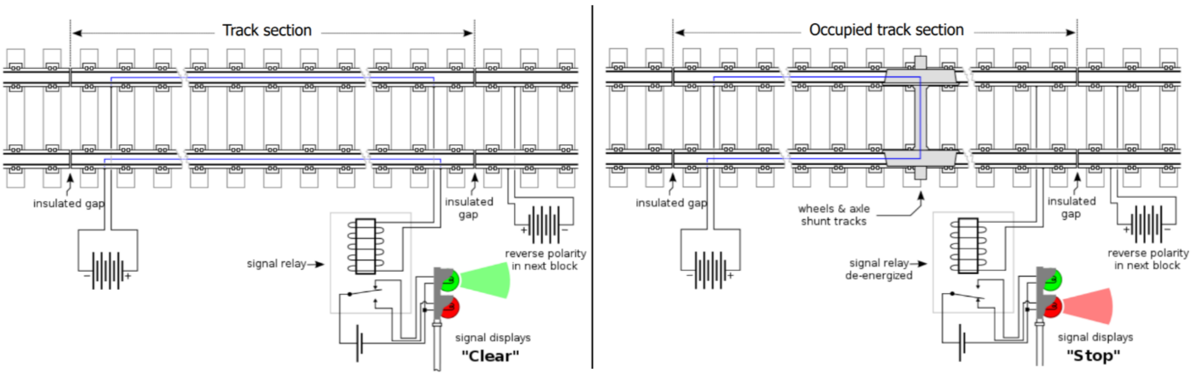

Figure 1 | Track circuits for train detection: track free and track occupied (Wikipedia, 2019a)

Axle counters are a form of spot train detection. An axle counter unit at the border of each section measures changes in the electromagnetic field (Figure 2). Each change represent the passage of an axle. This systems allows to measure the number of axles that pass and the direction in which the axles move. For each section the number of axles is evaluated by trackside equipment. When the number of axles is zero, the section is reported free; a number unequal to zero reports the section being occupied.

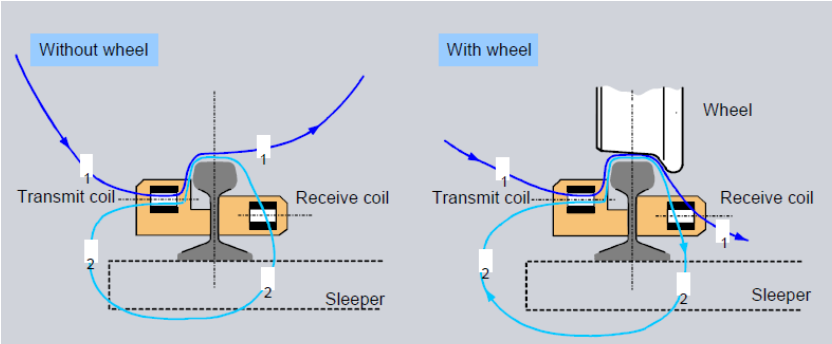

Figure 2 | Axle counters for train detection: track free and track occupied (RailSystems.net, 2019)

Onboard train localisation systems can be used additional to the existing trackside equipment or as the main train localisation system. These onboard systems include odometers, measuring position by wheel revolutions, radar (speed measurements) and GNSS (Global Navigation Satellite Systems).

2.2.4. Automatic Train Protection

Onboard ATP-systems act as a guard against train driver errors. The functionality of ATP-systems can include cab signalling, supervision and intervention as a fall back to errors. Supervision and intervention functionality of the system can be different between the available ATP-systems. Data can be transmitted intermittent or continuous.

The cab signalling functionality of ATP-systems can include audible warnings, visual repetition of trackside signals and static or dynamic speed information. The supervision functionality can include a driver ability check, driver attentiveness checks, check of signal passed at danger, overspeed supervision and braking supervision. When the supervision functionality of the system detects one or more violations, it could activate intervention functionality. This functionality can include traction switch off and service or emergency brake intervention.

To check the actions of the driver with the permits, the system has to be informed on the permits. The required data can be transmitted in two ways. Intermittent data transmission means that permits are communicated via beacons or balises to the train. Continuous data transmission can be obtained using coded track circuits, via cable loops or via a wireless radio or data communication protocol. Sensors onboard the train receive the data and send it to the ATP-system.

ATP-systems can be classified in six classes, depending on the type of data transmission and the brake and speed supervision functionality. The six classes and respective functionality and data transmission type are stated in Table 1.

Table 1 | Classification of ATP-systems

		Functionality		
		No brake supervision	Brake supervision	Dynamic speed profile
Data transmission	Intermittent	1	3	5
	Continuous	2	4	6

The main characteristics of the different classes of ATP-systems and some of the systems that comply to the different classes:

1. Attentiveness checks and train stops: e.g. Crocodile (FR/BE/LU), Signum (CH)
2. Attentiveness checks, train stops, simple check of brake application based on coded track circuits: *e.g. ATB-EG (NL), EVM (HU)*
3. Attentiveness checks, train stops, simple braking supervision: *e.g. ATB Vv (NL), ATS-P (JP), Indusi/PZB (DE)*
4. Attentiveness checks, train stops, simple braking supervision based on coded track circuits: *e.g. TVM300 (FR), ATC (JP)*
5. Dynamic speed profiles based on static and switchable balises: *e.g. ATB-NG (NL), ZUB (CH/DK) and ERTMS/ETCS Level 1*

6. Dynamic speed profiles based on coded track circuits, cable loops or radio communication: *e.g. LZB (DE/AT), ERTMS/ETCS Level 2 and ERTMS/ETCS Level 3*

2.3. Block signalling and train protection systems

This research focuses on the combination of the block signalling and ATP-systems. The current Dutch systems for main lines and the proposed future systems are described in this section.

2.3.1. Existing Dutch signalling system: NS'54 & ATB-EG

Most of the main railway lines in the Netherlands are currently equipped with the NS'54 trackside block signalling system. It is combined with the Dutch ATP-system ATB-EG onboard the trains (ProRail, 2018a). Figure 3 shows a map of the Dutch railway network and the existing ATP-systems on the corridors.

Figure 3 | Automatic Train Protection systems on the Dutch network, situation 2018 (ProRail, 2018a)

NS'54 (NS Railinfrabeheer, 2000) is the trackside signalling system which physically separates trains driving on the same track. The track is divided in physical block sections, protected by trackside signals and signs. The signals provide an authority to the driver, a grant to enter a block section. For the open track this is an automatic process that relies on the track free detection, for yards and controlled areas the authority is set by the dispatcher.

The most basic information along the track are the speed signs. The three existing signs are the local speed sign (white, square), the track speed sign (green, triangular) which allows the train driver to increase the speed to the indicated value, and the speed reduction sign (yellow, triangular) which orders the train driver to reduce the speed to the indication. More advanced indicators than signs are signals. The general principle of fixed block signalling systems is to allow a train to come to a halt before it enters an occupied block section and passes a signal at danger.

NS’54 is a 2-block 3-aspect signalling system, where each block signal shows information on up to two blocks ahead (see Figure 4). It is a progressive speed signalling system, allowing for shorter blocks by giving speed information together with an approach signal. Each signal can show three aspects: clear (green), indicating a train may pass with track speed; approach (yellow), indicating a train to reduce speed to a restricted speed indicated and prepares to stop before a red signal; stop (red), imposes to stop before the signal at danger.

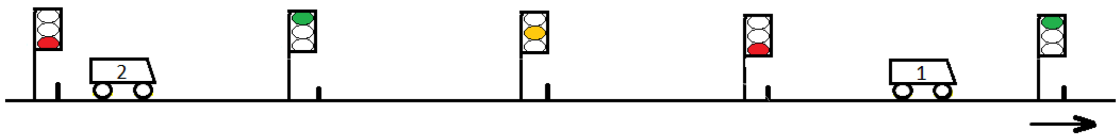

Figure 4 | NS'54 2-block 3-aspect signalling

The length of a block in the NS’54 signalling system is based on the brake performance of the worst braking train, plus a margin for the reaction time of the driver and system. The braking distance depends on the entry speed of the block section. ‘Regeling Spoorverkeer’ (Overheid, 2016) describes the maximum braking distances in which all trains should be able to come to a standstill. These maximum braking distances hold for situations with a maximum downhill slope of 5‰ .

In addition to the maximum braking distances, two additional distances for tracks equipped with ATB-EG are defined in OVS69132 (ProRail, 2014b): a time-addition for the reaction time delay of both the ATP-system and the driver, which is allowed to be at least 4,6 seconds of driving at track speed when the code changes, and an addition for the distance between the signal and the insulation joint at which the ATP-code changes. This distance should be at least 9 m and at most 15 m (ProRail, 2018b). Combination of the maximum braking distance with both additions provides the minimum corresponding block length for NS’54/ATB-EG tracks. See Table 2.

Table 2 | Minimum block length for different track speeds

Vmax [km/h]	Max. braking distance [m]	ATB-addition: Distance signal to joint	ATB-addition: Reaction time	Min. corresponding block length
Vmax ≤ 40 km/u	400 m	15 m	51 m	466 m
40 < Vmax ≤ 60 km/u	500 m	15 m	76 m	591 m
60 < Vmax ≤ 80 km/u	800 m	15 m	102 m	917 m
80 < Vmax ≤ 130 km/u	1000 m	15 m	166 m	1181 m
130 < Vmax ≤ 160 km/u	1150 m	15 m	204 m	1369 m

Shorter blocks can be used to shorten the headways. In this situation, the distance between two main signals decreases as well. Additional pre-signals will have to be added to make sure all trains are able to stop before a red signal. The braking than takes place over two or more blocks, as a continued braking action or a gradual phasing-in braking action. When the block length is sufficient for the maximum braking distance, the distant main signal acts as the pre-signal. The pre-signal orders a speed reduction by showing information of the status of the main signals ahead.

Signals can also be divided in automatic signals and manually controlled signals. Automatic signals provide the authorisation on the open track and do not require route setting by the dispatcher. Manually controlled signals are operated by the dispatcher and are protecting danger locations such as points, level crossings and station platforms. The setup time of automatic signals and manual signals is different.

The minimum distance between two main signals is 400 meter, with some exemptions. The maximum distance between two main signals is 2000 meter (ProRail, 2018a). A small example: when the follow-up times between trains requires small block sections of 400 m, the braking distance at the lowest speed (40 km/h) exceeds this block length. A pre-signal has to be used in this case to allow the trains to stop before the red signal if the allowed speed exceeds 40 km/h.

To detect the presence and position of a train on a block, trackside train detection (TTD) is used. The considered main lines are equipped with a GRS track circuit train detection system and insulated joints between track sections. (ProRail, 2018a). ATB-EG is the onboard ATP-system. The safety functions of ATB-EG include audible warming signals, visual repetition of trackside signals and continuous information on allowed speeds, as well as ability and attentiveness checks.

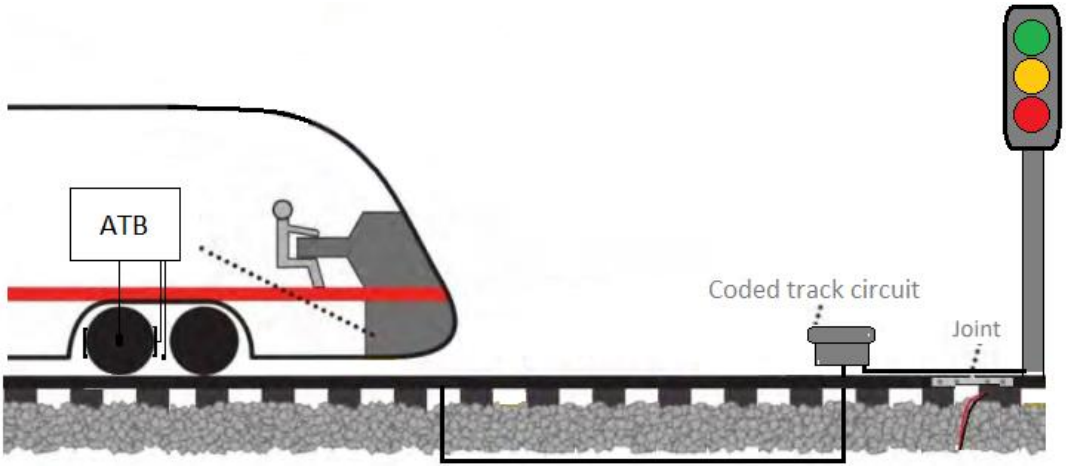

Figure 5 | NS'54/ATB-EG setup

Figure 5 shows the setup of NS'54/ATB-EG. Via continuous data transmission (coded track circuits) and the Driver Machine Interface (DMI) the driver is informed on the ruling speed limit. Five different speed steps can be transmitted: 40, 60, 80, 130 and 140 km/h. Speeds below 40 km/h are not monitored. When the allowed speed drops to a lower step, ATB-EG supervises whether the brakes are applied: however, the braking rate is not monitored. If the driver does not start braking within 2 seconds, the system will initiate an emergency brake.

Two successive trains following each other under NS'54/ATB-EG and normal operations with Red-Yellow-Green signalling and full block lengths will be separated at least 2 block lengths. This creates headways of minimum 3 km with blocks of 1500m at a speed of 130 km/h. See Figure 6.

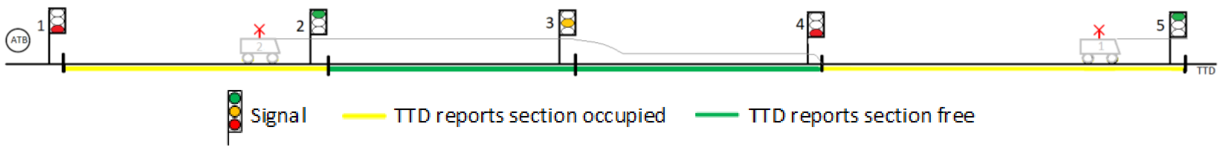

Figure 6 | Train following under NS'54/ATB-EG three aspect signalling

2.3.2. Replacing NS'54/ATB-EG

The combination of NS'54 and ATB-EG functions well, but it has some drawbacks. First, the functionality of ATB-EG is limited. The supervised speeds are limited to only five steps, corresponding to the nearest ATB-step above the permitted speed. Thus, the ATP-supervision speed and the permitted track speed are not necessarily equal. It is the responsibility of the train driver to stay below the permitted speed (Goverde, 2013).

Secondly, ATB-EG is not suitable for full brake supervision. The system can only detect whether the brakes are applied, not at what braking rate. Moreover, braking is required from the moment when a train passes an approach signal. Once the allowed speed has been met, the train should drive the remaining length of the block section at the restricted speed, while the actual speed restriction is effective from the next signal onwards. The block length is defined on the braking performance of the worst braking train. This implementation of speed and braking supervision has drawbacks in driving times. Braking actions at speeds below 40 km/h are not monitored at all (Tweede Kamer der Staten Generaal, 2012).

The lack of braking supervision in ATB-EG caused a near-accident in 2007 at Harmelen junction (Inspectie Verkeer en Waterstaat, 2008). A train driver missed a yellow signal and the audible warning signal from the ATB-EG. Still unaware of the red signal ahead, the train driver performed a light braking action, causing the ATP system not to intervene. The brake application was at such a small brake rate that the train would not be able to stop before the next (red) signal. At the moment the driver noticed he was approaching a red signal, he performed an emergency brake. Nonetheless the train passed the signal at danger with a speed of over 100 km/h, almost colliding with a freight train on the other track. Several other recent (near-)accidents as Hattemerbroek (2012) and Bilthoven (2012) partly have happened because of the lack of full brake supervision in ATB-EG.

Thirdly, most of the existing trackside equipment has been installed from the sixties onwards. Parts of the system are in use for up to 50 years. Components of the systems are to be renewed in the next years (Ministerie van Infrastructuur en Milieu, 2014a). Equipment replacement is a costly process as some components are specific for this safety system and have to be produced on special order. The dependency on track circuits for train detection is an issue as well. Especially reasonably light (diesel)-trains the trains are not always detected by the track circuits. Axle counters could solve this issue. Upgrading the signalling system to the European Rail Traffic Management System / European Train Control System (ERTMS/ETCS) is favoured over replacing components of NS'54 by the government.

2.3.3. Proposed system: ERTMS/ETCS

The European Rail Traffic Management System is proposed to be the new European standard safety system for railways. The goal of the project is to enhance cross-border interoperability by creating a single Europe-wide standard for railway signalling. The final aim of the ERTMS project is to improve the competitiveness of railways in Europe (UIC, 2018). ERTMS is composed out of three basic components:

- European Train Control System (ETCS) includes the signalling, control of movement authorities for the trains, onboard ATP-systems and the interface to the interlocking;
- GSM-R is the communication principle for both voice and data communication. Based on the public standard GSM with rail specific features, it serves the required communication between track and train;
- European Train Management Layer (ETML) involves the operational management to optimise train movements. Real-time train management, route planning and proving information to both customers and staff could be improved by ETML.

ERTMS/ETCS combines the functionality of trackside equipment (block signalling) and onboard automatic train protection. ERTMS/ETCS is available in several levels with different functionalities and offers more opportunities over NS'54/ATB. The main reasons to introduce ERTMS/ETCS in the Netherlands are the following (Ministerie van Infrastructuur en Milieu, 2014a):

First, as discussed before, the current signalling systems are old and to be renewed or replaced in the near future to guarantee availability of the infrastructure.

Secondly, ERTMS/ETCS offers higher safety standards (including dynamic braking supervision and continuous indication of movement authority to the train driver) and could lead to benefits regarding interoperability, capacity, speed and/or reliability compared to the existing track infrastructure (Ministerie van Infrastructuur en Milieu, 2014a). ERTMS/ETCS systems meet SIL4.

Moreover, the EU (European Commission, 2018) requested its member states to upgrade the safety systems of some (freight) corridors to ERTMS/ETCS by introducing Trans-European Transport Networks (TEN-t) projects. The international commitment for ERTMS/ETCS is in the light of safety and interoperability aspects. For the Dutch railway network these TEN-t projects include the 'Rhine - Alpine corridor' (Amsterdam – Utrecht – German border and Vlissingen – Rotterdam – Betuweroute – German border), the 'North Sea – Mediterranean corridor' (Amsterdam – Rotterdam – Belgian border) and the 'North Sea – Baltic Corridor' (Amsterdam – Utrecht, Utrecht – Amersfoort – German border and Utrecht – Rotterdam – Belgian border).

Some of the Dutch railway lines have already a version of ERTMS/ETCS installed, see the following list and Figure 7 (ProRail, 2018). Trains equipped with ERTMS/ETCS are backwards compatible with older baselines and releases of the track equipment.

- High Speed Line HSL-zuid (2007) Level 1 and Level 2, 2.3.0.c
- Betuweroute freight corridor (2007) Level 2, 2.3.0.d
- Havenspoorlijn (2007) Level 1, 2.3.0.d
- Amsterdam-Utrecht (2012) Level 2, 2.3.0.d
- Hanzelijn (2012) Level 2, 2.3.0.d
- Zevenaar-Zevenaar Oost (2017) Level 2, 2.3.0.d

By means of the state secretary of Infrastructure back in 2014 (Ministerie van Infrastrucuur en Milieu, 2014b), the decision for implementation of ERTMS/ETCS Level 2 on a number of mainlines in the central part of the Netherlands has been finalized. However, the geographic scope of the Dutch ERTMS programme recently changed due to new knowledge on the influence of ERTMS/ETCS and an update of the governmental decisions in July 2018. The corridors indicated in Figure 7 are currently in the scope to be upgraded to ERTMS by 2030 (Ministerie van Infrastructuur en Waterstaat, 2018):

- Kijfhoek – Roosendaal – Belgian border
- OV SAAL
- Hoofddorp – Duivendrecht
- Utrecht – Meteren
- Meteren – Eindhoven
- Eindhoven – Venlo – German border

Figure 7 | ERTMS/ETCS implementation strategy 2018 (Ministerie van Infrastructuur en Waterstaat, 2018)

2.3.3.1. Principles of ERTMS/ETCS Level 2

This subsection describes the principles of the ERTMS/ETCS L2 signalling and train protection system.

ERTMS/ETCS L2 is an integrated cab signalling and train protection system (Ministerie van Infrastructuur en Milieu, 2014c). It is a fixed block signalling system with trackside train detection, but without trackside signalling. The trackside signals are replaced by cab signalling and markerboards along the track between the different track sections. The trackside train detection is used by the trackside signalling system (for open track) and interlocking (station areas) to set safe routes. The trackside signalling system translates the routes into MAs, which are communicated via GSM-R to the train. The onboard European Vital Computer (EVC) in the train calculates the dynamic speed profile depending on the MA and the track and train characteristics. The driver is presented the dynamic speed profile on the DMI, while the system supervises both the permitted speed and allowed braking curves to be followed by the driver. This setup is visualized in Figure 8.

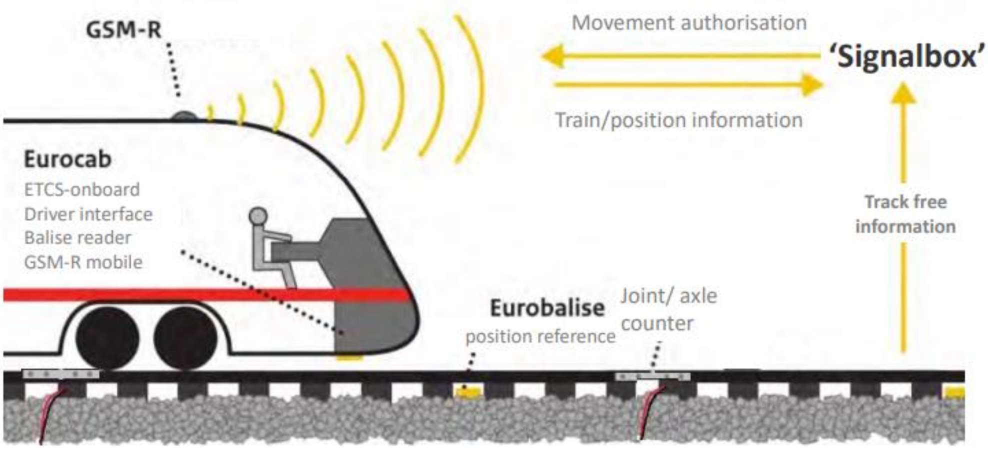

Figure 8 | ERTMS/ETCS L2 setup (Ministerie van Infrastructuur en Milieu, 2014c)

Furthermore, trains do not only receive messages via GSM-R, but they also send information back to the trackside signalling system. The train reports at regular intervals its position and speed, which are processed by the trackside signalling system into extended or new routes. These are translated in movement authorities which are sent to the train. The dynamic speed profile is updated accordingly.

The exact train position is determined by the use of trackside Eurobalises and onboard odometry. Once a train passes a group of Eurobalises, the location of the train is known. By extrapolating that location with the observed speed of the train, the position of the train is known at any moment in time. Errors in the onboard odometry, errors in the location of the Eurobalise and errors in detection of the balises lead to small errors in the position reports. The train location is therefore always known with a certain confidence interval. This interval increases in relation to the distance travelled from the last balise, where the known location was last calibrated. This principle is presented in Figure 9.

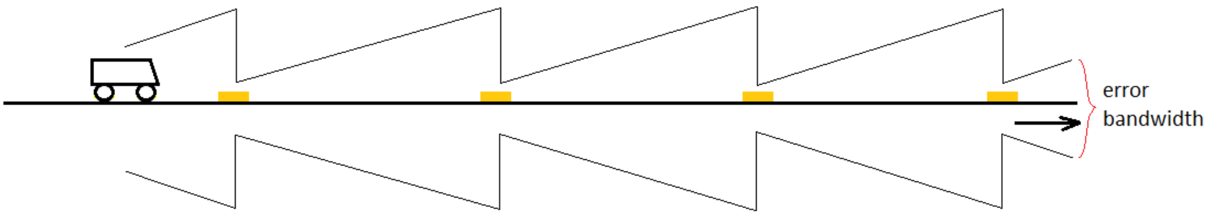

Figure 9 | Train localisation using Eurobalises and onboard odometry. Train location within confidence interval

The main advantage of ERTMS/ETCS L2 next to the interoperability aspect is the improved safety functionality. A train equipped with an ERTMS/ETCS L2 EVC has supervision on braking. The train driver is informed by the DMI when to brake and at which deceleration rate. Braking actions will occur at the end of the MA or at speed restrictions. When the drivers fails to follow the brake instructions, the EVC intervenes and the train will brake automatically. This process increases the safety by reducing the number of signals passed at danger.

The braking supervision in combination with the continuous updating of the movement authorities also lead to an increase in capacity. The driver is allowed to drive within its authority. This means that the braking curves are no longer calculated for the worst braking train, but calculated based on track and train characteristics. A train could drive at track speed for a longer period of time, when compared to ATB-EG. With the continuous updates of the movement authority, the driver can react to an extended authority immediately by accelerating to the new permitted speed, not having to hold the lower speed until the end of the block. The train following behaviour is graphically described in Figure 10.The main difference with the legacy system is the use of MA's and dynamic speed profiles for the MA.

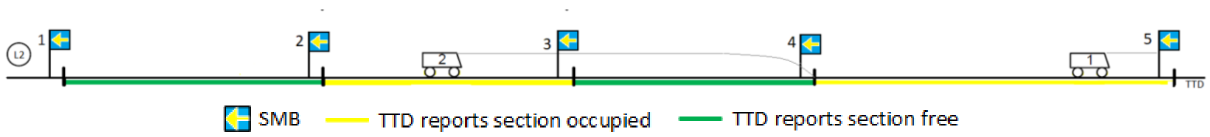

Figure 10 | Train following under ERTMS/ETCS Level 2

2.3.3.2. Principles of ERTMS/ETCS Level 3

The most advanced level of ERTMS/ETCS is ERTMS/ETCS L3 (Ministerie van Infrastructuur en Milieu, 2014c). Trains running under ERTMS/ETCS L3 conditions send a position report with the latest position, speed and information on the integrity of the train to the trackside. The difference with ERTMS/ETCS L2 is that this integrity information is actually used to calculate the location of both the safe front and safe rear end of the train. This information combined with track and train characteristics is used for the calculation of the MA for the following train by the trackside signalling system. See Figure 11.

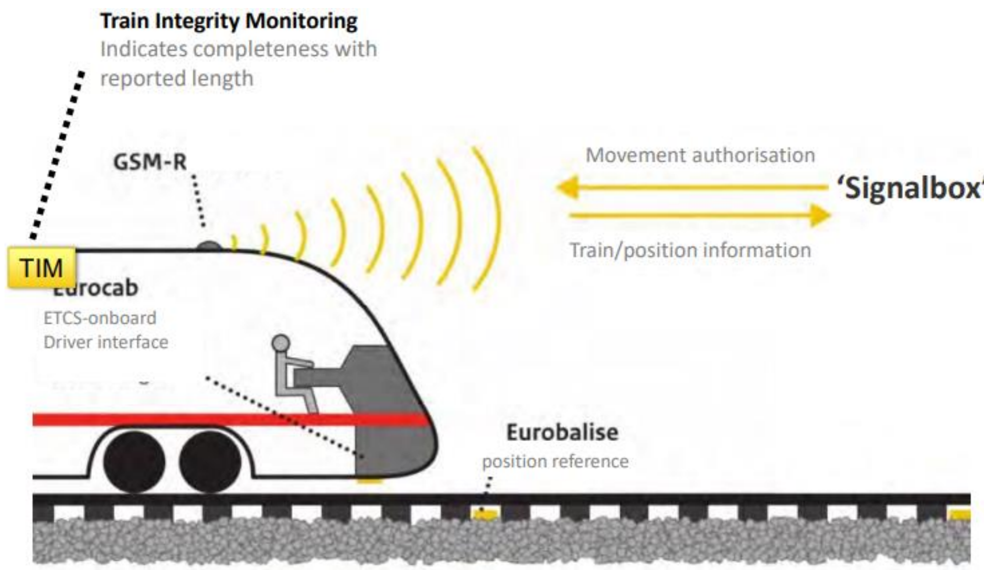

Figure 11 | ERTMS/ETCS L3 setup (Ministerie van Infrastructuur en Milieu, 2014c)

It is possible to implement ERTMS/ETCS L3 with two different approaches. The first approach introduces virtual blocks instead of the physical blocks of ERTMS/ETCS L2. The second ERTMS/ETCS L3 approach is introducing moving blocks instead of fixed virtual blocks. For both approaches, the existing trackside train detection is no longer required because the location of both the safe ends of the train are directly send to the trackside signalling system via GSM-R.

The known location of the safe front and rear end of the train are directly translated onto the virtual blocks it is occupying. The virtual block directly behind the last occupied block of the first train, can be reserved for the following train.

The main advantages of ERTMS/ETCS L3 over ERTMS/ETCS L2 are the increased capacity by reduced headways, reduced cost by removing trackside train detection and an improved infrastructure reliability, as the amount of equipment that could possibly break down is reduced. Train following behaviour under ERTMS/ETCS L3 with virtual blocks is presented in Figure 12.

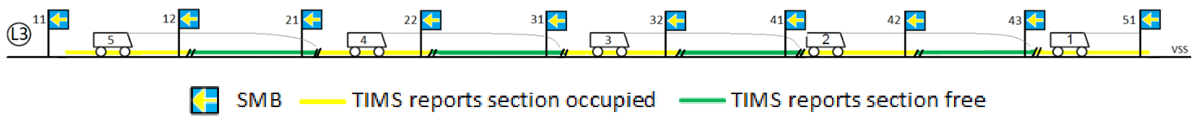

Figure 12 | Train following under ERTMS/ETCS Level 3

ERTMS/ETCS L3 has some disadvantages over ERTMS/ETCS L2 (Furness, 2017). The trackside signalling system needs to know the locations of all trains within its area at any given time and it needs to be sure that all trains are integer. Not knowing the location or integrity of a train directly leads to a deadlock: the system is unable to safely release infrastructure because of the absence of trackside train detection.

ERTMS/ETCS L3 sets requirements to the remaining track side equipment as well. The trackside signalling system links the train movements and the infrastructure occupation. The radio connection via GSM-R between track and train should be available for all trains at any given time. A big issue is the recovery from an (un)intentional shutdown of the trackside signalling system. The location of the trains on the tracks is completely unclear with ERTMS/ETCS L3 technology when trains are not reporting and the trackside signalling system cannot supervise the tracks safely until the locations of all trains is known again. Last but not least is the issue of non-reporting but moving trains under ERTMS/ETCS L3 conditions. The trackside signalling system is completely blind for those trains. The tracks might have to be swept manually. This requires cumbersome operational procedures for safety reasons.

To summarise, ERTMS/ETCS L3 sets a high demand on both track and train:

- Each train needs to be equipped with a positive TIMS, no tolerance accepted;
- Communication between track and train relies for 100% on GSM-R, to transmit train integrity, train position and MAs;
- The trackside signalling system needs to be available at any time and needs to know the characteristics (position and integrity) of all trains. Cumbersome operational procedures are required for sweeping sections in case of (un)intentional recovery of the trackside signalling system and suspected non-reporting but moving trains;
- Accuracy of position reports needs to be very high to prevent locks of critical infrastructure, while it is physically free.

These issues need to be addressed before ERTMS/ETCS L3 can be introduced as a safety system on the (European) railway network. Critically, a proven and standardized off-the-shelf solution for train integrity monitoring is not readily available, but solutions for monitoring integrity are being developed and in use outside Europe. Therefore, the proven technique of ERTMS/ETCS L2 was thought to be the ERTMS solution for the future.

2.3.4. ERTMS/ETCS Hybrid Level 3: L3 functionality with trackside train detection

To overcome the reported issues of ERTMS/ETCS L3 technology a solution is available: a hybrid version of the ERTMS/ETCS L3 signalling system (Furness, 2017). Several implementations of this hybrid ERTMS/ETCS L3 can be thought of. A hybrid version of ERTMS/ETCS L3 with fixed virtual subsections could be introduced with limited remaining trackside train detection of ERTMS/ETCS L2, or a hybrid version of ERTMS/ETCS L3 with moving blocks and limited remaining trackside train detection can be introduced.

The concept of ERTMS/ETCS HL3 offers most of the benefits of ERTMS/ETCS L3: a higher capacity and lower cost by reducing trackside train detection compared to ERTMS/ETCS L2 technology. The four challenges of ERTMS/ETCS L3 are dealt with by leaving some of the trackside train detection in place. Trains without position report, unknown integrity status, loss of GSM-R connection or failure of the trackside signalling system are not completely lost and can be dealt with (ERTMS User Group, 2018). The setup of ERTMS/ETCS HL3 is presented in Figure 13.

Two different approaches of the small headway separation between successive trains are thought of: large fixed physical block sections divided into small fixed virtual subsections and large fixed physical block sections with dynamic moving block sections for each train.

In the case of the moving block approach, the position of the block moves with the train. A position report can be send approximately every 3 seconds, currently the update frequency is about once every 5 seconds. Thus the known safe location of the rear end of a train jumps with that same frequency. At a speed of 140 km/h the jumps are approximately 200m with a 5 second position report interval. Near station areas, where speeds are generally lower, the jumps are smaller.

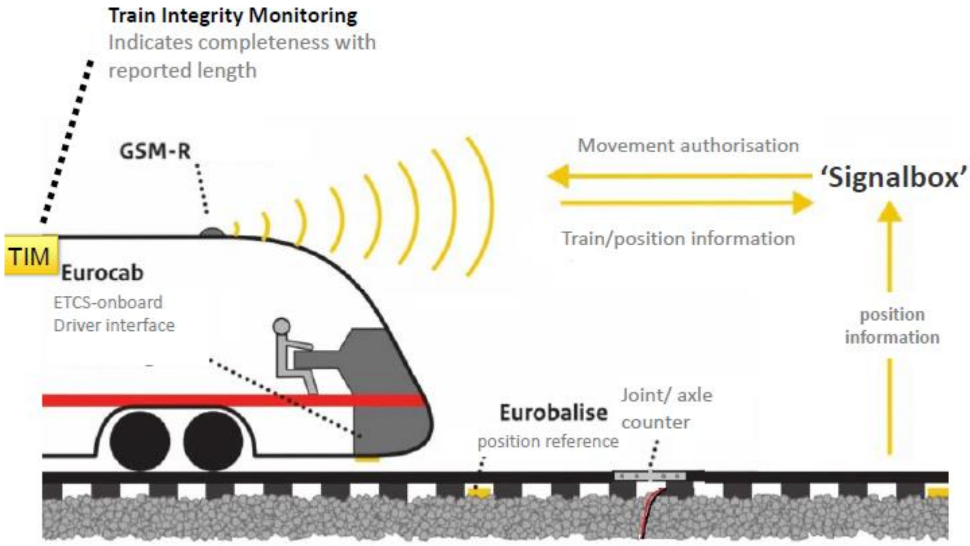

Figure 13 | ERTMS/ETCS HL3 setup

The approach with virtual subsections divides the fixed physical blocks into small virtual blocks. The size of the subsections could be aligned to the track speed, such that the jumps in the position reports coincide with the length of the VSSs. With VSSs of 200m on the open track, the performance of the VSS approach matches the performance of the MB approach. A second option is to ask the train for a position report and integrity confirmation on relevant locations. The VSS approach matches the operational procedures of ERTMS/ETCS L2, occupying and reserving block sections. The VSS approach is therefore more easily implemented than the MB approach.

Blocks containing movable infrastructure elements such as junctions and crossovers can be divided in VSS, but this is more complex for dispatching and train control. By locating trackside train detection around critical infrastructure elements, these sections can be released faster than solely relying on a new accurate position report.

The train following behaviour under ERTSM/ETCS HL3 is presented in Figure 14. The legacy system NS'54/ATB-EG and ERTMS/ETCS L2 are compared to three scenarios for ERTMS/ETCS HL3 operations. The MA for the trains are visualised as well. The scenarios considered are:

- NS'54/ATB-EG under normal operations: Train 2 has a Green, Yellow and Red signal and 2 block sections between him and train 1. Both trains are not connected directly connected to the track side equipment via a communication network;
- ERTMS/ETCS L2 under normal operations: the MA of train 2 reaches until the end of the last occupied physical block section by train 1;
- ERTMS/ETCS HL3 under normal operations: the MA of following trains reach until the end of the last occupied virtual block section by the previous train. No TTD required as long as all trains are equipped a TIMS and all trains are reporting;
- ERTMS/ETCS HL3, with train 1 (and train 3) being a non-TIMS-equipped train: the MAs of the following trains reach until the end of the last released physical block. From train 1 and 3 only the safe front end location is known. As train 1 and 3 lack a TIMS, the location of the safe rear end is unknown. For this scenario the ERTMS/ETCS HL3 system falls back on the TTD;
- ERTMS/ETCS HL3 with train 1 being a non-reporting or non-connected train: The location of both the safe front end and the safe rear end of train 1 are thus unknown. This train can drive to the end of the original MA, but does not get a new MA. The following train (train 2) gets a MA only until the end of the last released physical block. When there is no physical block in between the two trains, the MA of the second train is not extended any further. The system relies on the TTD.

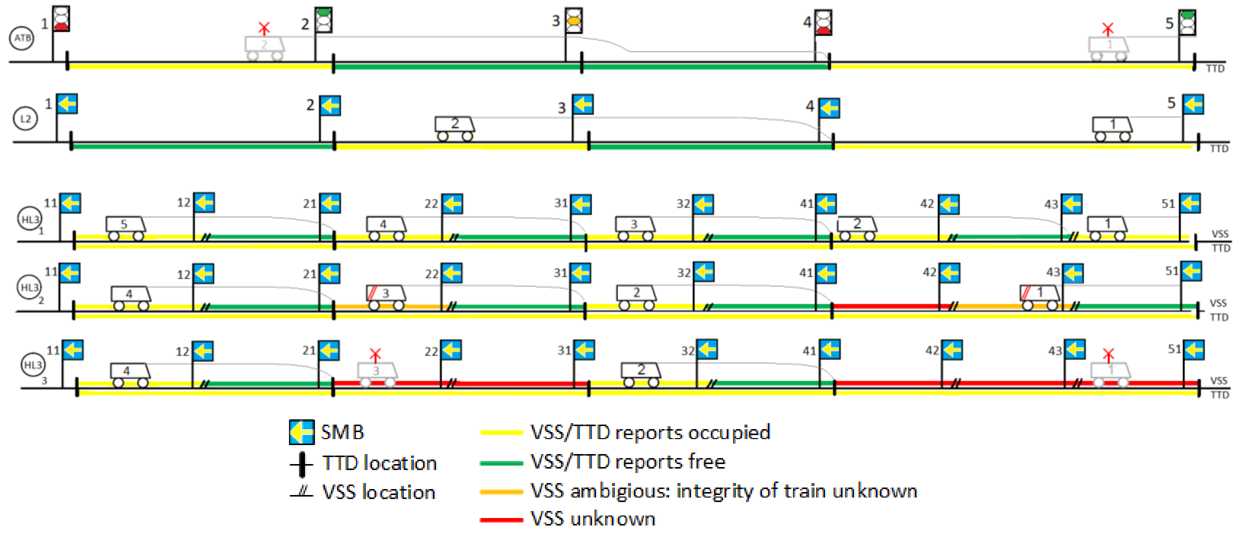

Figure 14 | Train following under ERTMS/ETCS HL3 compared to ATB-EG and ERTMS/ETCS L2

The VSSs of ERTMS/ETCS HL3 can be added additional to the trackside train detection. With a large share of TIM-equipped trains, the TTD will become of less use. Therefore, the TTD can be reduced, to create larger physical blocks with VSSs in between.

ERTMS/ETCS HL3 is a low-risk ERTMS/ETCS L3 implementation. The four challenges of ERTMS/ETCS L3 are mitigated by using existing ERTMS/ETCS L2 technology - the trackside train detection. ERTMS/ETCS HL3 could increase capacity and reduce trackside assets compared to ERTMS/ETCS L2.

Real-life tests of ERTMS/ETCS L3 and HL3 have been conducted over the past few years in the Netherlands (SpoorPro, 2017), England (ENIF, 2018) and Germany (Deutsche Bahn, 2018). The first test in Lelystad back in 2013 was a collaboration between ProRail, Arcadis, Alstom and Bombardier. The test in England was a collaboration between Network Rail and ProRail. In Germany, Deutsche Bahn conducted a ERTMS/ETCS L3 test at the 'DB Living Lab' near Annaberg.

2.4. Assessment methods

To provide an answer to the research questions, the concept of ERTMS/ETCS HL3 should be assessed on both the railway capacity and the ability to reduce trackside equipment. This subsection introduces the methods that are used in this thesis.

2.4.1. Capacity assessment: UIC Leaflet 406

In order to evaluate the capacity of a railway system, UIC Leaflet 406 (UIC, 2013a) provides a European standard for capacity assessment. Different railway systems between and within the different European countries represent different capacity needs. This could lead to misinterpretations or misunderstandings in capacity evaluation. With the approach of UIC code 406 the timetable is compressed and the train paths on a line, node or corridor are evaluated. As UIC Leaflet 406 is considered to be the standard capacity assessment method, this method is used for this thesis as well.

The general task of the infrastructure manager (IM) is to offer railway capacity to the railway undertakings (RU) to run trains. Demand from the RU and supply from the IM should match. IMs should review the capacity when the balance is off and act accordingly: plan for new infrastructure, upgrade existing railway infrastructure, improve the capacity consumption or revise the timetable.

2.4.1.1. Railway capacity

Railway capacity can be defined as the number of trains that can operate on a line or corridor during a given time period and with a fixed level of service. The capacity depends on the available infrastructure and the existing timetable. The capacity consumption represents the utilisation of infrastructure over a predefined time period. It can be expressed in two different ways. The first expression is known as the infrastructure occupation.

$$Infrastructure\ occupation\ [\%] = \frac{Infrastructure\ occupation\ time}{Predefined\ time\ period} * 100\%$$

A train path is the infrastructure required to run a train from origin to destination during a given time-period. A path is based on the technical minimum runtime with a runtime supplement on top. For stability a buffer time is inserted in between successive trains. In the Netherlands this buffer has a duration of 60 seconds (ProRail, 2018g). It is not included in the infrastructure occupation. Including the buffer between all trains in the equation results in the capacity consumption and indicates whether a timetable fits. To assess the capacity of a corridor, the infrastructure occupation and capacity consumption should be measured on a representative day, during a representative time period and with a representative timetable.

$$Capacity\ consumption\ [\%] = \frac{Infrastructure\ occupation\ time + buffer\ time}{Predefined\ time\ period} * 100\%$$

The infrastructure occupation time of a single block section is based on the blocking time theory. The total blocking time of each single block section is a sum of six separate attributes. These six attributes are also illustrated in Figure 15.

- Time for route formation: setup time
- Time for visual distance: sight and reaction time
- Time for approach section: approach time
- Journey time of occupied block: running time
- Time for clearing the block, depending on train length and speed: clearing time
- Time for route release: release time

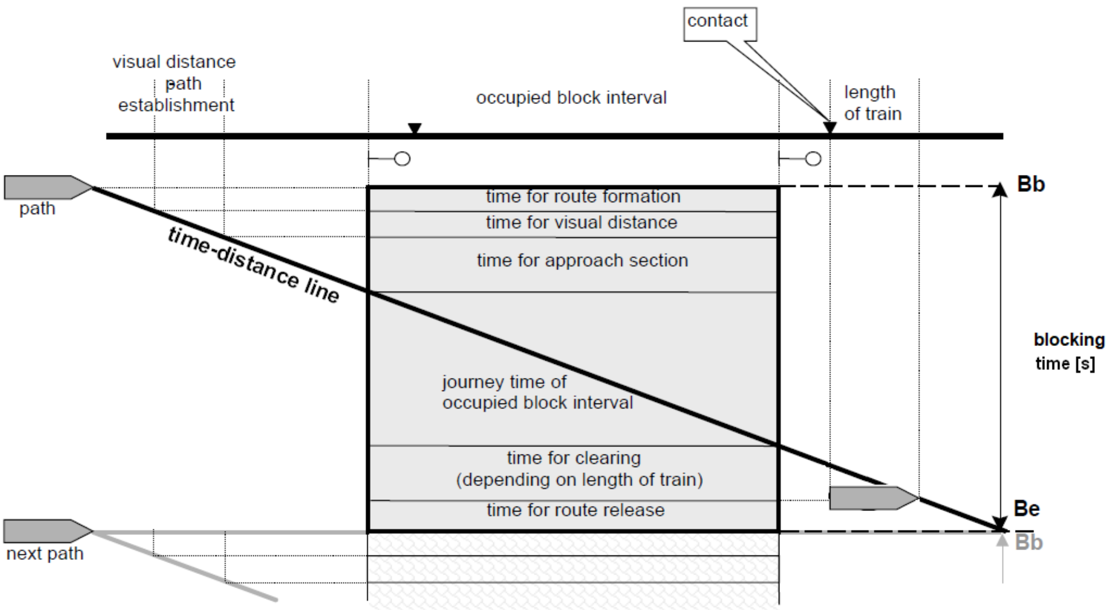

Figure 15 | Single block section – blocking time build up (UIC, 2013a)

2.4.1.2. Timetable Compression Method

Combining all successive block sections along a train path and combining all train paths over a certain time period, one obtains an overview of all train movements on a corridor during that time period (the cycle). By now compressing all train paths such that the blocking times of the individual trains touch each other, the compressed timetable is obtained. The value measured along a time scale between the first train and the moment the first train is able to run again after a full cycle, is the infrastructure occupation time. Figure 16 shows the blocking time diagram for corridor A-B-C according to the timetable before and after compression.

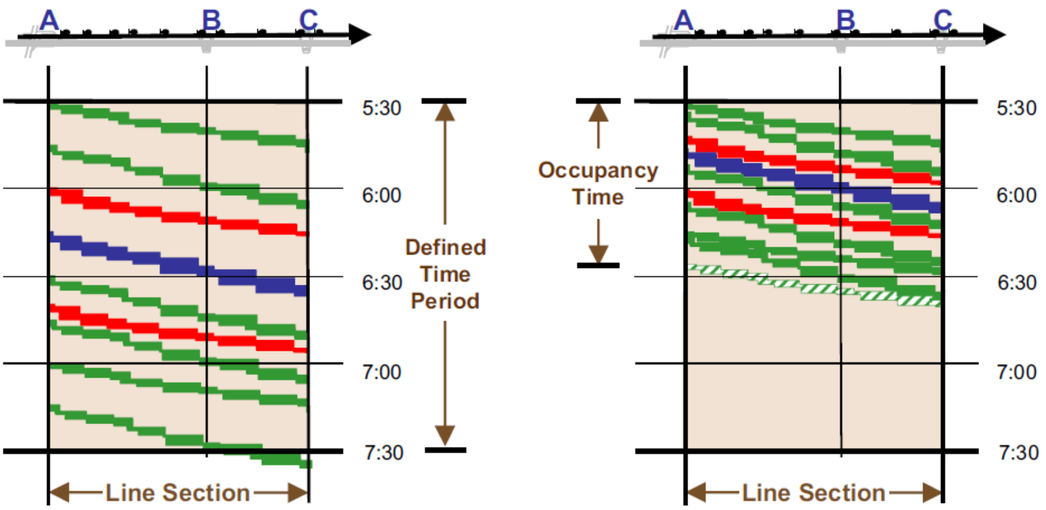

Figure 16 | Blocking time diagram, before and after compression (UIC, 2013a)

To secure a specific level of service, buffer time between successive trains has to be inserted. In the compressed timetable this could be implemented by limiting the infrastructure occupation to a maximum percentage of the available time. Leaflet 406 (UIC, 2013) provides an indication of the occupancy time rates and additional time rates according to the main timetable characteristics. For mixed traffic lines the proposed infrastructure occupation rate is 75%. Table 3 includes the proposed infrastructure occupation rates for all type of lines.

Table 3 | Proposed infrastructure occupation rates (UIC, 2013)

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

Infrastructure occupation values below the proposed occupation rate represents available capacity and thus potential for additional train paths on the corridor. The available capacity could also be used for creating resilience by inserting larger buffer times or reserve capacity for shunting movements, coupling and uncoupling, crossing traffic and/or infrastructure maintenance. Infrastructure occupation values exceeding the proposed rates represent a possible bottleneck, lowering the level of service, and should be subject to infrastructural works or timetable improvement measures. However, this is a theoretical approach and the application of this theory differs from IM to IM.

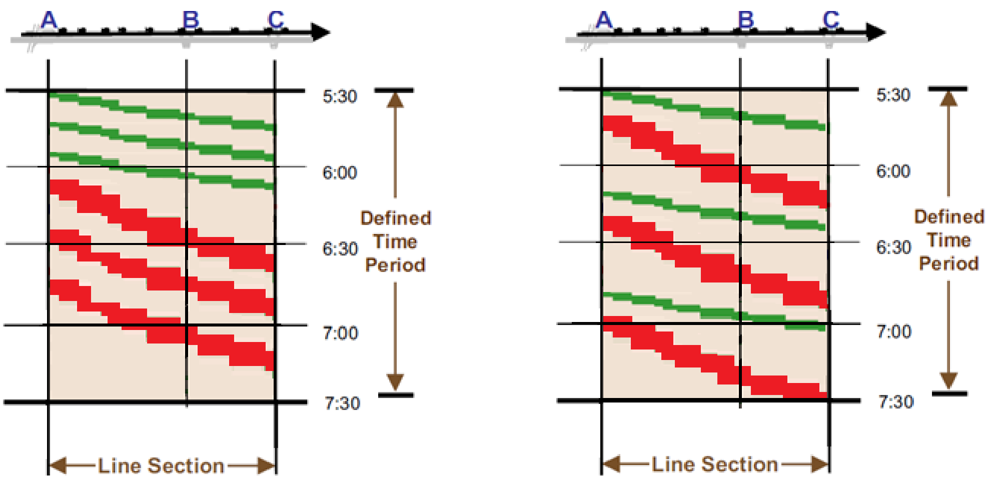

Figure 17 | Track occupation for homogeneous and mixed traffic (UIC, 2013a)

The order and speed of the different trains in a timetable is of influence on the capacity consumption of a corridor. Intercity trains are usually running at a higher speed, clearing block sections faster, thus occupying block sections for a shorter period of time compared to local trains. Regarding capacity, this difference in block occupancy between different train types would favour homogeneous train traffic. For example, first running all intercity trains, followed by all local trains would result in a lower capacity consumption compared to mixed traffic, where trains with higher and lower speed alternate. However, this bundling of homogeneous services is not desired by operators and customers, so mixed traffic is introduced. This negatively influences capacity consumption. Figure 17 presents the difference in track occupation between homogeneous and mixed traffic.

2.4.2. Assessment of asset reduction: Train Depleting Irregularities

The role of the infrastructure manager ProRail is to manage the railway infrastructure and to control the railway traffic. Part of this responsibility is to manage the availability and reliability of the infrastructure. This study analyses the effects of different ERTMS/ETCS HL3 projections on track (un)availability by analysing the reliability of relevant components.

2.4.2.1. Track unavailability: Train Depleting Irregularities

ProRail keeps up a database of unplanned track unavailability. As a measure of unavailability the number of Train Depleting Irregularities (TDIs, Dutch: Treindienst Aantastende Onregelmatigheid, TAO) are counted, as well as the components that were harmed and the cause of the irregularity. A Train Depleting Irregularity is defined as an infrastructural failure, causing at least one train to be delayed more than three minutes.

Over the year 2018, a total of 10.136 TDIs were recorded. This total breaks down in the categories of systems that were harmed (Table 4) and the causes of the TDIs (Table 5). The categories with the highest failure rates are ‘Rail systems’ (e.g. tracks, junctions, civil constructions, power supply) and ‘Train Protection systems’ (e.g. ATP-systems, signalling systems, train detection systems). In general most TDIs are caused by technical causes (e.g. defects) and by third parties (e.g. vandalism). The TDIs registered under technical causes and process errors are TDIs that could have been prevented by the infrastructure manager and should be minimized to reduce track unavailability.

Table 4 | TDIs per subsystem, 2018 (ProRail, 2019)

Harmed system	TDIs (2018)	Percentage
Rail systems	7.636	74,9%
Train protection systems	2.098	20,7%
ICT	49	0,5%
Unknown breakdown	347	3,4%

Table 5 | Causes of TDIs of all subsystems, 2018 (ProRail, 2019)

Causes	TDIs (2018)	Percentage
Technical cause	3.229	31,7%
Process error	665	6,5%
Third parties	5.529	54,2%
Weather	614	6,0%
Unknown cause	94	0,9%

The relevant assets for this study are collected in the category ‘Train protection systems’, with 2.098 TDIs (20,7%). Of the train protection systems related TDIs 66,8% has a technical cause and 11,8% of the TDIs are related to flaws in the processes, see Table 6. The distribution of causes of TDIs for train protection systems is completely different than the distribution of causes of TDIs for all subsystems. Over 75% of the TDIs of the train protection systems should have been prevented. Eliminating the amount of trackside train protection and train detection equipment could give an enormous boost in trackside reliability.

Table 6 | Causes of TDIs of subsystem 'Train protection systems', 2018 (ProRail, 2019)

Causes	TDIs (2018)	Percentage
Technical cause	1.402	66,8%
Process error	248	11,8%
Third parties	266	12,7%
Weather	155	7,4%
Unknown cause	27	1,3%

3. Operational benefits of ERTMS/ETCS Hybrid Level 3

This chapter describes the operational benefit of ERTMS/ETCS Hybrid Level 3. First the results of a quick review of literature on ERTMS/ETCS are presented, followed by a more extensive research into track-to-train communication, the ERTMS/ETCS brake model, headways calculations and the effects of ERTMS/ETCS on the capacity balance.

3.1. Literature review

Several studies have been conducted in the recent past to estimate the impact of the different levels of ERTMS/ETCS. This subsection briefly describes the results and conclusion of those studies.

According to the Verkehrswissenschaftliches Institut Aachen (2008) the capacity of a railway corridor depends on the type of signalling, the train mix and speed profiles of the trains and the braking system of the trains. Compared to ERTMS/ETCS Level 1, ERTMS/ETCS L2 allows for 5% additional capacity, ERTMS/ETCS L2 with short blocks offers 37% additional capacity and ERTMS/ETC L3 offers 42% additional capacity, with the capacity being expressed according to UIC Leaflet 406. ERTMS/ETCS L3 only offers a modest increase in capacity, whilst eliminating a lot of assets. The more restrictive ERTMS/ETCS braking curves could lower capacity in some cases.

Goverde (2012) predicts a better use of capacity by the cab signalling functionality of ERTMS/ETCS combined with the brake curve protection and the speed restriction in small steps. Two-way data communication via GSM-R allows for continuous updates of the movements authorities. The extended braking, short blocks and flexible implementation that ERTMS/ETCS L2 and L3 offer allow for minimizing the headways, increasing the speeds, offering more stability at delays and increasing the heterogeneity.

A study on the capacity effects of ERTMS/ETCS L2 on the corridor Utrecht – Den Bosch (ProRail, 2010b) shows that, when comparing ERTMS/ETCS L2 with the legacy system NS’54/ATB-EG, the robustness increases whilst keeping the timetable and infrastructure at the same level. The running times slightly decrease while the headways decrease significantly. For this corridor, the capacity consumption under ERTMS/ETCS L2 decreases from 91% to 75%.

This conclusion is in line with another study on the capacity effects of ERTMS/ETCS L2 (Goverde, R., Corman, F., D’Ariano, A. (2013)). Running times under ERTMS/ETCS L2 decrease when compared to NS’54/ATB-EG, and when introducing ERTMS/ETCS L2 with short blocks the running times slightly decrease compared to ERTMS/ETCS L2. The headways significantly decrease under ERTMS/ETCS L2 compared to the legacy system. These benefits result from the extended braking functionality under ERTMS/ETCS, the smaller approach times of ERTMS/ETCS L2 and the train dependent braking. For the corridor Utrecht – Den Bosch with 2 paths for cargo trains every hour, the capacity consumption under NS’54 / ATB-EG, ERTMS/ETCS L2 and L2 Short Blocks decreases from 88,3% to 74,5% to 72,8%.

The article in Signal+Draht (Bartholomeus et al, 2018) does not give a numerical prediction for the capacity increase under ERTMS/ETCS HL3, but predominantly TIMS-equipped trains allow for a high capacity whilst reducing trackside train detection. Trains without a TIMS use a lot of the available capacity, these trains should be scheduled in off-peak timetable slots to maximize the capacity benefit during peak hours. ERTMS/ETCS HL3 offers flexibility by allowing both TIMS-equipped and non-TIMS equipped trains, as well as non-ERTMS trains and reduced train operations in degraded scenarios.

ERTMS/ETCS HL3 uses the same software coding and operational procedures, according to Bartholomeus, M. & Zweers, M. (2014). The concept allows for short-following and is suitable for different scenarios in the amount of trackside train detection. The (re-)use of existing TTD and the mix of equipped and non-equipped trains does not require a big bang introduction of this signalling system. Moreover, the risk profile is low: it requires a fairly low building volume and cables to be installed and offers a fall-back for malfunctioning and degraded scenarios.

3.2. Track – train communication

ERTMS/ETCS L2, L3 and HL3 all offer two-way data communication between track and train. This two-way data communication provides the train with updates on movement authorities faster when compared to solely track-to-train communication.

Trains running under ERTMS/ETCS L2 and higher send data on the train identity (ETCS-ID of the on-board equipment), a position report, an identifier of the last main signal balise group and a time stamp to the trackside signalling system via GSM-R to the trackside equipment. The position report should contain at least information on the distance between the last passed balise group and the estimated front end of the train, the minimum and maximum safe front end distances, the orientation of the train, the estimated speed based on the odometry and the direction of movement of the train.

Trains running under ERTMS/ETCS L3 send additional data from the onboard TIMS to the trackside. The integrity of the train checked in both ERTMS/ETCS L2 and L3. The difference between the two systems is the way this information is used. In ERTMS/ETCS L3, the position report, train length and integrity confirmation are combined to locate the safe rear end of the train. As a result, the onboard does not only know the location of the estimated front end of the train (with a margin to the maximum safe and minimum safe front end locations), but also the location of the estimated rear end of the train (with a margin to the maximum safe and minimum safe rear end locations). This additional data allows the system to authorize following trains closer. Trains without TIMS do not confirm integrity. For these train the block release and authorizing following trains relies on the trackside train detection.

For both ERTMS/ETCS L3 implementations, the track side sends information on the ceiling speed, the movement authorities and a dynamic speed profile to the train. The movement authorities are based on the Supervised Location (SvL) which corresponds to the End of Authority (EoA) for the Dutch system. The EoA (thus also SvL) are always located at an SMB. The full brake supervision is displayed on the DMI and provides the train driver with the most up-to-date speed profile. The train driver still has to operate the brakes to follow the profile. This information can result in reduced running times and reduced headways.

3.3. ERTMS/ETCS brake model

The national block signalling and automatic train protection systems vary drastically from country to country. The safety level of the braking behaviour of the different train protection systems is obtained according to assumptions with regards to the braking performance and safety margins. In the legacy systems, the trackside and on-board systems cannot be apportioned easily.

A unified speed, distance and braking control implies that the train behaviour and its braking characteristics must be predictable, and that the safety margins of the braking actions can be divided into a part on the trackside margins and train margins.

ERTMS/ETCS Baseline 2 specifications lay down the principles for the braking curves, but there are no harmonised algorithms and methods to compute them. This leads to different braking distances for the same type of rolling stock, as the suppliers of the ETCS-onboard use different methods. As a consequence, the trackside margins cannot directly be computed from one algorithm. Moreover, the different national rules and practices require the implementation of several national braking curves in the ETCS on-board system. ERTMS/ETCS Baseline 3 has been released as a new specification in which the ETCS braking curve functionality is harmonised.

Compared to ATB-EG, ERTMS/ETCS offers train dependent, block independent, route dependent and speed dependent braking. This allows the train to start braking not earlier than required for the specific track/train combination, independent from the block section boundaries, for a specific route with reduced braking distances at lower speeds. This is illustrated in Figure 18. The functionality reduces the minimum runtimes of trains.

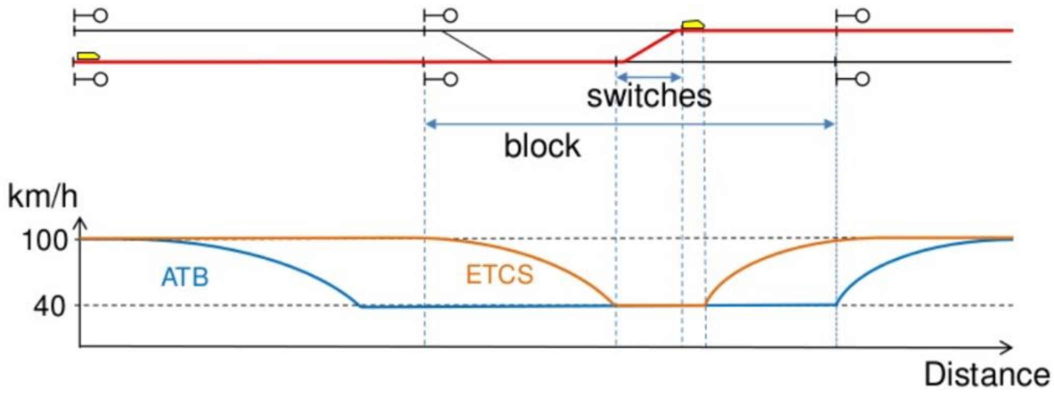

Figure 18 | Block independent and route dependent, train dependent, speed dependent braking under ERTMS/ETCS compared to NS'54/ATB-EG (Goverde, 2018)

3.3.1. ERTMS/ETCS brake models

For the different types of rolling stock, the brake characteristics and thus brake curves have to be implemented differently. ERTMS/ETCS includes two different types of braking models: a model for so-called 'gamma' trains and a conversion model for 'lambda' trains (European Railway Agency, 2016).

Gamma trains are trains with a fixed composition or a limited number of predefined compositions. Most of the regular passenger trains can be thought of to be gamma trains: these trains run in fixed compositions (trainsets) or are a combination of trainsets with a limited number of possible combinations. The brake model calculates nominal deceleration profiles, corresponding to the rolling stock factors and the brake build up times preconfigured in the on-board.

Lambda trains are trains with a variable composition. It is not possible to directly express or predefine the braking performance of those trains with deceleration data, as the brake performance varies from composition to composition. Freight trains and locomotive-hauled passenger trains are examples of lambda trains. Unique data for each train is characterising the braking power of the train: the braked weight percentage. The conversion model translates the braked weight percentage according to a value for the brake setting of the train (P for passenger trains and G for freight trains).

3.3.2. Inputs for speed and distance monitoring

The EVC must be aware of the characteristics of both track and train to monitor speed and distance and calculate the braking curves accordingly. The data collected by the EVC is split in train data and track data (ERTMS User Group, 2016).

Train data:

a) Traction model
b) Braking models (gamma, lambda)
c) Brake setting (P, G)
d) Special brakes interface (yes/no
e) Service brake interface (yes/no)
f) Traction cut-off interface (yes/no)
g) On-board correction factors
h) Nominal rotating mass
i) Train length
j) Fixed values
k) Speed restrictions
l) National Values

Track data:

a) Speed restrictions
b) Gradients
c) Brake inhibitions
d) Powerless sections
e) Reduced adhesion conditons
f) Speed and distance limits (EoA, SvL)

The EVC calculates two types of braking curves from the inputs for speed and distance monitoring: safety braking curves and braking curves for guidance of the train driver. The relation between the different ERTMS/ETCS braking curves and the related supervision limits is presented in Figure 19.

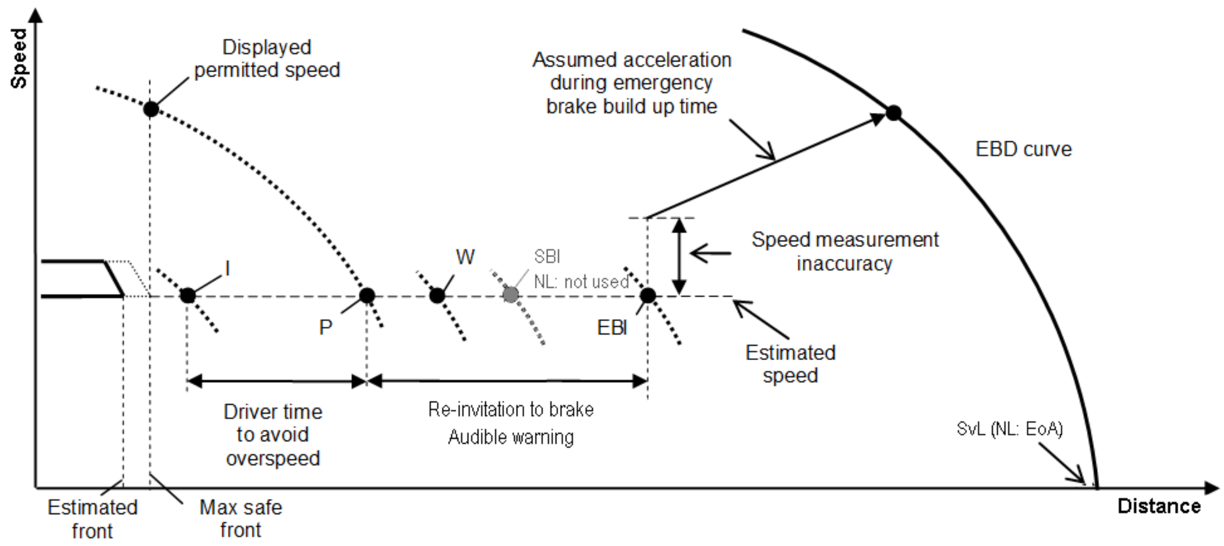

Figure 19 | ERTMS/ETCS braking curves and supervision limits (European Railway Agency, 2016)

3.3.3. Safety braking curves

The safety braking curves are the safety critical ERTMS/ETCS braking curves. These are determined by the safe train deceleration, captured in the relevant braking model and brake settings. The safety braking curves include the Emergency Brake Deceleration (EBD) curve, based on the nominal brake deceleration of the rolling stock, and the Emergency Brake Intervention (EBI) supervision limit, both indicated in Figure 19. The Service Brake Deceleration (SBD) curve and Service Brake Intervention (SBI) supervision limit are facultative curves. These curves are used to prevent trains from running into the EBD curve too often. This could damage both the rolling stock and the infrastructure. The SBD-curve and the accompanying SBI-limit are not used on the Dutch railway network by means of the National Values.

The EBD-curve is based on the safe deceleration for the rolling stock and reaches zero speed at a distance equal to the permitted braking distance. The safe deceleration depends on the track and train characteristics as described in subsection 3.3.2. The shape of the EBD-curve *A_safe* will thus vary according to the type of rolling stock (*A_brake_safe* for gamma trains, *A_brake_tuned* for lambda trains) and track characteristics.

3.3.3.1. Safe braking for gamma trains

The infrastructure manager and the railway undertaking both set correction factors that influence the braking performance of gamma trains. The nominal brake performance of the rolling stock is captured in *A_brake_emergency*, a step function of deceleration against speed (maximum 7 steps).

The required Confidence Level (CL) for the rolling stock performance is set by the IM. The Dutch National Values (NVs) prescribe M_NVEBCL to minimum 1E-04 (CL4). Figure 20 illustrates the use of the CL to derive the guaranteed emergency brake deceleration from the nominal emergency brake deceleration.

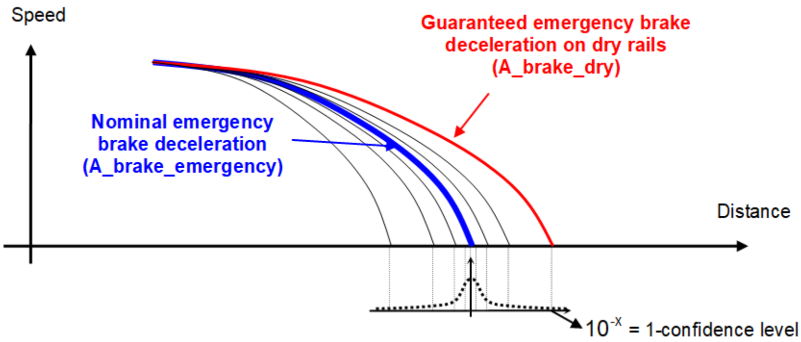

Figure 20 | Dispersion of emergency braking performance (European Railway Agency, 2016)

The railway undertaking sets correction factors related to the rolling stock depending on the type and performance of braking elements, the reliability of the system, the brake system architecture and the efficiency and performance of the rolling stock brake systems under wet conditions.

- K_dry quantifies the emergency braking performance on dry rails as a factor of *A_brake_emergency*. The values are gathered by combining a prescribed CL for the braking performance and a Monte Carlo analysis on the braking performance of the rolling stock. Typical values for K_dry for Dutch rolling stock are in the range of 0,70 - 0,88;
- K_wet quantifies the loss of emergency braking performance on wet rails with regards to dry rails. As the Dutch law prescribes the safe braking deceleration to be based on the braking performance in dry conditions, K_wet is mitigated via weighting factor M_NVAVADH. This factor is included in the NVs with a default value of 1,0. This implies that factor K_wet is not used.

Figure 21 shows the construction of the safe brake deceleration A_brake_safe for gamma trains with the relevant input and the correction factors K_dry and K_wet (via M_NVAVADH). The relevant Dutch NVs are included in Table 7.

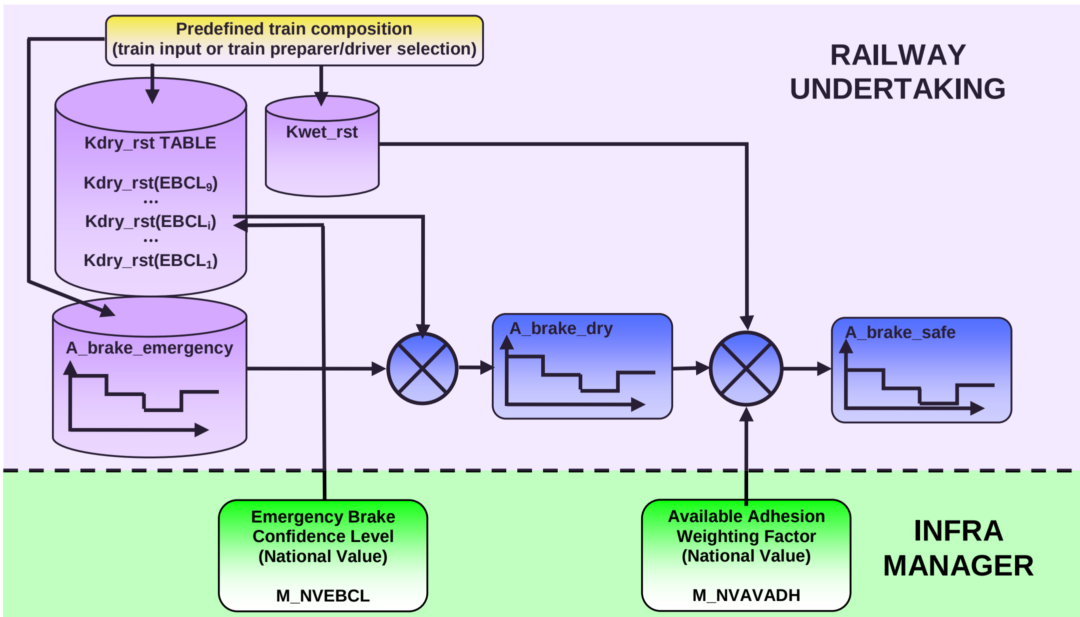

Figure 21 | Gamma braking: braking characteristics & correction factors (European Railway Agency, 2016)

Table 7 | Relevant Dutch National Values for gamma trains

	M_NVEBCL	K_dry (M_NVEBCL)	M_NVAVADH	K_wet (M_NVAVADH)
Values	CL4 to CL8: 99,99 % to 99,9999999%	0,70 – 0,88	1,0	-

Thus, *A_brake_safe* (the guaranteed braking deceleration) for the rolling stock is calculated based on the known *A_brake_emergency*, K_dry, K_wet, the CL of the EBD-curve and a correction to the adhesion, according to the following general formula:

$$A_{brake\_safe}\,(V) = A_{brake\_emergency}\,(V) *\ K_{dry}\,(M_{NVEBCL}) * \left(K_{wet} + M_{NVAVADH} * (1 - K_{wet})\right)$$

For the Dutch railway network, this results in the factor K_wet to be eliminated from the equation:

$$A_{brake\_safe}\,(V) = A_{brake\_emergency}\,(V) *\ K_{dry}\,(M_{NVEBCL})$$

3.3.3.2. Safe braking for lambda trains

The braking behaviour of trains with variable compositions cannot be expressed directly in deceleration values. The braking behaviour is captured by the braked weight percentage of the train (λ, 30% - 250% of the total train weight) and converted into an emergency brake profile *A_brake_converted* (UIC, 2013b).

$$A_{brake\_converted} = 0{,}075 * \lambda + 0{,}076$$

The IM is offered the possibility to define integrated correction factors for lambda trains as step functions of speed and train length. The number of steps is limited to five for both functions. The principle of the correction factors is illustrated in Figure 22. The following factors are included in the NVs:

- Correction factors Kv_int for P- and G-brake settings, as a step function of speed;
- Correction factor Kr_int for train length, as a step function of the train length.

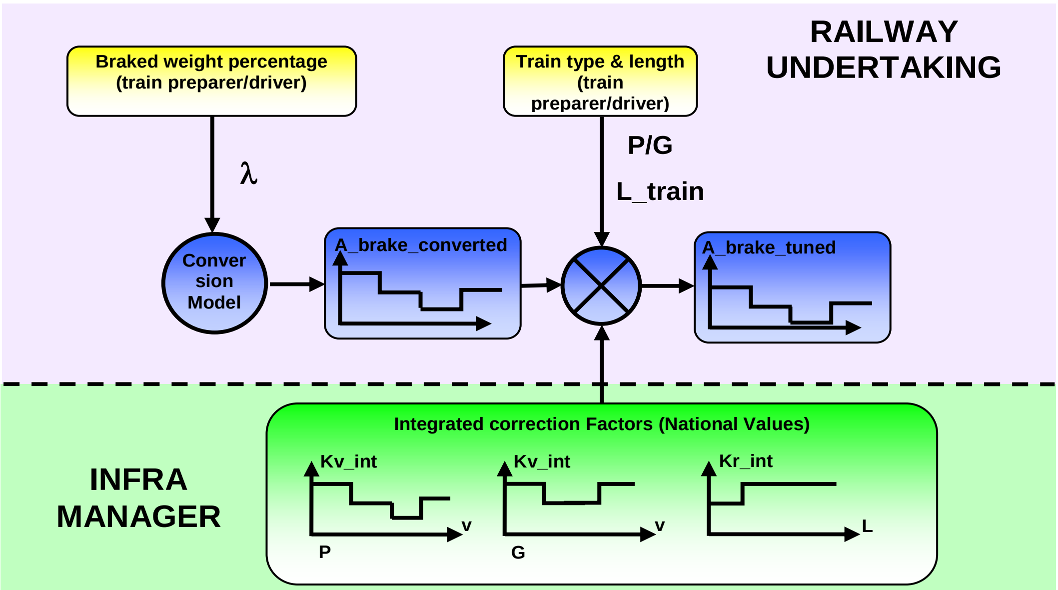

Figure 22 | Lambda braking: Conversion Model & Integrated Correction Factors (European Railway Agency, 2016)

The Dutch NVs (Table 8) prescribe a value of 1,0 for Kr_int. This implies the factor is not in use. Instead, the train length dependency is integrated in the brake build-up time (T_be) for the individual rolling stock, see subsection 3.3.3.3.

Table 8 | Integrated Correction Factors on the braking performance of lambda trains

Correction factor	Kv_int (P)	Kv_int (G)	Kr_int
Default values	v ≤ 160 km/h: 0,9 v > 160 km/h: 0,76	v ≤ 160 km/h: 1,0 v > 160 km/h: 0,76	1,0

A_brake_safe for lambda trains is a similar deceleration as *A_brake_safe* for gamma trains. For lambda trains it is calculated based on the conversion model deceleration, train speed correction factor and train length correction factor:

$$A_{brake\_safe}\ (V) = A_{brake\_converted}\ (V) * \ Kv_{int}\ (V) * \ Kr_{int}(L\_TRAIN)$$

A third Integrated Correction Factor for lambda trains is the correction on the brake build-up time. As this factor does not influence the brake deceleration but the construction of the EBD-curve, this factor is elaborated on in the next subsection.

3.3.3.3. Calculation of the EBD-curve

The deceleration values for gamma trains are obtained by field tests or parameters from the manufacturer. The deceleration values for lambda trains calculated by the conversion model have been validated by extensive field tests with a large variety of train types. *A_brake_safe* is modelled through a step function of deceleration against speed and known by the EVC. The track correction factors (e.g. gradients) are sent to the EVC as a step function as well, see Figure 23 and the following formula. Combination of the train characteristics and the track characteristics lead to A_safe, the safe deceleration.

$$A_{gradient}\ = 9{,}81 * \ gradient\ \ / \ (1000 + 10 * rotating\ mass\ of\ the\ rolling\ stock);$$

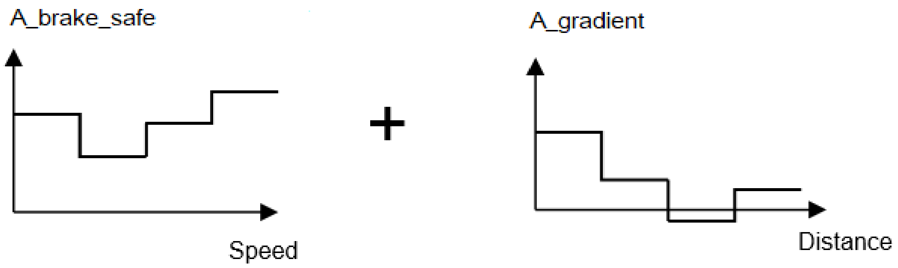

Figure 23 | Composition of A_safe: A_brake_safe + A_gradient (European Railway Agency, 2016)

$$A_{safe}\ (V, d) = A_{brake\_safe}\ (V) + A_{gradient}\ (d);$$

Combining the step functions results in a set of interconnected decelerations, each of them representing a constant deceleration valid for the relevant speed step and the distance to the EoA (Figure 24).

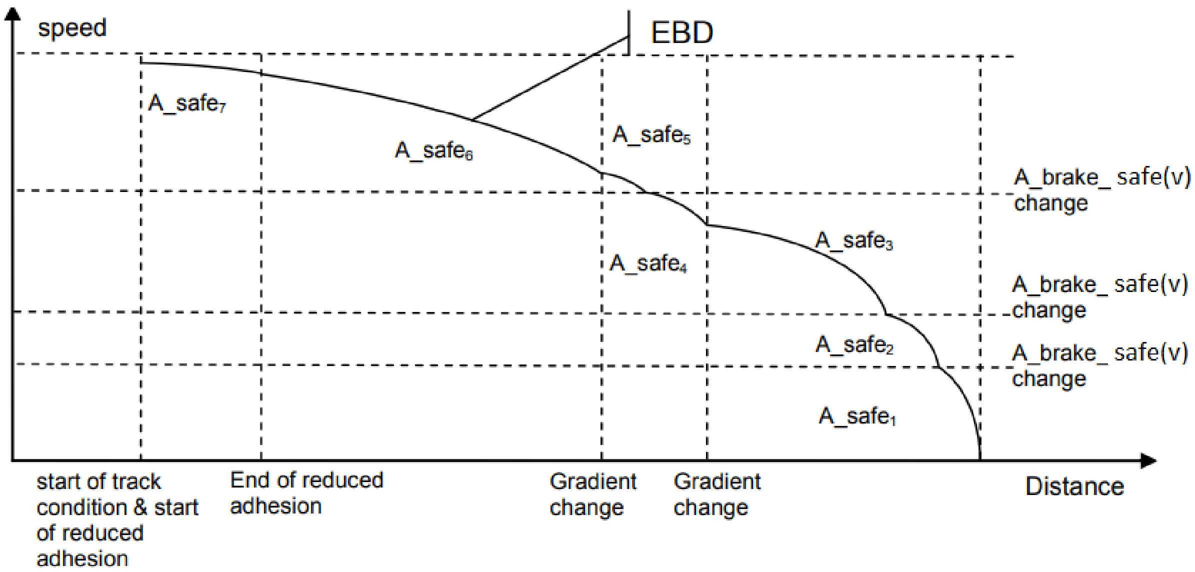

Figure 24 | Construction of the EBD-curve (European Railway Agency, 2016)

Next to the braking rate *A_safe* also the brake build-up time (*T_be)* is required for the real-time distance to stop. For gamma-trains the brake build-up time should be measured together with the braking characteristics and is known to the operator. For lambda-trains the brake build-up time depends on the length of the train and the speed of the air being pumped to the brake system. As this calculation is a general approach of reality, an Integrated Correction Factor can be implemented by the IM. This factor (*Kt_int*) can mitigate the uncertainty of *T_be* for long and heavy trains with lambda-braking. *Kt_int* is by default set to 1,0 according to the Dutch NVs. The general formula for calculation of the brake build-up time of lambda trains is the following, with coefficients *a, b* and *c* dependent on the brake setting of the rolling stock (UIC, 2013b), and L being the train length:

$$T_{be} = Kt_{int} * \left(a + b * \left(\frac{L\_TRAIN}{100}\right) + c * \left(\frac{L\_TRAIN}{100}\right)^2\right)$$

From the EBD-curve, the on-board unit calculates in real-time the distance required to stop. Included in this calculation are the train dynamics, e.g. the brake build-up time (T_be), time to cut-off traction (T_traction) and assumed acceleration of the train. The dynamics of the train acceleration are included in parameters V_{bec} (speed change compensation) and D_{bec} (distance change compensation). These factors compensate the changes of speed and position during the brake build-up time. The factors are included in Table 9. The distance at which ETCS intervenes the human train driver is called the EBI-limit. The full calculation of the safe deceleration and the compensation is included in ERTMS/ETCS System Requirements Specification Subset-026 (ERTMS User Group, 2016).

Table 9 | Factors in the real-time distance required to stop

	Brake build-up time T_be [s]	**Traction cut-off time T_traction [s]**	**Speed build-up compensation V_bec [km/h]**	**Distance compensation D_bec [m]**
Typical values	Passenger trains: 1,0 – 2,5 Freight trains: 5 - 20	2	Depending on train speed, target speed, T_be, T_traction and measured acceleration	Depending on train speed, target speed, T_be, T_traction and measured acceleration

This leads to the following formula for the compensated EBI-limit (ERTMS User Group, 2016):

$$d_{EBI}(V) = d_{EBD}(V_{bec}) + D_{bec}$$

3.3.4. Guidance braking curves

The guidance curves of ERTMS/ETCS assist the driver and allow him to drive and brake at comfortable rate by maintaining the speed of the train within the appropriate limits. Several guidance curves are calculated, of which in the Netherlands the two Service Brake intervention limits (SBI1, SBI2) are excluded by the National Values. These curves would hinder traffic operations by showing limits of authority to the driver earlier. Guidance curves that are in use in the Netherlands:

- Warning (W): An audible warning is given to the driver prior to passing the EBI-limit. The system re-invites the driver to apply the brakes. Without a reaction from the driver, the train hits the EBI-limit 2 seconds after passage of the W-limit and the system will intervene.

  $d_{Warning} = d_{EBI} + T_{Warning} * v$; $T_{Warning}$ is 2,0 seconds.

- Permitted (P): The time between the P-curve and W-curve allows the driver to correct for overspeeding without the system directly intervening. If he does not apply the brakes the train hits the W-curve.

  $d_{Permitted} = d_{EBI} + T_{driver} * v$; T_{driver} is 4,0 seconds.

- Indication (I): This curve functions as an indication to the driver that the authority is about to end. The time between the indication and the permitted curve allows the driver to react to the new target, without directly overpassing the permitted speed.

  $d_{Indication} = d_{Permitted} + T_{indication} * v$; $T_{indication}$ minimum 9,0 seconds.

In total, the first indication before the EBI-limit is at a distance of 13 seconds at local track speed.

3.3.5. Braking curves for capacity assessment

Trains and train drivers are assumed to be able to drive on the P-curve. For corridor capacity assessment, the I-curve is the curve to deal with. Train drivers are thought not to want to drive exactly on the P-curve. Moreover, basing the block occupation and capacity on the P-curve results in the train driver continuously being warned about the EoA that is nearby (but will be extended). In practise, braking is thought to start 4 seconds after passing the I-curve with a continuous increasing braking rate until the P-curve is reached. The different ERTMS/ETCS braking curves and the ATB-EG curve are presented in Figure 25.

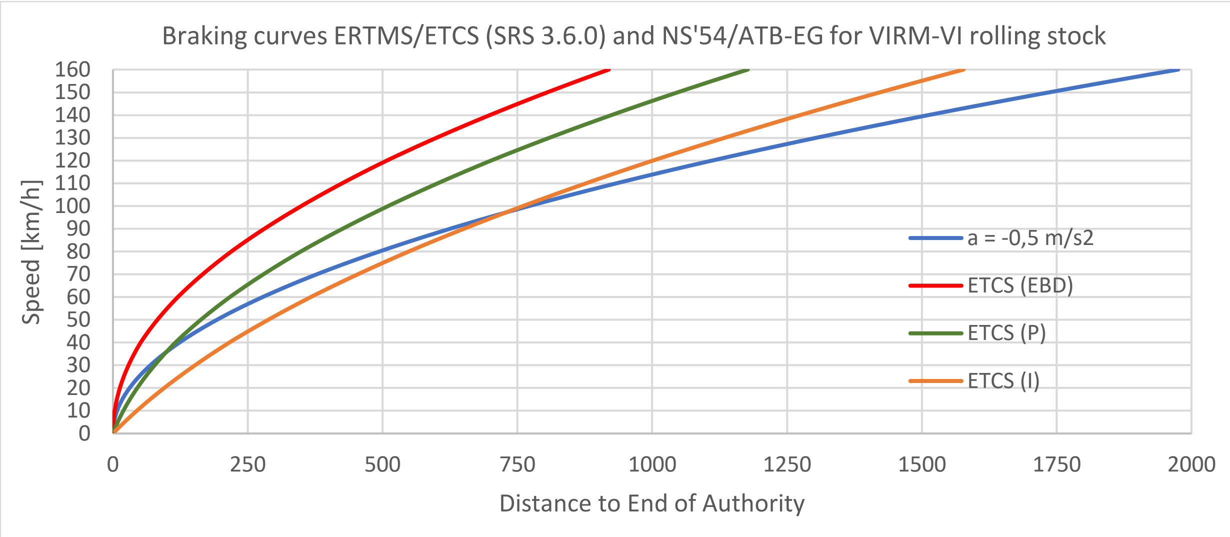

Figure 25 | ATB-EG curve and the ETCS-curves (EBD, P, I) according to SRS3.6.0 (ERTMS User Group, 2016)

These track and train dependent braking curves allow the train driver to brake just in time on the permitted curve, instead of block-dependent braking as in NS'54/ATB-EG. However, this holds for all ERTMS/ETCS levels, not only for ERTMS/ETCS HL3. The impact of the blocks and block-dependent braking on the minimum running times and block occupation is bigger than Figure 25 suggests. This is illustrated in Figure 26 where the ATB-EG curve is shifted towards the start of a block. This implies that a train has to run at a speed of maximum 40 km/h for a while when the length of a block exceeds the braking distance.

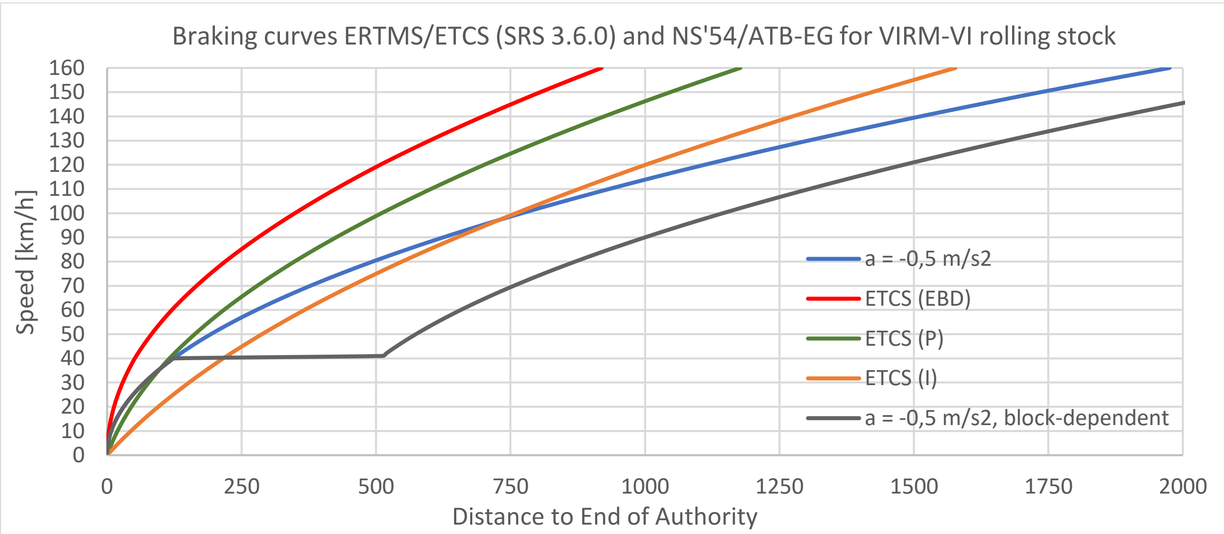

Figure 26 | ATB-EG curve, ATB-EG block-dependent curve and the ETCS-curves (EBD, P, I)

3.4. Reduced headways

Another benefit of ERTMS/ETCS L2 and ERTSM/ETCS HL3 is the reduced headway between successive trains. At normal operations under NS'54/ATB-EG trains are occupying the block section they are running in and the block section ahead. Under ERTMS/ETCS the headways are reduced by track and train dependent braking behaviour and optimized block lengths.

Opposed to the braking behaviour without difference between ERTMS/ETCS L2 and HL3, in the headways there is a difference between ERTMS/ETCS L2 and HL3. ERTMS/ETCS L2 requires the track to be equipped with trackside train detection. A block section is released only when the train passes the detection equipment. Short blocks are possible in ERTMS/ETCS L2 signalling but it requires a substantial amount of trackside train detection. ERTMS/ETCS HL3 projects short virtual subsections in between the physical blocks. The release of the VSSs is based on the position reports that are send from train to the trackside signalling system and the integrity monitoring on-board of the trains. The sections can therefore be released earlier, allowing the trackside signalling system to grant a movement authority to the next train at shorter headways.

Different processes in railway operations require headways between successive trains. Not only the actual train operations between timing points, but also the dwelling, turning and shunting of trains require separation in time. The duration of these processes can be expressed in two ways:

- net time: technical minimum duration;
- gross time: including primary delays (incidents and irregularities);

To allow for a spread in the process times and neutralize primary delays (partly), a running time supplement of a few percent of the technical minimum running time is added to the net time. The net time with the supplement is the scheduled duration.

In order to reduce the delays of a second process which cannot take place when the first process has not yet finished, a buffer is created in the timetable between coupled processes. This reduces the secondary delays. In timetabling practice in the Netherlands, this buffer has a minimal duration of 60 seconds which is a rather arbitrary engineering choice. Coupled processes (event relations) can be one of the following:

- headway: two trains in the same direction with the same start or end track;
- cross-over: two trains, not necessarily in the same direction, use the same infrastructure, without having the same start or end track;
- transition of rolling stock;
- transition of staff;
- passenger transfer.

The headways between successive trains are based on the net time, with a 8% running time supplement and the 60 seconds buffer time. The resulting times are rounded down for timing points and short stops, and rounded up for big stations. According to practice this results in a headway of around 3 minutes between successive trains at timing points.

For timetabling, the following times between successive train operating processes have been included in the timetabling norms of the Network Statement 2018, see Table 10 (ProRail, 2018).

Table 10 | Timetabling norms 2018, headway between successive activities (ProRail, 2018)

		Activity of 2nd train			
		Arrival (A)	Passage (P)	Short stop (S)	Departure (D)
Activity of 1st train	Arrival (A)	3 min	2 min	3 min	n/a
	Passage (P)	3 min	3 min	3 min	2 min
	Short stop (S)	4 min	4 min	4 min	3 min
	Departure (D)	4 min	4 min	4 min	3 min

However, as both the track characteristics and the rolling stock characteristics differ from situation to situation, the timetabling norms can only be used as an indication for the actual required time of headways between successive trains and cross-overs between trains. By adjusting the timetabling process and base the required times on the track and train characteristics as used in ERTMS/ETCS, the infrastructure could be used more optimal. Therefore the Network Statement 2020 (ProRail, 2018c) replaces the general norms by individual headway and cross-over calculations.

3.5. Block occupation processes

The track - train communication, ERTMS/ETCS braking curves and shorter blocks of ERTMS/ETCS HL3 result in a change of the infrastructure blocking times compared to the legacy signalling system and ERTMS/ETCS L2. The blocking time theory of subsection 2.4.1. is projected on the legacy signalling system NS'54/ATB-EG, ERTMS/ETCS L2 and ERTMS/ETCS HL3. The legend for figures 28, 29 and 30 is presented in.

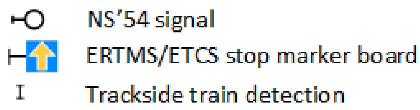

Figure 27 | Legend for figures 30, 31 and 32

3.5.1. NS'54/ATB-EG

Block occupation under NS'54/ATB-EG signalling is based on block sections and trackside train detection. Block sections are created from signal to signal and work according to the three-aspect signalling approach. Sections are released when a train is no longer detected on a section. Sections are created by track-circuits and electric insulated joints in the rails. These are located shortly after each signal (9 - 15m) and (additionally) in between signals.

The block setup time, sight and reaction time and block release time are fixed system parameters. The other aspects of the block occupation time (approach, journey and clearing times) are based on block and train characteristics: the approach time is based on the length of the previous block section and train speed, the journey time within the block is based on the length of the block and train speed and the clearing time for the trackside train detection is based on train length and train speed. Figure 28 visually presents the blocking time diagram of NS'54/ATB-EG with the six attributes of the blocking time diagram.

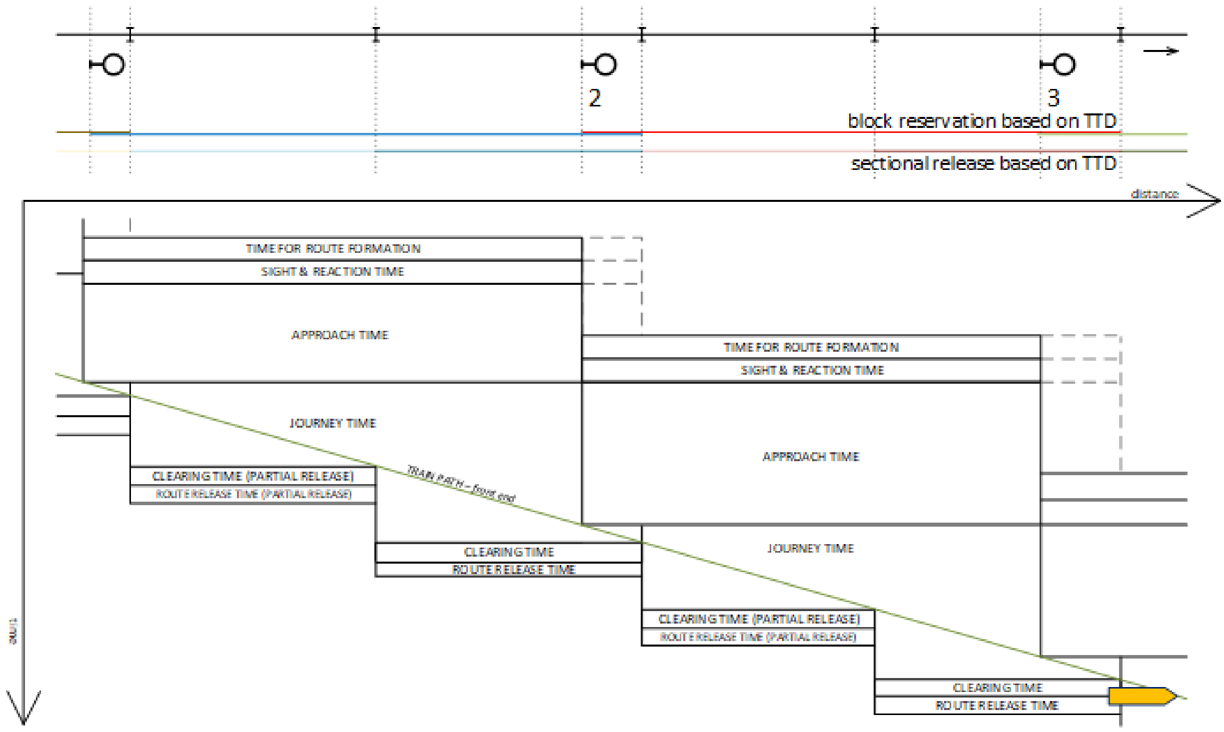

Figure 28 | NS'54 / ATB-EG blocking time diagram

3.5.2. ERTMS/ETCS Level 2

Under ERTMS/ETCS L2 blocks are created from Stop Marker Board (SMB) to SMB. Train detection is still relying on trackside detection units. However, the braking model of the trains is no longer dependent on the block sections but based on the individual train characteristics in combination with track parameters.

ERTMS/ETCS requires an additional 6 seconds between block setup and the movement authority being received by the train (RLN60560-4, ProRail). This is modelled in the setup time. The other aspects of the ETCS block occupation time (approach, sight & reaction, journey and clearing times) are based on block and train characteristics. The approach time is based on the brake distance and speed of the train. Sight & reaction time includes the reservation of the I-curve instead of the P-curve. The journey time is based on the length of the block and train speed. The clearing time for the trackside train detection is dependent on train length and train speed. The block signalling principle is of ERTMS/ETCS L2 is presented in Figure 29.

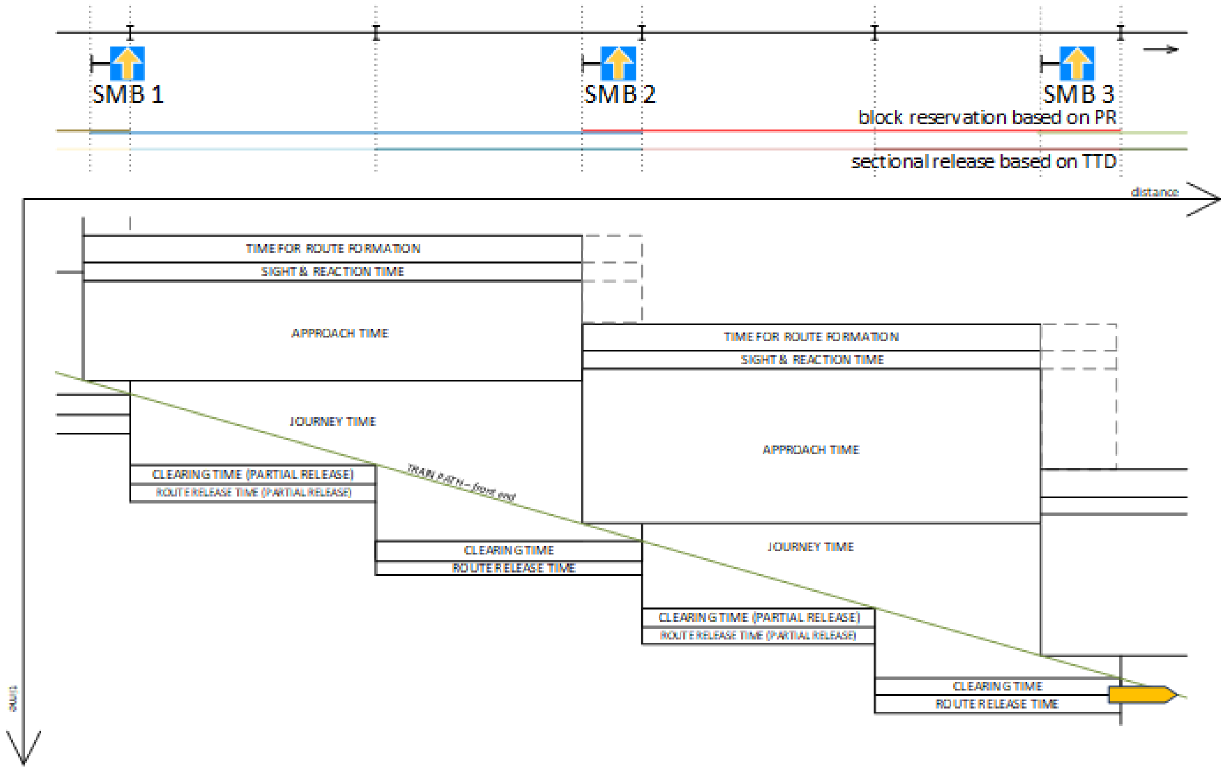

Figure 29 | ERTMS/ETCS Level 2 blocking time diagram

3.5.3. ERTMS/ETCS Hybrid Level 3

ERTMS/ETCS HL3 consists of small block sections between stop markerboards. The block sections are independent of the remaining trackside train detection: the trackside train detection can be located at any required trackside location. The block sections are therefore 'virtual' as apart from the stop markerboards no other equipment has to be present at the border of these subsections.

For ERTMS/ETCS HL3 trains the block release procedure depends on the train type: trains equipped with and without TIMS handle the block release differently.

Trains equipped with TIMS use the Position Report combined with the known train length and the confirmed train integrity to determine the position of the rear end of the train. When the rear end of the train has passed the border of a virtual block section, the previous section can be released. For trains without a TIMS, the position of the confirmed rear end of the train still relies on trackside train detection. The train has to pass a detection point to be able to release the previous block section(s).

As with ERTMS/ETCS L2, an additional 6 seconds delay for MA transmission is modelled in the setup time. The setup time and block release times are fixed. The other aspects of the block occupation time are based on block and train characteristics: the approach time is dependent on the brake distance and train speed, sight & reaction time is based on the I-curve instead of the P-curve, the journey time within the block is based on block length and train speed. Smaller virtual blocks reduce the journey time of TIMS-equipped trains compared to ERTMS/ETCS L2. The journey time of non-equipped trains depends on the distance between trackside train detection units. The clearing time is still based on train length and speed. The blocking time diagrams of both TIMS-equipped trains and non-TIMS-equipped trains are presented in Figure 30.

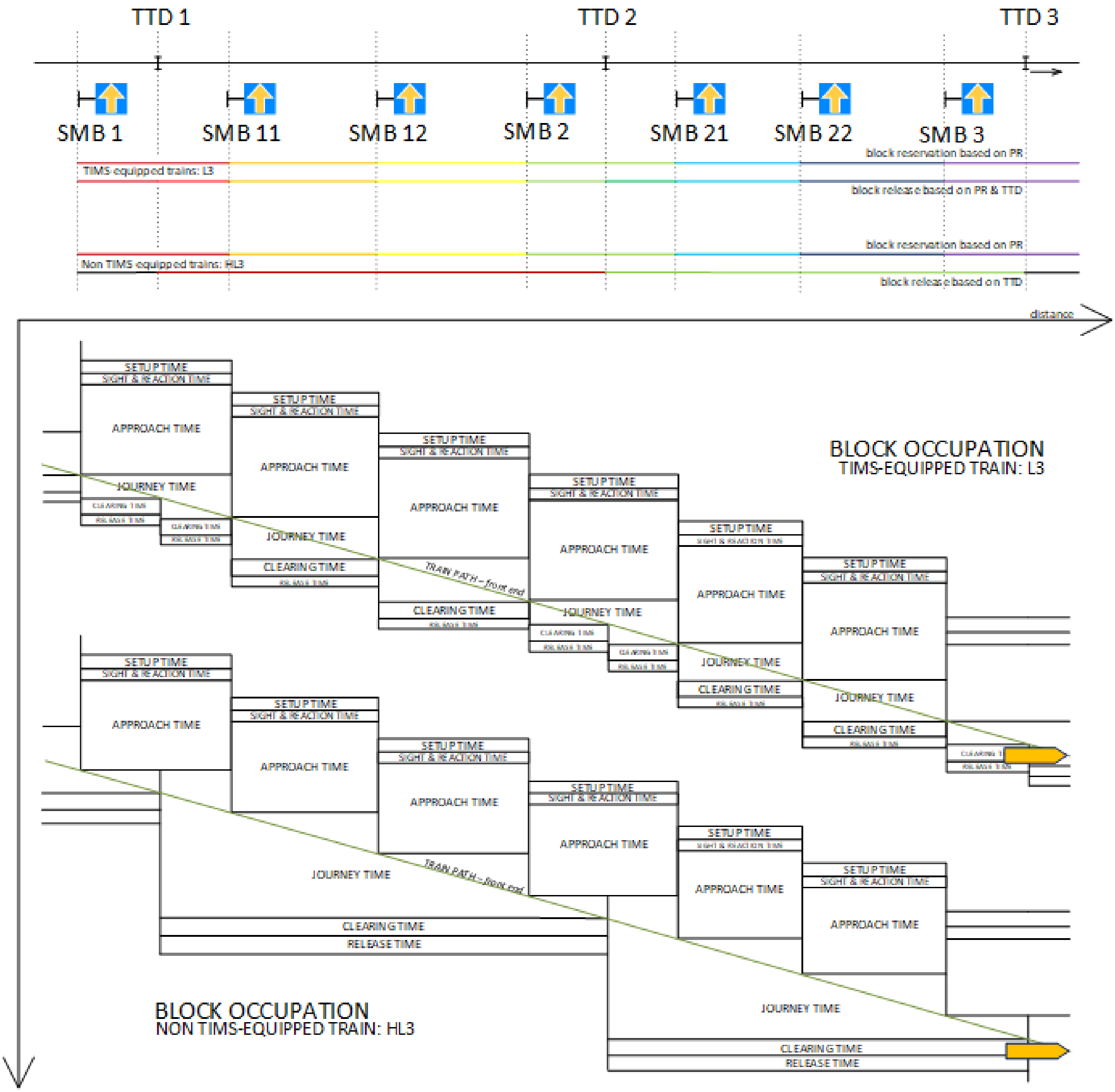

Figure 30 | ERTMS/ETCS Hybrid Level 3 blocking time diagram

3.6. Change in capacity balance

Analysing the capacity that is generated by building new rail infrastructure, upgrading existing infrastructure or using the existing infrastructure more efficiently is a multifaceted task. It does not only include the railway infrastructure, but also the rolling stock, the timetable and the human factor in operations. The capacity balance is the balance between the number of trains, stability, heterogeneity and the average speed, where the capacity is the length of the chord connecting the four axes. The capacity is a trade-off between quantity and quality. There is always a conflict between adding train paths and remaining the quality of the existing train services.

ERTMS/ETCS L2 changes the capacity balance compared to the legacy signalling system, see Figure 31. Running trains under ERTMS/ETCS L2 with a similar timetable increases stability. Running trains under ERTMS/ETCS L2 with a higher frequency increases the number of trains but reduces stability slightly. Running trains with a higher speed increases the average speed but reduces stability slightly.

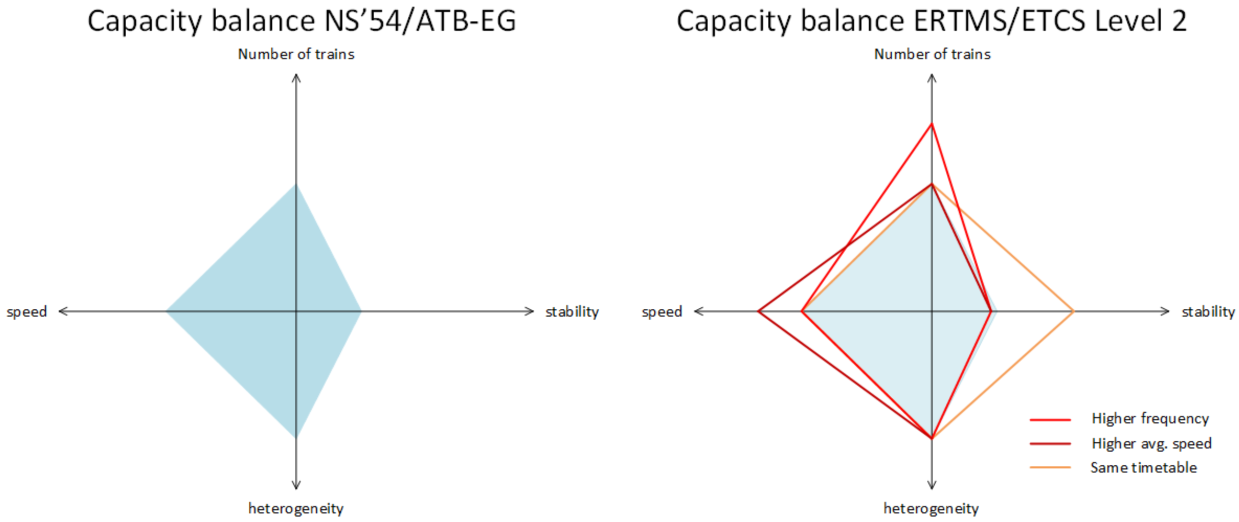

Figure 31 | Change in capacity balance under ERTMS/ETCS Level 2: three scenarios

With ERTMS/ETCS HL3 signalling a further capacity improvement can be realized. The system architecture of ERTMS/ETCS HL3 changes the train detection from trackside to onboard. Capacity-wise ERTMS/ETCS HL3 offers similar performance as ERTMS/ETCS L2 with short blocks.

4. ERTMS/ETCS Hybrid Level 3 implementation

The Dutch engineering rules (OVS or Ontwerpvoorschriften) regarding the implementation of ERTMS/ETCS Level 2 are laid down in OVS60040 ‘ERTMS’ (ProRail, 2015). Together with document RLN60560-4 ‘Richtlijn berekening rij- en opvolgtijden’ it forms the core of the main principles and projection rules for ERTMS/ETCS in the Netherlands.

4.1. Engineering Rules ERTMS: OVS60040

The main Dutch engineering rules on ERTMS implementation that have an impact on the ERTMS/ETCS HL3 implementation and configuration are described in this section per subject.

4.1.1. ERTMS/ETCS Specification & Levels

The ERTMS/ETCS version to be implemented in the trackside is Baseline 3, Release 2 (B3R2), System Version 2.1, System Requirements Specification 3.6.0 (ERTMS User Group, 2016). Older versions of ERTMS are no longer to be installed in the Netherlands.

ERTMS/ETCS provides operations under ERTMS/ETCS Levels and Level NTC (LNTC). LNTC is National Train Control which for the main lines is the current NS’54/ATB-EG combination. Trains will be equipped with a STM-module, which converts the ATB-signal into ERTMS/ETCS language and sends the converted signal to the EVC.

To avoid double systems in both track and train, the trackside will only be equipped with one signalling system. Overlay systems will no longer be installed. OVS60040 is based on ERTMS/ETCS L2. However, ERTMS/ETCS HL3 uses the same principles and operational procedures. These Engineering Rules are also used for this study on ERTMS/ETCS HL3.

4.1.2. Block section length

Block sections should have a minimum length of 200m. In consultation with ProRail, exceptional values with a minimum of 100m are allowed. The maximum length of a block section is 5000m. The distance between the SMBs and the actual section break should be between 9m and 15m.

4.1.3. Balises, balisegroups and balise(group) placement

Balises are used for transferring data from track to train, for location referencing and for direction referencing. Balises should be placed in balisegroups (BG) consisting of minimum 2 balises for direction referencing and message duplication. In case multiple BGs are required close to each other, the BGs should be spaced by a distance of minimum 0,2s * Vmax + 2,6m. For consistency balises in a single group are always placed 3m center to center.

A BG should be placed in rear a SMB: one balise at 6m and the other balise 3m before the SMB. This BG contains a message ‘stop if in SR’ (Staff Responsibility) to mitigate the risk of passing the SMB incorrectly. The location confidence interval will be reset when passing the BG, causing the train to trip in case of a signal passed at danger when running in release speed.

If the SMB protects a danger location, a BG should be located approximately. 100m in rear of the SMB to minimize the confidence interval when approaching the SMB. In order to minimize the confidence interval when approaching the EoA, a third BG is located approximately 600m in rear of the SMB.

To reduce the confidence interval for the location referencing principle, BGs should be spaced at most 1000m, to keep the location within a maximum margin of 5m + 5% of the travelled distance.

4.1.4. Movement Authorities

The End of Authorities and Supervised Locations should be located at the end of a section, at the SMB/signal/marker. The use of a Limit of Authority is inhibited by the NVs.

4.1.5. Braking curves

The ERTMS specification and the National Values allow for the following braking curves and intervention limits to be calculated and used onboard of the trains:

- EBD-curve (Emergency Brake Deceleration curve): braking to a complete standstill, based on the safe deceleration for the rolling stock;
- EBI-limit (Emergency Brake Intervention limit): this is the limit where the train intervenes the driver to start braking to follow the EBD-curve. The limit is based on the emergency brake application time;
- W-limit (Warning limit): 2 seconds prior to reaching the EBI a warning is given to the driver that the system is about to intervene when the train driver does not react;
- P-curve (Permitted curve): 4 seconds prior to reaching the EBI is the permitted curve. This is the braking curve the train driver is allowed to follow, comfortable braking;
- I-limit (Indication limit): 9 seconds prior to reaching the P-curve the train driver is notified about the nearby End of Authority, action is required shortly after.

The default release speed from the braking curves is 15 km/h. This allows the train driver to be able to reach the location of the EoA. The release speed can be lowered when the non-protected distance in advance of the EoA and the danger point is not sufficient (ProRail, 2015).

4.1.6. Special track sections

Several special track sections are present on the Dutch railway network. These specials require separate engineering rules. Think of steep slopes (railway tunnels and bridges), level crossings, overhead wiring electric groups and stations & platforms. These are discussed in the subsections below. The special track section could limit the optimal placement of SMBs, limiting capacity benefits.

4.1.6.1. Tunnel regime: X/G-signals

A tunnel regime has three functionalities. To prevent long & heavy freight trains from stopping on a steep slope and not being able to accelerate up the slope, to prevent these trains from overspeeding on a downhill slope and incur brake intervention, and to prevent these trains from re-occupying the block section behind the train after braking (the train stretches its buffers and becomes longer). The tunnel regime of NS’54/ATB-EG is facilitated by X/G-signals. These signals are valid for classified trains only.

A green wave should be implemented to prevent heavy and long trains from stopping in the tunnel and not being able to accelerate up the hill. To prevent a passenger train following a freight train at block distance in the tunnel and possible calamities from occurring, the tunnel entry signal should show the red aspect to the passenger train until the freight train has exited the tunnel.

ERTMS/ETCS does not include similar functionality. Therefore, the existing additional signals can be maintained or this functionality should be realised in Vervoer Per Trein (VPT), software used by traffic control for route setting, or other train control (TC) systems.

4.1.6.2. Slopes with large gradients: L/H-signals

L/H-signals on slopes with large gradients have a similar functionality as the tunnel regime. To prevent trains from stopping on a track section with a large gradient and not being able to accelerate up the slope, additional L/H-signals are in use. These signals order the driver of classified trains to increase the margin to the previous train.

As with the tunnel regime, ERTMS/ETCS does not include similar functionality. A solution in the VPT/TC system to set integral routes for freight trains is required under ERTMS/ETCS. This thesis model an approach similar to the legacy L/H-signals for freight trains.

4.1.6.3. Level crossings

To prevent trains from stopping on a level crossing and blocking the level crossing, SMBs should be placed at least 425m in rear of the section release for passenger trains and 750m for freight trains. This requirement limits the creation of short virtual blocks. Solutions in the VPT/TC systems are required to mitigate the limitations. In the case study, short blocks are modelled near level crossings to optimize infrastructure occupation and traffic flow.

4.1.6.4. Neutral sections & section breaks

Neutral sections are sections without overhead wiring or sections without power supply on the overhead wiring. If a train halts under a neutral section, it is powerless and can not accelerate anymore. The train driver should be notified 12,5s * Vmax + 19m ahead. This allows the driver to prepare in time for the required actions.

Section breaks of the overhead wiring are locations where the power supply on the catenary sections changes. Different types of sections breaks are in use. The details of the overhead wiring and the section breaks in relation to possible locations of SMBs are included in OVS69133-1 (ProRail, 2018f). Most limiting are a special type of section breaks called Open Span Inrichting (OSI). A train stopping under an OSI could cause severe damage to the OSI and the rolling stock itself. To prevent trains from stopping under an OSI, the SMB should be placed at least 425m in rear of the OSI. This limits the creation of short blocks. In the modelled infrastructure for this thesis, the yard of Utrecht contains a lot of OSIs. Creation of short blocks is a difficult task. Implementation of ERTMS/ETCS HL3 and the overhead power supply should go hand in hand.

4.1.6.5. Junctions

After a point in diverging direction, a minimum sighting distance of 100m to the SMB in rear shall be taken into account. For a converging point the minimal distance to the SMB in rear is 6m. Furthermore, it shall be avoided that a train can run over a set of points and comes to a halt on the points due to an EoA, blocking the set of points and obstruct operations. When this is solved in the VPT/TC systems, it should be possible to create short blocks around junctions. This is modelled in the infrastructure for this thesis.

4.1.6.6. Platforms

A sight distance from the stop location to the SMB of 10m to 15m should be taken into account. If a platform is enclosed by SMBs, the distance between the start of the platform and the SMB should be at least 100m. A train having dwelled at the platform is only allowed to leave when the train has a MA that stretches further than the maximal train length or 425m. Lastly, two trains cannot dwell at the same platform at the same time, unless the platform is sectioned and both trains fit within the platform. The platforms are the longest (virtual) sections on the corridor Utrecht – Den Bosch. These form the bottleneck of the corridor, limiting capacity.

4.2. Impact on implementation

The lower block section length limitation can limit the capacity improvement at low speeds near stations. Virtual block sections smaller than 200m near stations can reduce the headways between successive trains. Smaller blocks (minimum length of 100m) are possible within the regulations in consultation with ProRail. The upper limit of 5000m for block section length is not an issue for the capacity of this corridor. When the aim of an ERTMS/ETCS HL3 implementation project is to reduce the trackside train detection to the minimum and there are no infrastructural requirements for trackside train detection, the upper limit of 5000m might be too low.

To fully benefit from reduced headways near station areas, the transition between LNTC and Level 2/3 signalling should occur at such a distance from stopping locations / station areas that the obliged length of the first block section does not hinder the headways. Block sections and SMBs should be placed around special sections carefully. The location of existing phase breaks and section breaks can be limiting to SMB placement. Sections with large gradients and/or tunnels require operational procedures to meet the requirements set by the engineering rules.

The issues that arise from the special sections could possibly result in large headway in between successive (freight) trains. The track ahead should be free to allow the freight train to pass without being hindered. Moreover, the special sections can limit the possibility to create short (virtual) blocks and limit the placement of block sections where they will be optimal for performance. These issues are not safety relevant, but create operational risks that should be mitigated. Maintaining the existing procedures or solving the issues in the VPT/TC systems using flow dependent authorisation, train dependent authorisations based on the train classification or other solutions to reduce headways of these trains can be a solution.

In the case study of this thesis short virtual subsections are created along the open track. The overhead wiring at the yard of Utrecht is limiting the creation of short blocks. However, with the 2019 timetable this is not a problem, as the yard itself is not the most restrictive area for the trains to Den Bosch, due to the four tracks to Houten Castellum. On other corridors (e.g. to Arnhem, only two tracks available from the yard onwards) the yard can result in capacity issues.

A solution in the VPT/TC systems for the existing L/H-signals, level crossings and junctions is assumed to be operational in this study. Short virtual blocks are created on these special sections. X/G-signals are not present on the relevant corridor, thus form no bottleneck for the ERTMS/ETCS HL3 implementation of this thesis.

The concept of ERTMS/ETCS HL3 signalling and train protection is in the first place a safety system. The system layout should guarantee safe train operations. Traffic management and operations regarding special trains that require specific solutions can also be solved in other systems than the safety system, such as the ETML to be developed or the legacy national traffic management systems.

5. Case study

The theory of the ERTMS/ETCS Hybrid Level 3 signalling system has been discussed in the previous chapters. Actual implementation of this new signalling system in the Netherlands is yet to come: no real-life quantification of capacity and asset impacts is readily available or can be tested. This chapter introduces the case study which is used to assess the signalling concept. Section 5.1 describes the tooling that is used for the simulation. The selection and description of a relevant corridor for simulation purposes is described in section 5.2. The input for the simulation model is explained in section 5.3.

5.1. Simulation tooling

Simulation will be used for answering the main research questions. This method allows for a direct comparison of performances between different block signalling and train protection systems. The main advantages of simulation are the following:

- Direct comparison of the capacity performance of infrastructure and timetable variants;
- Direct comparison of the timetable robustness;
- Indication of conflicts between train paths;
- Testing future timetable adjustments.

For this study, the main use of simulation is the possibility of testing several alternative variants of ERTMS/ETCS HL3 infrastructure and comparing them with ERTMS/ETCS L2 and the legacy signalling system NS'54/ATB-EG. This requires a microscopic infrastructure simulation model.

Currently, during the planning, testing and operational phases different macroscopic and microscopic planning and simulation tools are in use at ProRail and the operators, e.g. DONNA, DONS, SIMONE, FRISO/ROBERTO and OpenTrack. Data exchange between software tools is a cumbersome procedure and often requires manual data transmission. The use of one simulation tool throughout the different phases of planning and design is a wish of several foreign infrastructure managers and operators and ProRail is facing this challenge as well.

This thesis uses the integrated microscopic planning and simulation tool RailSys, developed by RMCon. RailSys 11 is already widely used in the railway sector, e.g. in Sweden (Trafikverket), Austria (ÖBB), Germany (DB) and Switserland (SBB), as well as several operators worldwide, engineering firms, consulting offices and research institutes (RMcon, 2018). It features native ERTMS/ETCS support, allows for distinctive infrastructure and timetable models and includes a rolling stock database. RailSys allows the user to change multiple settings, both on simulation settings as well as on ERTMS/ETCS-parameters and rolling stock characteristics.

The biggest advantage of RailSys is the integration of planning and simulation modules. Changes in infrastructure, rolling stock or timetables directly lead to recalculation of scheduled train paths and includes conflict detection. More detailed system behaviour can be obtained by running the simulation module. A disadvantage of using RailSys as simulation and planning tool is the unavailability of the ERTMS/ETCS HL3 signalling system. However, this signalling system is developed by RMCon for use in this thesis and is available for future use.

5.2. Simulation corridor

To assess the impact of ERTMS/ETCS HL3 on railway capacity a relevant corridor is to be simulated. Simulating the Dutch network as a whole would be too cumbersome. The corridor should be representative for the Dutch network. The following criteria for selection are used:

- High infrastructure occupation rates;
- Mixed traffic (IC's, Sprinter-trains and freight trains) to be able to assess regular train traffic;
- Mainly used by passenger trains, as those trains are the trains that can be equipped with TIMS. The headways of TIMS-equipped trains can be reduced and will benefit capacity consumption;

- At least two railway tracks (one track for each direction).

Of all the available corridors of the Dutch railway network, the corridor Utrecht – Den Bosch has been chosen to perform the case study. It satisfies the criteria mentioned, with it the existing infrastructure occupation, high frequent passenger services and frequent freight services to the Betuweroute and Den Bosch. Several reference studies for this corridor are available as well.

5.2.1. Infrastructure

The corridor between Utrecht and Den Bosch (full name: 's-Hertogenbosch) has a length of 48 km. It is the main connection between the north-west and the south-east of the Netherlands. Seven smaller stations are located in between: Utrecht Vaartsche Rijn, Utrecht Lunetten, Houten, Houten Castellum, Culemborg, Geldermalsen and Zaltbommel. Figure 32 presents the corridor on a topographic map.

Between Utrecht and Lunetten the corridor to Arnhem runs parallel, and near Den Bosch the corridor to Nijmegen runs parallel over a short distance. However, all mentioned corridors have separate tracks. Near Geldermalsen a connection with the corridors to Dordrecht and Tiel is present. Just south of Geldermalsen the corridor is connected to the Betuweroute freight corridor.

Between Utrecht and Houten Castellum the corridor has four tracks for the train services, two tracks for Sprinter-services and two tracks for all ICs and freight trains. From Houten Castellum to Geldermalsen there are just two tracks, one for each direction. At Geldermalsen, the Sprinter trains, the IC's and the freight trains all have their own tracks, to allow for overtaking. From Geldermalsen to Den Bosch two tracks are available, with a third track present over only small distances along the corridor. A schematic overview of the track layout is included in Figure 33.

The corridor crosses four rivers and canals between Utrecht and Den Bosch: the Amsterdam-Rijnkanaal, Lek, Waal and Maas are being crossed. In the direction from Utrecht to Den Bosch the slopes to the bridges over the rivers Lek and Waal are rather steep and long (1.750m at 8,5 promille and 1.300m at 8 promille respectively). To prevent freight trains from having to stop on the slope and not being able to accelerate from standstill, L/H-signals are present prior to these slopes.

Figure 32 | Topographic overview Utrecht - Den Bosch (ProRail)

5.2.1.1. Corridor development

The station and railway yard of Geldermalsen are going to be upgraded from 2020 onwards. Trains on the corridor Geldermalsen – Dordrecht currently share the tracks with the trains on the corridor Utrecht – Den Bosch, but this dependency is being removed. Geldermalsen will be equipped with an additional platform for the trains to Dordrecht. The emplacement of Geldermalsen will be transformed as well, with only one track remaining for the freight trains to be overtaken.

Station Utrecht Centraal and the emplacements has been upgraded in project 'DoorStroomStation Utrecht'. A large number of switches around Utrecht have been removed, to undo corridor connectivity. The risk of transfer of infrastructure disturbances or timetable pertubations from one corridor to another is hereby reduced. This project has also had influence on the station flexibility: all IC trains to Den Bosch now have to depart from tracks 18/19, all Sprinter-trains depart from tracks 20/21 and the freight trains pass platform 15. Departure for the direction of Den Bosch from other platforms is no longer possible.

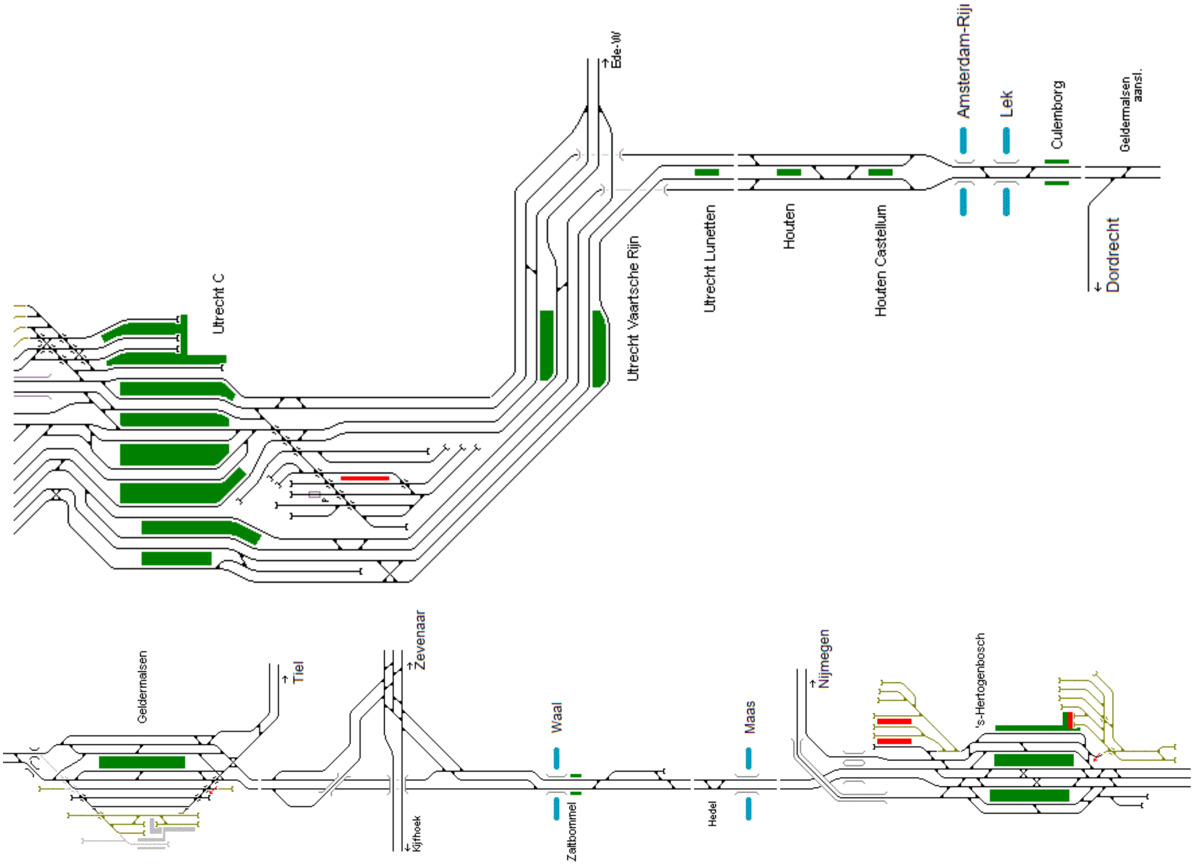

Figure 33 | Schematic overview of the track layout Utrecht - Den Bosch (Sporenplan, 2018)

In the railway industry, the stations and timing points all have their own abbreviations. Mostly these are used instead of the full names. The relevant abbreviations for this corridor are denoted in Table 11.

Table 11 | Abbreviations of railway stations and timing points, Utrecht - Den Bosch

Abbreviation	Full name	Abbreviation	Full name
Ut	Utrecht Centraal	Gdm	Geldermalsen
Utge	Utrecht goederenemplacement	Mta	Meteren aansluiting
Utvr	Utrecht Vaartsche RIjn	Mtaz	Meteren aansluiting zuid
Utln	Utrecht Lunetten	Zbm	Zaltbommel
Htn	Houten	Ozbm	Oud-Zaltbommel
Htn	Houten Castellum	Hdl	Hedel
Cl	Culemborg	Htda	Den Bosch Diezebrug aansluiting
Gdma	Geldermalsen aansluiting	Ht	Den Bosch

5.2.2. Timetable

5.2.2.1. Train services

Trains in the Dutch timetable are classified by series of train services that all follow the same route, have the same scheduled stops and a fixed pattern. Each train has a unique number, consisting of the series and a runner-up/counter. The corridor Utrecht – Den Bosch has mixed traffic, with 6 IC's, 6 Sprinter-trains and 2 freight trains each hour. The pattern of services on the corridor is indicated below and visualised in Figure 34:

- Series 800 (IC) from Den Helder/Alkmaar to Maastricht;
- Series 3500 (IC) from Schiphol to Venlo;
- Series 3900 (IC) from Enkhuizen to Heerlen. The IC-trains of series 800, 3500 and 3900 form a 10-minute pattern between Utrecht and Den Bosch;
- Series 6000 (Sprinter) from Woerden to Tiel;
- Series 6500 (Sprinter) from Utrecht to Houten Castellum;

- Series 6900 (Sprinter) from Den Haag Centraal to Den Bosch. The trains of series 6000 and 6900 form a 10/20 minute-pattern between Utrecht and Geldermalsen and the series 6000, 6500 and 6900 forms a 10-minute pattern between Utrecht and Houten Castellum;
- Series 7200 (Sprinter) from Dordrecht to Geldermalsen;
- Additional to the regular passenger trains, two paths each hour are available for freight trains between Utrecht and Den Bosch and Utrecht and the Betuweroute, with an overtake for the IC-services in Geldermalsen.

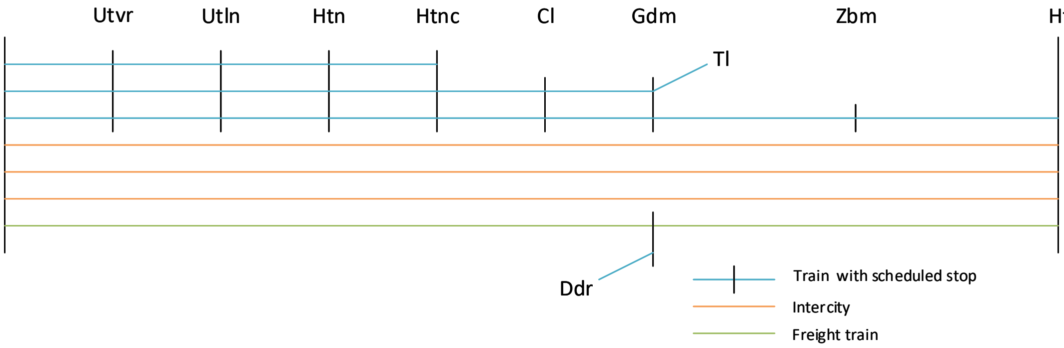

Figure 34 | Schematic overview of the train services, each line represents 2 trains per hour

5.2.2.2. Scheduled timetable

The scheduled timetable (Table 12) is the actual timetable used by ProRail, NS and other operators. It is based on the technical minimum runtimes and includes a runtime supplement (8% runtime supplement when planning in 1/10 minute). The path of the IC-trains (series 800, 3500 and 3900) is 2 minutes longer than the technical minimum runtime + 8% between Geldermalsen and Den Bosch to fit the timetable.

Table 12 | Scheduled timetable Utrecht, pattern of half an hour

	Ut		Utvr		Utln		Htn		Htnc		Cl		Gdm		Zbm		Ht	
	A	D	A	D	A	D	A	D	A	D	A	D	A	D	A	D	A	D
SPR 6500	:59	:04	:06	:06	:09	:09	:13	:13	:16	-								
IC 800	:01	:03															:30	:36
Freight	:02 - :05												:25 - :29				:49	
SPR 6000	:08	:11	:13	:13	:16	:16	:20	:20	:22	:23	:30	:30	:36	:41				
IC 3900	:12	:14															:40	:45
IC 3500	:18	:24															:52	:54
SPR 6900	:20	:22	:24	:24	:27	:27	:31	:31	:34	:34	:40	:40	:46	:51	:57	:57	:07	-
SPR 7200													:03	:09				

The timetable contains overtakings at both Houten and Geldermalsen, allowing the IC's in front of the Sprinter train. The exact timing of the freight paths from Utrecht to Geldermalsen depends on the destination of the specific train. Trains heading for the Betuweroute pass Utrecht at :05, arriving at the Betuweroute (Metbr) at :28 without a stop at Geldermalsen. Freight trains from Utrecht to Den Bosch and Eindhoven pass Utrecht at :02, arriving at Geldermalsen at :21, with a departure at :28 to Den Bosch.

5.2.3. Rolling stock

Over the day, different types and combinations of rolling stock are in use throughout the series on the corridor. This subsection describes the rolling stock that is in use.

All ICs in the series 800, 3500 and 3900 are of the type VIRM. It is a heavyweight double-deck passenger train. The length depends on the series and the time of the day: the smallest possible composition is a VIRM-IV, with a length of 108m, the longest possible composition is a VIRM-12 (6+6 or 4+4+4) with a length of 324m.

Most Sprinters trains are of the type Sprinter Light Train (SLT), a modern and light type of rolling stock. The smallest possible composition is a SLT-IV with a length of 69m, the longest composition is a SLT-12 (6+6) with a length of 201m. Some of the Sprinter services use the older SGM type of rolling stock. The SGM rolling stock is to be phased out with the introduction of new types of Sprinter trains.

The freight trains on the corridor have different characteristics from train to train. The traction locomotive, length and mass of the trains are all different. Most traction units are e-locs of types Baureihe 186 (Bombardier TRAXX) or Baureihe 189 (Siemens ES64), with one or two traction units per train. The trains are usually loaded with general cargo or coals.

5.3. Simulation model

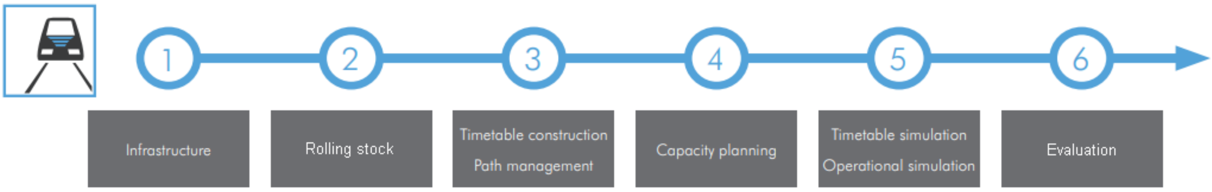

Figure 35 | RailSys workflow (RMcon, 2018)

The input for the RailSys simulation consists of the three mentioned aspects: infrastructure, rolling stock and the timetable. The input forms the basis for the next steps in the RailSys procedure, capacity planning, timetable and operational simulations and evaluation of the results. See Figure 35. The model input and other assumptions for the simulation study are described in the next subsections.

5.3.1. Infrastructure model

The Dutch rail infrastructure network is available as a detailed RailSys model. Included in the infrastructure model are all relevant track characteristics. The model is built around the legacy NS’54/ATB-EG signalling system. Signals, block sections and interlockings are adapted to the ERTMS/ETCS counterparts for the ERTMS/ETCS L2 and HL3 variants. The ruling schematic drawings of the track layout are used to complete the infrastructure model and to build the ETCS model. Appendix A1 provides an overview of the valid OBE-drawings that have been consulted for the projection.

The two long and steep slopes towards the railway bridges over the rivers Lek and Waal are equipped with L/H-signals for freight trains in the NS’54/ATB-EG model. This long block reservation for freight trains is maintained in the ETCS implementations.

The timetable is only considered in the direction from Utrecht Centraal to Den Bosch. This study compares the NS’54/ATB-EG legacy signalling system with ERTMS/ETCS L2 and different projections of ERTMS/ETCS HL3 on the existing tracks. The simulation setup for the different signalling systems is described in the following subsections. The legend of the figures is presented in Figure 36. An overview of the infrastructure model from RailSys is included in Appendix A2.

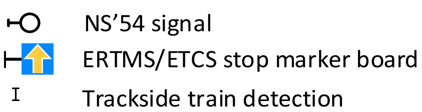

Figure 36 | Legend for Figure 37, Figure 38 and Figure 39

5.3.1.1. NS’54/ATB-EG model

The NS’54/ATB-EG signalling model in RailSys consists of two main infrastructural items, signals (in direction of travel) and release contacts. Blocks are created from signal to signal and work according to the three-aspect signalling approach. Blocks are reserved from a signal to the release in rear of the next signal. Sectional release is triggered by trains passing a release contact, which can be either track circuits or axle counters. Release contacts are located shortly after each signal and could additionally be located in between signals, e.g. at the division of two track circuits. The infrastructure model of NS’54/ATB-EG is presented in Figure 37.

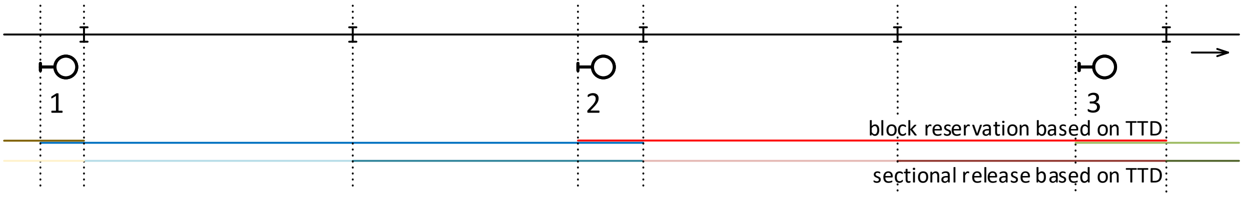

Figure 37 | Infrastructure modelling and block reservation/release of NS’54/ATB-EG in RailSys. The colors indicate the reservation and release of the blocks

NS’54/ATB-EG signalling makes a clear distinction between automated signals and manually controlled signals. Automated signals are used along the open track, where the aspect of the signal depends on the occupation of the (two) block sections in rear of the signal. Manually controlled signals protect block sections with switches and turnouts. These are controlled by the dispatcher. The interlocking setup of NS’54/ATB-EG in included in Table 13.

Table 13 | Interlocking setup NS'54/ATB-EG in RailSys

Signalling	Type	Block occupation	Setup time [s]	Block release	Partial release	Release time TTD [s]
NS’54	Automated	Signal to signal + overlap	0	TTD	TTD	3
	Manual	Signal to signal + overlap	12	TTD	TTD	3

5.3.1.2. ERTMS/ETCS Level 2 model

The RailSys model of the NS’54/ATB-EG infrastructure is transformed to an ERTMS/ETCS-model by replacing the signals by stop markerboards and replacing the interlocking by the ETCS-equivalent, see Figure 38. The braking model is no longer dependent on the block sections, but is based on the individual train characteristics. Blocks are reserved from an SMB to the release contact shortly in rear of the next signal. The release of blocks is still dependent on the trackside train detection.

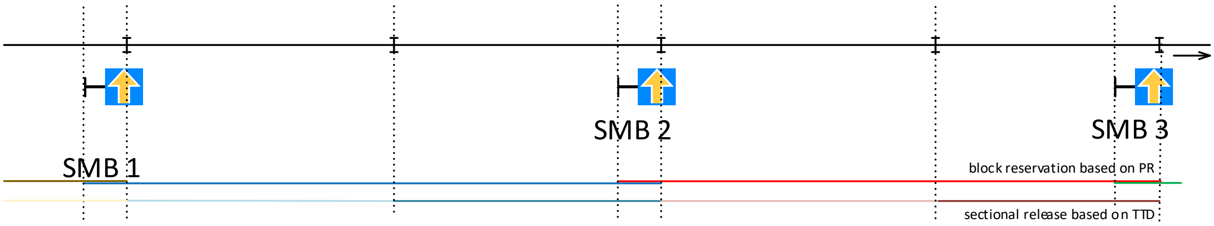

Figure 38 | Infrastructure modelling and block reservation/release of ERTMS/ETCS L2 in RailSys. The colors indicate the reservation and release of the blocks

ERTMS/ETCS has different setup times for blocks containing movable elements compared to blocks without movable elements. The setup is provided in Table 14.

Table 14 | Interlocking setup ERTMS/ETCS Level 2 in RailSys

Signalling	Type	Block reservation	Setup time [s]	Block release	Partial release	Release time TTD [s]
ETCS L2	No movable elements	SMB to SMB + overlap	0 + 6	TTD	TTD	3
	Movable elements	SMB to SMB + overlap	9 + 6	TTD	TTD	3

5.3.1.3. ERTMS/ETCS Hybrid Level 3 model

ERTMS/ETCS HL3 consists of small blocks between stop markerboards. The block sections are independent of the remaining trackside train detection: the trackside train detection can be located at any required trackside location. The block sections are therefore ‘virtual’ as apart from the stop markerboards no other equipment has to be present at the border of block sections.

All trains in the ERTMS/ETCS HL3 approach reserve (virtual) blocks based on their Position Reports. The block release procedure depends on the type of train: trains equipped with TIMS handle the block release differently compared to train without TIMS.

Trains equipped with TIMS use the Position Report combined with the known train length and the confirmed train integrity to determine the position of the rear end of the train. When the rear end of the train has passed the border of a virtual block section, the previous section can be released. For trains without a TIMS, the position of the confirmed rear end of the train still relies on trackside train detection. The train has to pass a detection point to be able to release the previous block sections. A detection point in the HL3 infrastructure is modelled as a signal in opposite direction.

To be able to simultaneously run trains with and without a TIMS, the infrastructure model is equipped with dual signalling. ERTMS/ETCS L3 blocks are modelled for trains with TIMS and ERTMS/ETCS HL3 blocks are modelled for trains without TIMS. For each train in the simulation the right ERTMS/ETCS level has to be selected case by case. This distinction between TIMS-equipped trains and trains without TIMS is presented in Figure 39.

This type of signalling and train protection system still requires a distinction between blocks with movable elements and blocks without movable elements. As with ERTMS/ETCS L2, the additional 6 seconds delay for MA transmission is modelled in the setup time. The characteristics of the different ERTMS/ETCS interlockings are featured in Table 15.

Table 15 | Interlocking setup ERTMS/ETCS Hybrid Level 3 in RailSys

Signalling	Type	Block reservation	Setup time	Block release	Partial release	Release time TTD [s]
ETCS L3	No movable elements	SMB	0 + 6 s	SMB	TTD	3 s
	Movable elements	SMB	9 + 6 s	SMB	TTD	3 s
ETCS HL3	No movable elements	SMB	0 + 6 s	TTD	-	3 s
	Movable elements	SMB	9 + 6 s	TTD	-	3 s

The setup time and block release times are fixed. The other aspects of the block occupation time are based on block and train characteristics. The approach time is based on the brake characteristics and speed of the rolling stock as well as on the length of the block section. The journey time is based on the length of the block and the speed of the train. With the smaller virtual blocks the distance headway of TIMS-equipped trains is smaller compared to ERTMS/ETCS L2. The journey time of non-equipped trains depends on the distance between trackside train detection units. The clearing time for the trackside train detection equipment is still based on the length and speed of the train.

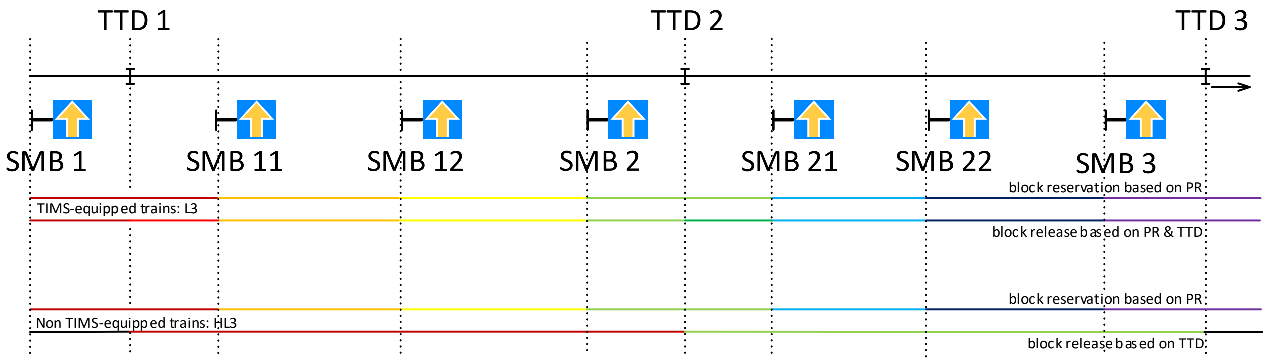

Figure 39 | Infrastructure modelling and block reservation/release of ERTMS/ETCS Hybrid Level 3 in RailSys. The colors indicate the reservation and release of the blocks

5.3.2. Timetable model

For simulation purposes, the trains of series 7200 are not included. With the future upgrade of Geldermalsen station and emplacement the train path of this series no longer interacts with the paths on the corridor Utrecht-Den Bosch. The trains of series 6000 are only simulated up to and including the stop in Geldermalsen. From Geldermalsen onwards they will branch to Tiel. All freight trains are simulated to continue to Den Bosch.

As some of the scheduled paths are bent, it is not directly possible to compute the capacity of the unhindered schedule. In the simulation the order and departure times of the trains are used to create unhindered train paths. The Sprinter trains are scheduled to have a dwell time of 42 seconds at intermediate stations.

The IC trains can overtake in Geldermalsen. IC800 overtakes the Sprinter of series 6900, that has a scheduled dwell to let the IC pass. IC3900 overtakes the freight train, that dwells at the emplacement. The minimum dwell time of the freight train is set to 120 seconds, to simulate the brake release and air compression over the full length of the freight train before departure is possible. The simulated timetable is included in Table 16 and the pattern is visualised in Figure 40.

Table 16 | Simulated timetable, 30 minute-pattern

	Ut		Track Ut	Scheduled dwell times [s]	Scheduled dwell time Gdm [s]	Minimum dwell time Gdm [s]	Track Gdm	Track Ht
	Arrival	Departure						
SPR 6500	:59	:04	21	42	300	42	-	-
IC 800	:01	:03	18	-	-	-	505	6A
Freight	:03		15	-	300	120	506	705
SPR 6000	:08	:11	21	42	300	42	4B	-
IC 3900	:12	:14	18	-	-	-	505	6A
IC 3500	:22	:24	18	-	-	-	505	6A
SPR 6900	:20	:22	21	42	-	42	4B	4A

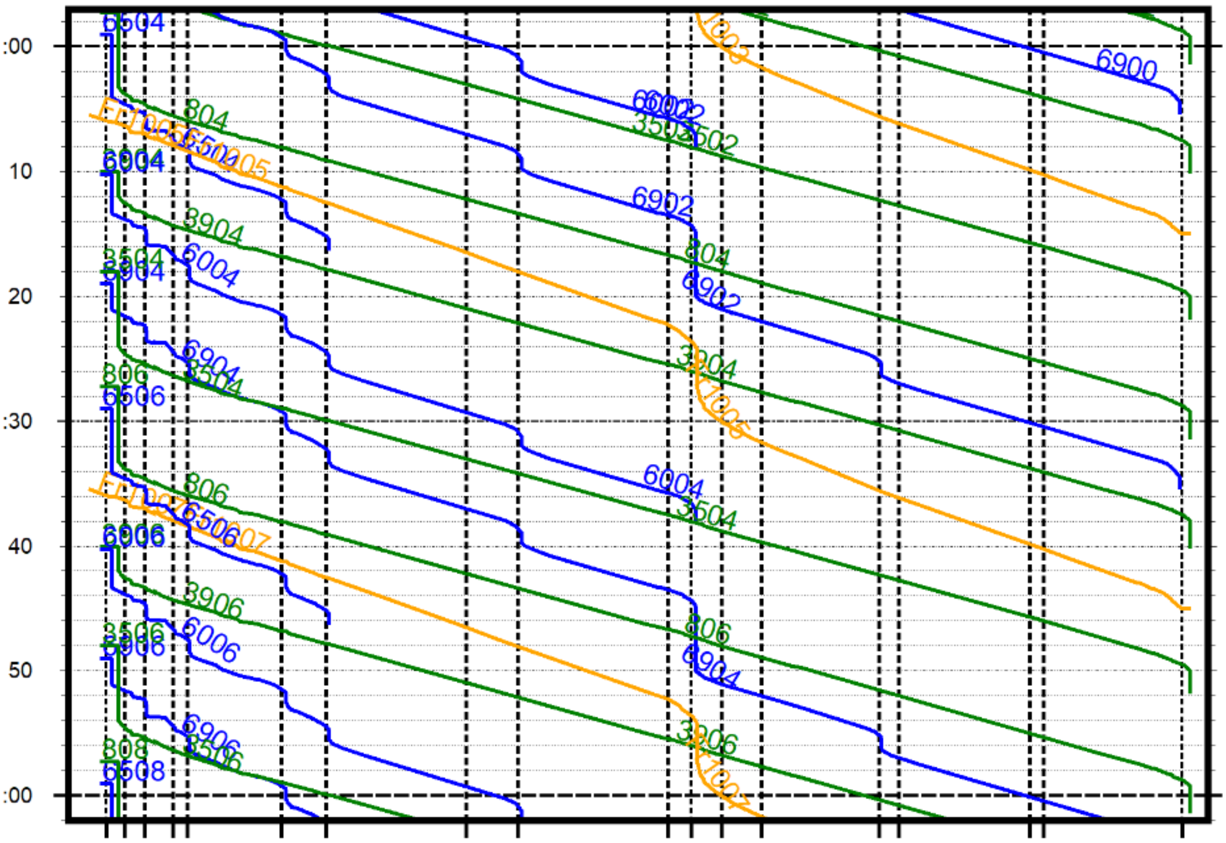

Figure 40 | Pattern of the simulated timetable

The simulated unhindered operations are provided by a combination of the runtimes and the dwell times. For passenger trains the technical minimum runtimes between timing points are adjusted by a runtime supplement of 8%. This supplement is meant to cover stochastic variables and processes during operations. Several ways can be thought of to implement this runtime supplement, see Figure 41.

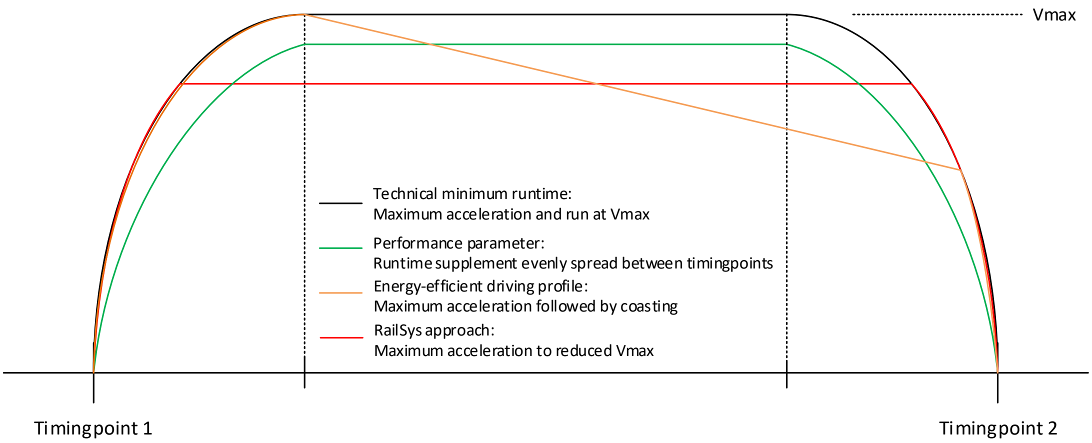

Figure 41 | Different approaches of runtime supplement

For planning purposes the use of a performance parameter is preferred. This leads to an even spread of the runtime supplement over the whole train run, including the acceleration and deceleration phase. When using an energy-efficient runtime supplement, the train accelerates at the maximum rate to V_{max} and then starts coasting. As the performance parameter is not available for ERTMS/ETCS signalling in RailSys, this thesis uses an approach that models maximum acceleration to a reduced V_{max}, followed by cruising and braking at the maximum deceleration rate. Both the energy-efficient approach and the RailSys approach can result in optimistic results regarding headways and cross-over calculations near origin and destination stations, as no runtime supplement is included during the acceleration and deceleration phases. However, all three runtime supplements are approaches of the reality: none of these approaches is exactly the right way to model the individual train (driver) behaviour. All three approaches for the runtime supplement result in the same runtime and the same total supplement between origin and destination.

The 60-second buffer scheduled between successive train operations prevents the handover of small delays from train to train is not modelled for compression and perturbation purposes. The buffer is a rather arbitrary number and only generates soft conflicts between train paths. However, the buffer time is included after compression, to compare the feasibility of the compressed timetable including the required buffer.

5.3.3. Rolling stock model

RailSys contains a library of rolling stock types and their characteristics. The characteristics of each type of rolling stock and every possible composition can be tweaked individually.

For the simulation runs, standard types of rolling stock is used. The standard intercity train is a VIRM (VIRM-VI). This is a heavy double-decker IC for which the acceleration and braking behaviour is known quite well. The standard Sprinter train is of the type SLT (SLT-VI). This is a light sprinter train that will be in use in large parts of the Dutch network for at least the next 20 years. As with the VIRM, the braking and acceleration behaviour of SLT is known quite well. For the simulation of ERTMS/ETCS HL3 signalling and train protection, these passenger trains will be equipped with a TIMS thus following the ERTMS/ETCS L3 interlocking principles. The braking behaviour is modelled as gamma-braking, as the full braking performance of the rolling stock is known.

The standard freight train is a lambda-modelled train, modelled using the ETCS conversion model. Only the brake percentage of the train is known. This train is not equipped with a TIMS. It is being hauled by a Traxx BR186 e-locomotive, which will be in use as freight locomotive for a substantial time in the future. For simulation purposes the freight train has a fixed length of 550 m, a fixed weight of 2.000 ton without the locomotive, with a fixed brake percentage of 65% and the brakes of the locomotive in P-setting. The setup of the rolling stock is included in Table 17.

Table 17 | Rolling stock setup in RailSys

Train type	Standard rolling stock	Length	Weight	Brake model	Brake position	Rotating mass	Safe brake deceleration
IC	VIRM-VI	162 m	352 ton	Gamma	P	6%	see Table 20
Sprinter	SLT-VI	100 m	176 ton	Gamma	P	6%	see Table 20
Freight train	Traxx BR186	550 m	2.000 ton	Lambda	P – 65%	-	0,31 m/s²

The brake deceleration values for the gamma trains have been determined by measuring actual brake actions and calculating safe deceleration values accordingly. For the standard rolling stock passenger trains the nominal deceleration values have been determined. The brake performance is determined without the electrodynamic (ED) brake and 80% electromagnetic rail (Mg) brake for VIRM-VI, and without ED-brake and without Mg-brake for SLT-VI. The ED-brakes for both types of rolling stock and the Mg-brake for the SLT-VI are not considered to be safe. The resulting nominal braking performance of the rolling stock is presented in Table 18.

Table 18 | Nominal brake deceleration VIRM & SLT (ERTMS-programma, 2016)

Rolling stock	Speed [km/h]	[0-40]	[40-60]	[60-80]	[80-100]	[100-120]	[120-140]	[140-160]	
VIRM-VI	A_brake_nominal [m/s²]	1,55	1,44	1,42	1,40	1,39	1,37	1,34	Overloaded
		1,67	1,55	1,52	1,50	1,49	1,47	1,44	Normal
SLT-VI	A_brake_nominal [m/s²]	1,32	1,15	1,06	1,03	1,07	1,16	1,25	Overloaded
		1,43	1,25	1,16	1,12	1,16	1,26	1,36	Normal

The nominal brake deceleration is corrected by the factor K_dry, based on the allowed Confidence Level and a best- & worst-case scenario for the braking performance of the rolling stock. Indications for possible values of K_dry (ERTMS-programma, 2016) are presented in Table 19.

Table 19 | K_dry (ERTMS-programma, 2016)

Confidence Level	CL4 (10^{-4})	CL5 (10^{-5})	CL6 (10^{-6})	CL7 (10^{-7})	CL8 (10^{-8})
K_dry, best-case	0,88	0,86	0,83	0,81	0,78
K_dry, worst-case	0,80	0,78	0,75	0,73	0,70

The nominal braking deceleration corrected with K_dry results in the predicted safe braking behaviour. The Dutch national laws prescribe the use of Confidence Level 4 (10^{-4}). The braking behaviour of the modern rolling stock is assumed to fit in the best-case scenario. This results in a value for K_dry of 0,88. The resulting predictions for the safe EBD-deceleration of the rolling stock are included in Table 20.

Table 20 | Safe brake deceleration VIRM & SLT (ERTMS-programma, 2016)

Rolling stock	Speed [km/h]	[0-40]	[40-60]	[60-80]	[80-100]	[100-120]	[120-140]	[140-160]	
VIRM-VI	A_brake_safe [m/s²]	1,36	1,27	1,24	1,23	1,22	1,20	1,18	Overloaded
		1,47	1,36	1,33	1,31	1,31	1,29	1,26	Normal
SLT-VI	A_brake_safe [m/s²]	1,16	1,01	0,94	0,90	0,93	1,00	1,09	Overloaded
		1,26	1,10	1,01	0,99	1,02	1,10	1,20	Normal

When braking under NS'54/ATB-EG and unguided braking under ERTMS/ETCS (dwelling at intermediate stations while a movement authority has been granted beyond the stopping location) the drivers are assumed to brake at a fixed rate of $a = 0{,}50$ m/s² for passenger trains and $a = 0{,}31$ m/s² for freight trains.

5.4. Infrastructure variants

This study focuses on a comparison between the legacy signalling system NS'54/ATB-EG, ERTMS/ETCS Level 2 and ERTMS/ETCS Hybrid Level 3. Five infrastructure variants are modelled to support this comparison.

1. NS'54/ATB-EG

This infrastructure variant leaves the existing infrastructure, signalling and train protection system in place. It models the behaviour of the legacy system as is, as a reference to the ERTMS/ETCS signalling implementations. See Figure 42.

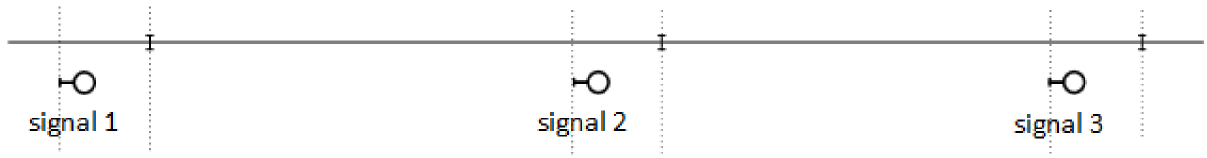

Figure 42 | NS'54/ATB-EG infrastructure model

2. ERTMS/ETCS Level 2

The second infrastructure variant introduces ERTMS/ETCS to the infrastructure model, see Figure 43. The NS'54 signals are replaced by ERTMS/ETCS SMBs and the ATB-EG block sections are replaced by the ERTMS/ETCS L2 equivalents. This variant is a simplification of the implementation of ERTMS/ETCS L2, without modification and optimization of the block layout to the new signalling system. The existing trackside train detection is maintained. All trains will release the block sections based on the TTD locations. The speed profile is adjusted to match the infrastructure restrictions instead of the block restrictions. This benefits the minimum technical runtimes of all trains slightly.

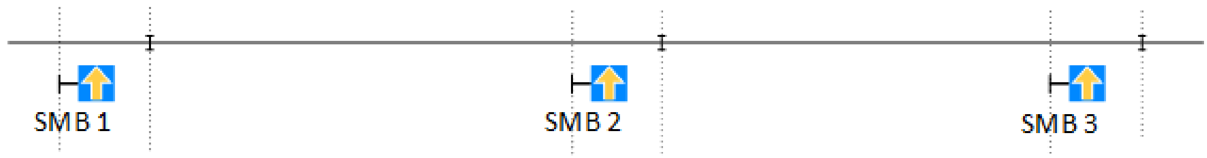

Figure 43 | ERTMS/ETCS Level 2 infrastructure model

3. ERTMS/ETCS Hybrid Level 3 with intermediate virtual subsections

Thirdly, ERTMS/ETCS HL3 is introduced. The ERTMS/ETCS L2 block sections are divided in smaller virtual subsections with a length of approximately 500 meters. See Figure 44. Trains equipped with TIMS release these blocks on the (virtual) block ends and on the trackside train detection, trains without TIMS release on the trackside train detection. All original TTD locations are maintained.

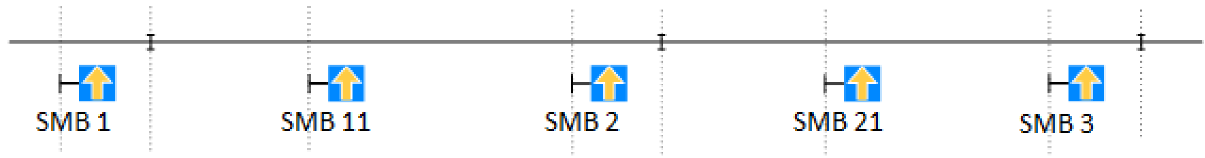

Figure 44 | ERTMS/ETCS Hybrid Level 3 infrastructure model, intermediate virtual subsections

4. ERTMS/ETCS Hybrid Level 3 with small virtual subsections

The ERTMS/ETCS HL3 infrastructure is further optimized by reducing the length of the virtual subsections on critical locations, introducing more and smaller blocks of ca. 100m on parts of the corridor. This is illustrated in Figure 45. The sizes of the virtual subsections is increasing with the expected train speeds. All existing trackside train detection is maintained in this infrastructural variant.

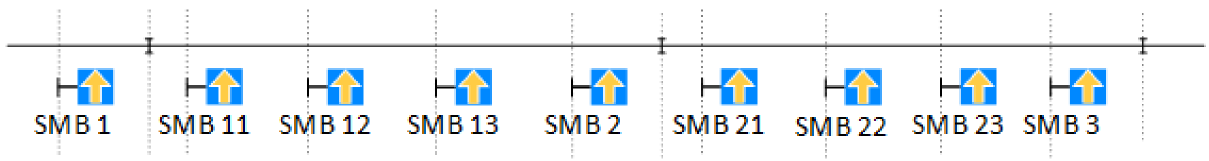

Figure 45 | ERTMS/ETCS Hybrid Level 3 infrastructure model, small virtual subsections

5. ERTMS/ETCS Hybrid Level 3 with small virtual subsections & reduced trackside train detection

The same block section infrastructure of the previous ERTMS/ETCS HL3 projection is used in this variant. The main difference is in the amount of trackside train detection: ERTMS/ETCS HL3 offers the possibility to reduce the remaining trackside train detection to the bare minimum. All existing TTD is removed in this infrastructure variant and replaced by detection on the critical locations only: all switches and level crossings on the corridor are equipped with trackside train detection to ensure safe operations for all train types. This is presented in Figure 46.

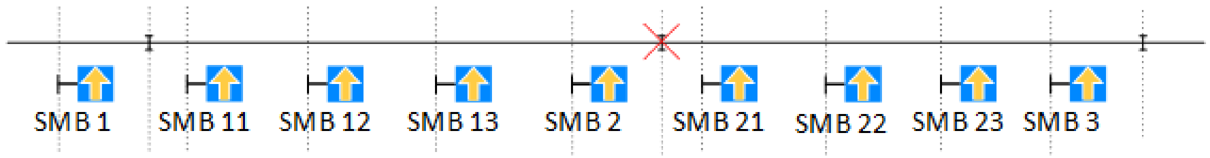

Figure 46 | ERTMS/ETCS Hybrid Level 3 infrastructure model, small virtual subsections, reduced trackside train detection

5.5. Other assumptions

The following assumptions are included in the infrastructure, rolling stock and timetable models:

- Sprinters with a stop at intermediate stations on the open track are modelled to arrive on green under NS'54/ATB-EG. The track ahead is preoccupied for the train, as if it is to continue without a dwell. This procedure is not required for ERTMS/ETCS signalling;
- The catenary system has a nominal voltage of 1.500V DC;
- Neither a future upgrade of the infrastructure to allow track speeds of 160 km/h nor the temporary speed restriction at Culemborg is included in the infrastructure model;
- The simulation includes dwelling at the start and end stations;
- The area outside of the simulation corridor is assumed to be free of conflicts;
- The simulation corridor does not interact with other corridors.

6. Case study results

This chapter provides results of the ERTMS/ETCS Hybrid Level 3 simulations and timetable planning. Section 6.1 analyses the runtimes of the trains, section 6.2 contains an analysis on the infrastructure occupation and capacity consumption. In section 6.3 the system performances under perturbated scenarios are analysed, while section 6.4 analyses the sensitivity of the different ERTMS/ETCS implementations to changes in the braking model. Finally, section 6.5 provides an indication of the usability of the capacity benefits.

6.1. Runtimes

The technical minimum runtimes for the different signalling systems and the corresponding infrastructure variants have been determined by planning train paths and corresponding trains in RailSys. The scheduled runtimes consist of the technical minimum runtimes, 8% runtime supplement for the IC and the Sprinter trains as well as scheduled dwell times for all trains.

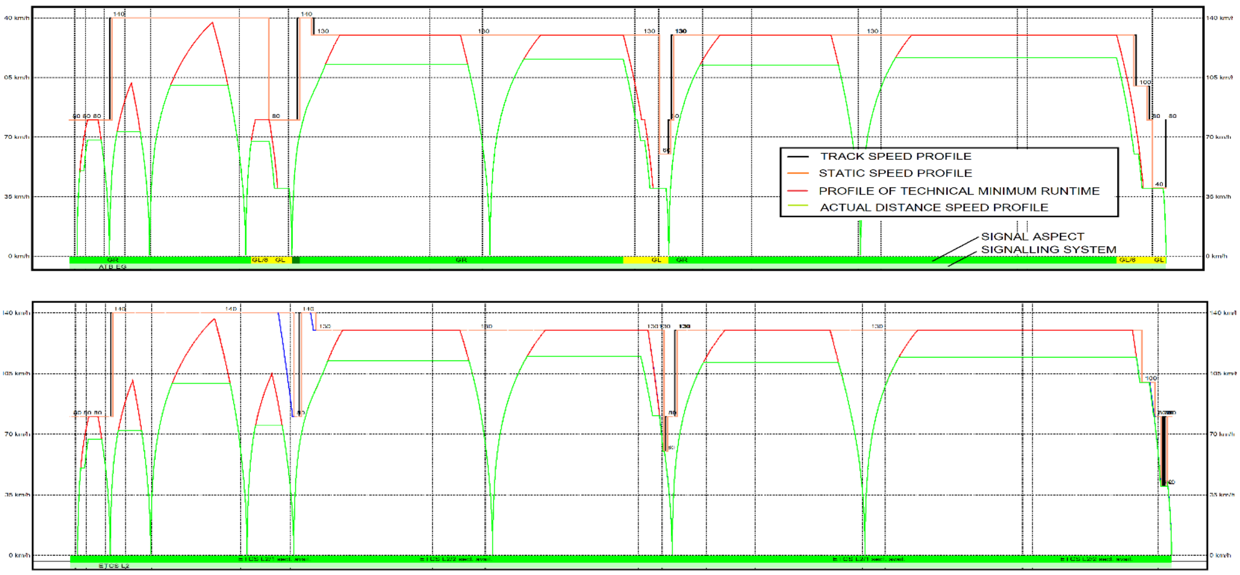

Figure 47 | Speed-distance graphs of a series 6900 train, NS’54/ATB-EG (top) and ERTMS/ETCS Level 2 (bottom)

Figure 47 shows the speed-distance graphs of a series 6900 Sprinter. All scheduled stops are visible by the speed drops. The graph of NS’54/ATB-EG indicates the block-dependent braking and speed reduction to 40 km/h at a yellow signal at three locations: the stops at Houten Castellum, Geldermalsen and Den Bosch. The other stops are unguided. Under ERTMS/ETCS the extended block-independent braking is visible in the graph, as the deceleration start later in distance.

Table 21 | Technical minimum runtimes

	IC		Sprinter		Freight train	
	Technical minimum runtime	Scheduled runtime	Technical minimum runtime	Scheduled runtime	Technical minimum runtime	Scheduled runtime
NS’54/ATB-EG	00:24:28	00:26:25	00:33:02	00:35:40	00:36:59	00:36:59
ERTMS/ETCS	00:24:04	00:26:00	00:32:04	00:34:38	00:36:12	00:36:12

Table 21 shows only small differences in runtimes between NS’54/ATB-EG and ERTMS/ETCS. These are caused by the extended braking of ERTMS/ETCS. As the number of braking actions on the corridor is limited (8 for the Sprinter, 1 for the IC, 1 for the freight train), the impact of the extended braking on the technical minimum runtimes is also limited.

The infrastructure of NS’54/ATB-EG is modelled with the ‘Arrival on green’ procedure activated for scheduled stops at stations along the open track, as this simulates reality. This procedure ensures that the signal behind the platform shows the green aspect upon arrival of the train at the station. It thereby allows for a fast platform approach. When ‘Arrival on green’ is disabled the NS’54/ATB-EG runtimes will increase as these trains will run into yellow prior to each stop, having to reduce the speed to 40km/h for the whole block section prior to the stop location. The ‘Arrival on green’ procedure is a solution to reduce runtimes under NS’54/ATB-EG. For ERTMS/ETCS no such procedure is available, nor required.

The runtimes of ERTMS/ETCS HL3 trains do not differ from ERTMS/ETCS L2 trains. The profit of train-dependent and block-independent braking is already introduced with ERTMS/ETCS L2.

6.2. Capacity analysis

The constructed conflict-free timetable has been compressed for the different signalling systems. The compression of a 1 hour period and a repeated first train leads to the Minimum Cycle Times of the systems and the corresponding infrastructure occupation, see Table 22.

Table 22 | Minimum Cycle Times and infrastructure occupation

		Minimum Cycle Time	Infrastructure occupation	Infrastructure occupation
NS’54/ATB-EG		00:50:24	3024 s	84,0%
ERTMS/ETCS L2		00:44:35	2675 s	74,3%
ERTMS/ETCS HL3	500m virtual subsections & existing trackside train detection	00:42:14	2534 s	70,4%
ERTMS/ETCS HL3	Virtual subsections up to 100m, existing trackside train detection	00:40:02	2402 s	66,7%
ERTMS/ETCS HL3	Virtual subsections up to 100m, reduced trackside train detection	00:43:00	2580 s	71,7%

ERTMS/ETCS L2 provides a benefit of almost 10 percent point compared to the legacy signalling system. Projecting smaller blocks decreases the infrastructure occupation by another 4 percent point, whilst creating blocks of 100m on critical locations can provide another 4 percent point. Finally, when reducing the trackside train detection, the larger headways around lambda freight-trains causes an increase of the infrastructure occupation to almost 72%. However, the infrastructure occupation is still more beneficial than the ERTMS/ETCS L2 implementation.

All compressed blocking time diagrams of the five infrastructure variants are collected in Appendix A3. Figure 48 presents the legend for all compressed blocking time diagrams in the remainder of this chapter and for the blocking time diagrams in the appendix. Each of the blocking time diagrams represents a one-hour period, with additionally 2 minutes prior and 10 minutes after the period presented in the graphs.

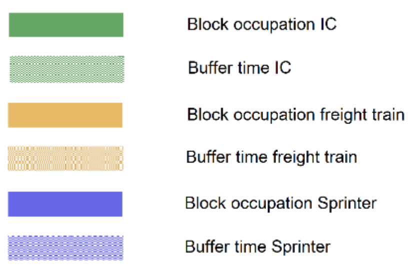

Figure 48 | Legend for the blocking time diagramsmm and compressed timetables

Figure 49 shows an overview of the compressed timetables of ERTMS/ETCS HL3 with small virtual subsections and existing trackside train detection (left) and with reduced trackside train detection (right). Clearly visible from these graphs is the decrease of the number of block releases of freight trains when the trackside train detection is reduced. This causes a larger headway between the freight train and the successive Intercity train.

The 14 train-pattern results in 10 critical headways per hour with NS’54/ATB-EG signalling: the trains of Sprinter series 6500 and 6000 are not critical within the compression. There are no other paths that depend on the paths of these trains. The freight train does hinder an IC twice, once before entering Geldermalsen and once before entering Den Bosch.

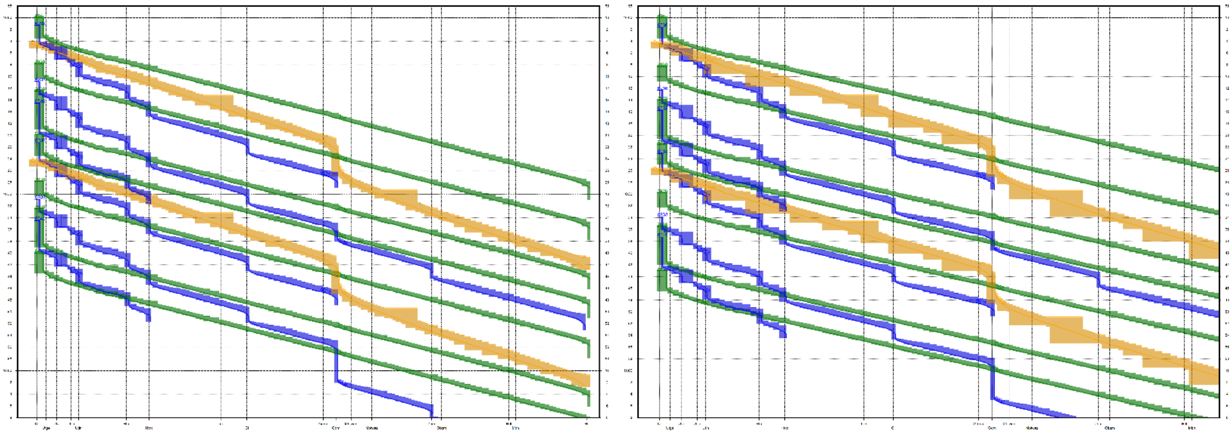

Figure 49 | Compressed timetables for ERTMS/ETCS HL3 with existing TTD (left) and ERTMS/ETCS HL3 with reduced TTD (right)

The different ERTMS/ETCS variants all have less critical headways compared to NS'54/ATB-EG. The compressed timetables contain more unused space between the individual trains and the dependability of train paths on previous paths is lower. An example: the freight train has a minimum dwell time of 120 seconds in Geldermalsen. In the NS'54/ATB-EG variant, the dwell has to be longer than the minimum, as the infrastructure is still occupied by the overtaking IC after 120 seconds. The freight train can only depart once the infrastructure has been released. The freight path is therefore fully dependent on the IC. With ERTMS/ETCS the IC has passed within the minimum 120 seconds. The freight train has to wait for the minimum dwell time before it can continue. The freight path is therefore independent from the IC.

All trains in the compressed timetable should have a 60 second buffer according to the timetabling norms. With less critical headways, the total buffer time to be added to all paths is lower. Table 23 presents the required buffer times and the resulting capacity consumption per infrastructure variant. Running the conflict-free and unbent timetable with the proposed buffer with NS'54/ATB-EG is strictly seen impossible: the simulated timetable including the buffer requires more than 3600 seconds before the first train of the cycle could be repeated. This issue is in practice solved by bending the critical paths of the Intercity trains between Geldermalsen and Den Bosch, allowing for an earlier departure of the successive trains.

Table 23 | Required buffer and the resulting capacity consumption

		Required buffer	Capacity consumption	Capacity consumption
NS'54/ATB-EG		720 s	3744 s	104,0%
ERTMS/ETCS L2		600 s	3275 s	90,9%
ERTMS/ETCS HL3	500m virtual subsections & existing trackside train detection	606 s	3140 s	87,2%
ERTMS/ETCS HL3	Virtual subsections up to 100m, existing trackside train detection	564 s	2966 s	82,4%
ERTMS/ETCS HL3	Virtual subsections up to 100m, reduced trackside train detection	616 s	3196 s	88,8%

Because of the lower dependability the ERTMS/ETCS implementations require less additional time to provide each train with a 60 second buffer. Figure 50 provides two compressed timetables with the buffer.

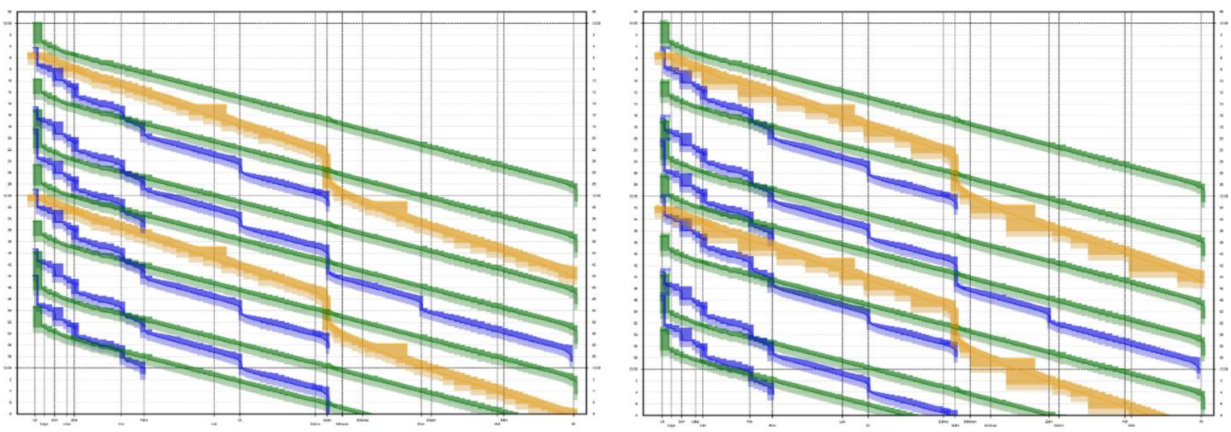

Figure 50 | Compressed timetables for HL3 with existing TTD (left) and HL3 with reduced TTD (right) including 60 seconds buffer time per train

6.3. System performance in perturbated situations

The performance of the different signalling system implementations is tested for perturbated situations in Zaltbommel. Two different departure delays are tested to compare the ability to mitigate perturbations.

6.3.1. 10-minute departure delay of train 6900, Zaltbommel

The first perturbation considered is a 10-minute dwell time extension in Zaltbommel. During the perturbation the trains behind are queued. The delays of the queued trains and the total time before the situation is solved is measured. The results are included in Table 24.

Table 24 | Delay performance perturbation 1

		Departure delay	Primary delay	Secondary delay	Perturbation solved after	Affected trains
NS'54/ATB-EG		00:10:00	00:09:20	00:25:48	00:32:55	5
ERTMS/ETCS L2		00:10:00	00:09:22	00:22:09	00:29:55	4
ERTMS/ETCS HL3	500m virtual subsections & existing trackside train detection	00:10:00	00:09:22	00:14:11	00:25:18	4
ERTMS/ETCS HL3	Virtual subsections up to 100m, existing trackside train detection	00:10:00	00:09:22	00:12:26	00:24:42	4
ERTMS/ETCS HL3	Virtual subsections up to 100m, reduced trackside train detection	00:10:00	00:09:22	00:13:47	00:26:19	4

The delay at the end station of the first train is a little smaller for the NS'54/ATB-EG than for the ERTMS/ETCS variants. Due to the reduced minimum runtimes of ERTMS/ETCS, the 8% runtime supplement is also smaller. As this runtime supplement can be used to reduce the primary delay of the first train, this results in a 2 second difference between NS'54/ATB-EG and the ERTMS/ETCS variants. The smaller blocks of ERTMS/ETCS HL3 result in a decrease of the headways in the queue, and a decrease of the secondary delays. With reduced TTD the headways behind the non-TIMS-equipped trains becomes larger, resulting in larger secondary delays.

6.3.2. 30-minute departure delay of train 6900, Zaltbommel

The second perturbation is a dwell time extension of 30 minutes in Zaltbommel. Due to the location of Zaltbommel, there is no possibility for trains to overtake the delayed train.

Table 25 | Delay performance perturbation 2

		Departure delay	Primary delay	Secondary delay	Perturbation solved after	Affected trains
NS'54/ATB-EG		00:30:00	00:29:20	03:10:46	01:27:11	14
ERTMS/ETCS L2		00:30:00	00:29:22	02:42:28	01:09:09	11
ERTMS/ETCS HL3	500m virtual subsections & existing trackside train detection	00:30:00	00:29:22	01:55:23	00:56:22	9
ERTMS/ETCS HL3	Virtual subsections up to 100m, existing trackside train detection	00:30:00	00:29:22	01:43:34	00:50:34	8
ERTMS/ETCS HL3	Virtual subsections up to 100m, reduced trackside train detection	00:30:00	00:29:22	01:58:38	00:57:34	9

Similar results for the primary delays can be found in this perturbated scenario, see the results in Table 25. The secondary delays as well as the time before the perturbation is solved decrease as the number of virtual blocks increase. The total number of delayed train is lower compared to the legacy signalling system as well.

From both the perturbated scenarios it can be concluded that the ERTMS/ETCS HL3 approach is able to absorb perturbations much better. Due to the small virtual blocks, trains can queue much closer to each other. When the perturbation has settled, the distance between departing trains is much closer, limiting the secondary delays. The variant with limited trackside train detection limits the resolving power: the train following the freight train has to keep a bigger distance. Visual results of the simulation of the 30-minute perturbation are presented in Figure 51. High resolution graphs are included in Appendix A4.

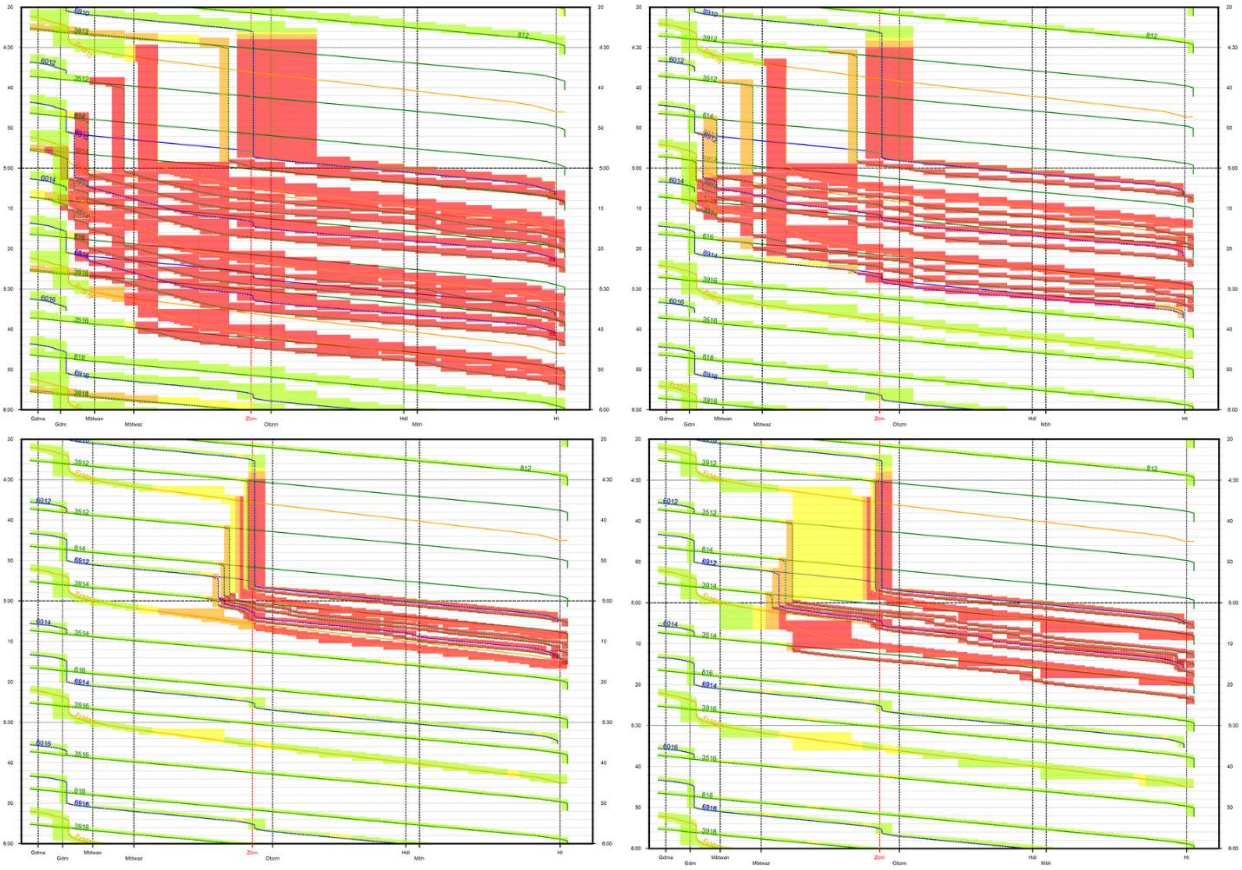

Figure 51 | 30-minute perturbation, Zaltbommel: NS'54/ATB-EG (top left), ERTMS/ETCS L2 (top right), ERTMS/ETCS HL3 with existing TTD (bottom left), ERTMS/ETCS HL3 with reduced TTD (bottom right)

6.4. Sensitivity analysis of the ERTMS/ETCS brake model

This section analyses the sensitivity of capacity to different ETCS parameters. Parameters regarding the ERTMS/ETCS braking model that can be influenced by the IM are analysed: the behaviour of trains by changing K_dry, Kr_int, Kv_int and Kt_int.

The ERTMS/ETCS parameters that influence the braking behaviour and the block occupation differ between gamma-trains and lambda-trains. For gamma-trains, the infrastructure manager has influence on the required confidence level. This confidence level in combination with the tested brake performance of the rolling stock sets a correction (K_dry) to the nominal brake deceleration. Lambda-trains are influenced by integrated correction factors depending on the train length, train speed and brake build-up time.

6.4.1. Integrated Correction Factor for gamma-trains

According to the national law and the corresponding National Values, the required ETCS Confidence Level (M_NEBCL) is 99,99% or CL4. Together with the best-case and worst-case scenario brake performance based on a Monte Carlo simulation, the confidence level results in a value for the parameter K_dry. The emergency brake deceleration for gamma-trains is corrected by this value. The adhesion coefficient (M_NVAVADH) is regulated to be 1,0: the K_wet factor is therefore not used in the calculation of the safe brake deceleration. The impact of K_dry on the safe brake deceleration follows the next equation:

$$A_{brake_{safe}} = A_{brake_{emergency}} * K_{dry}\ (M_{NVEBCL})$$

6.4.1.1. K_dry

Four values of K_dry are considered to be feasible, of which three values for K_dry are tested in this sensitivity analysis:

- Confidence Level 4, best-case scenario: K_dry = 0,88. Base case.
- Confidence Level 4, worst-case scenario: K_dry = 0,80;
- Confidence Level 8, best-case scenario: K_dry = 0,78;
- Confidence Level 8, worst-case scenario: K_dry = 0,70.

As the value of K_dry for *CL4, worst-case scenario* (K_dry 0,80) and *CL8, best-case scenario* (K_dry 0,78) are very close to each other, only very small differences are expected in the braking behaviour of gamma-trains. Therefore, the value of 0,78 is not included in the sensitivity analysis. Figure 52 provides an indication of the impact of K_dry on the guided brake characteristics of a train. To illustrate the impact of smaller values of K_dry on the braking behaviour, the figure also includes K_dry 0,40.

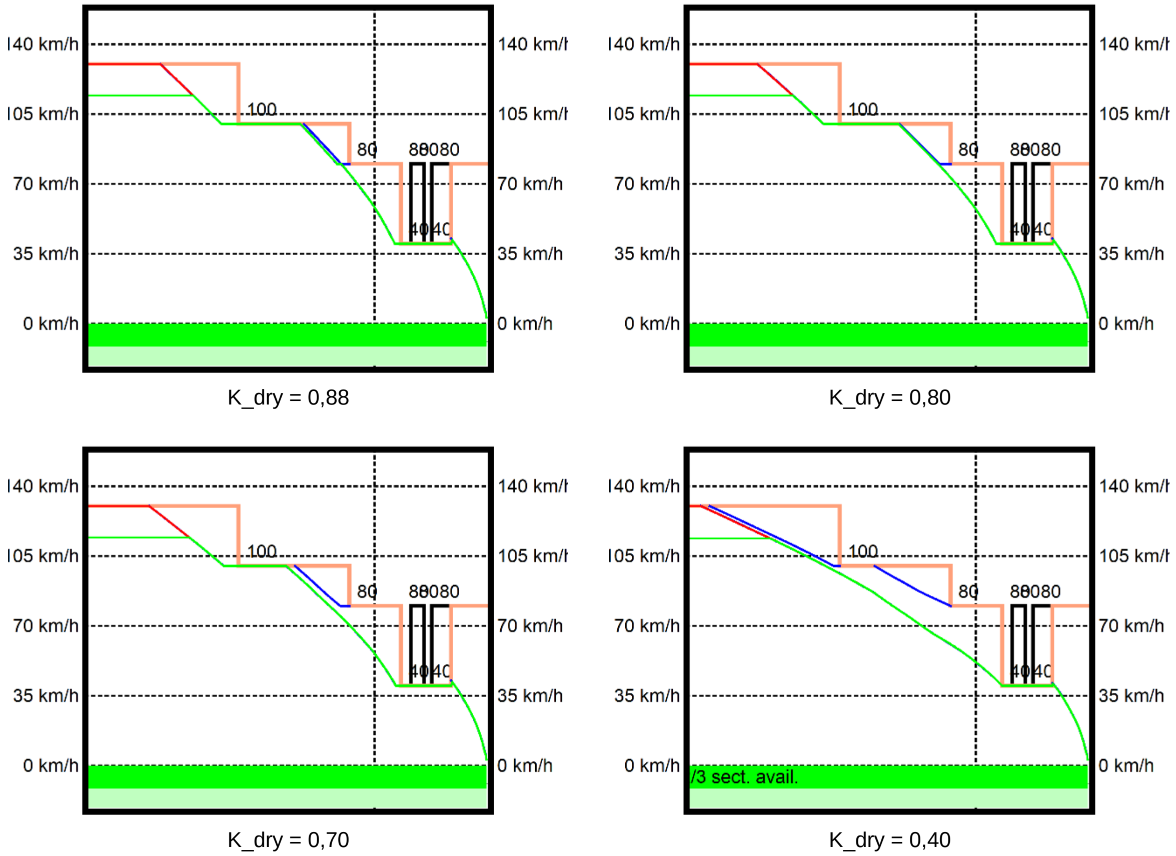

Figure 52 | K_dry influence on the ETCS braking curve, series 6900 train

The results of the minimum technical runtimes for the Sprinter and IC's for the three considered values of K_dry can be found in Table 26. Lambda trains are not effected by changing the K_dry value, as these trains use a different braking model.

Table 26 | Technical minimum runtimes for K_dry variation

	IC		Sprinter		Freight train	
	Technical minimum runtime	delta	Technical minimum runtime	delta	Technical minimum runtime	delta
K_dry 0,70	00:24:06	+2s	00:32:07	+3s	00:36:12	0
K_dry 0,80	00:24:05	+1s	00:32:05	+1s	00:36:12	0
K_dry 0,88	00:24:04	0	00:32:04	0	00:36:12	0

The technical minimum runtime of the individual trains changes only slightly. The parameter only influences the braking curves towards an EoA. The IC has only one EoA location, the Sprinter has 2 EoA situations. Therefore the impact is of the correction on guided braking actions is only limited.

The impact of the change in braking behaviour also influences the block occupation slightly. With reduced braking capacity, a train will have to occupy the next block section from a bigger distance. When the headway is critical, this influences the capacity negatively. Table 27 provides the results of the timetable compression for the three considered K_dry values.

Table 27 | Infrastructure occupation, K_dry 0,88 / 0,80 / 0,70

		K_dry 0,88	K_dry 0,80	K_dry 0,70
ERTMS/ETCS L2		74,3%	74,4%	74,5%
ERTMS/ETCS HL3	500m virtual subsections & existing trackside train detection	70,4%	70,4%	70,7%
ERTMS/ETCS HL3	Virtual subsections up to 100m, existing trackside train detection	66,7%	66,9%	67,1%
ERTMS/ETCS HL3	Virtual subsections up to 100m, reduced trackside train detection	71,7%	71,9%	72,2%

As can be found from the table, K_dry is negatively correlated to the capacity. Moreover, the influence of K_dry on capacity of systems with smaller block sections (the ERTMS/ETCS HL3 variants) is smaller when compared to 'regular' block lengths of ERTMS/ETCS L2. The maximum difference of infrastructure occupation between the different K_dry values is 0,5%.

6.4.2. Integrated Correction Factors for lambda-trains

Lambda trains are not influenced by the factor K_dry. The braking behaviour of lambda trains is determined by the conversion model. The IM can influence the safe brake deceleration by changing the Integrated Correction factors. The speed-dependent correction factor Kv_int, length-dependent correction factor Kr_int and brake build-up time correction factor Kt_int are analysed.

Table 28 | Integrated correction factors (National Values)

Integrated Correction Factor	Default value	Upper limit	Lower limit
Kr_int	1,0 (for all train lengths)	1,0	0,9
Kv_int	0,9 (for speeds 0-160 km/h)	1,0	0,76
Kt_int	1,0 (for all train length)	1,3	0,82

The NVs are quite strict in the allowed factors. Only one combination of integrated correction factors for lambda trains is possible in the Netherlands. The speed of freight trains will not exceed 160 km/h and the correction factor on train length is fixed to 0,9 for all length. However, it could be useful to tweak the values to improve the performance of freight trains and to mitigate uncertainty of braking performance. Based on the different national values of other European countries, the impact on minimum runtimes and the corresponding infrastructure occupation of the following values for Kr_int, Kv_int and Kt_int are examined:

- The default values for Kr_int (1,0), Kv_int (0,9) and Kt_int (1,0);
- Kr_int of 0,9 for all train lengths;
- Kv_int of 0,76 and 1,0 for all train speeds;
- Kt_int of 0,80 and 1,30 for all train lengths.

Changing these parameters individually will influence the performance of the lambda trains only. These factors influence both the technical minimum runtime as well as the capacity consumption of the variants. Applying these factors results in the following correction on the train deceleration:

$$A_{brake_{tuned}} = A_{brake\_converted} * K_{v_{int}}(train\ type) * K_{r_{int}}(train\ length)$$

6.4.2.1. Kr_int

The first analysed parameter is Kr_int, the train length dependent correction factor. The default value as indicated by the National Values is 1,0. The second value that is tested is 0,9. Results of the technical minimum runtimes are provided in Table 29. As with the factor K_dry for gamma trains, the Kr_int influences the runtime negatively. The differences in runtime compared to the default value are limited with a runtime deviation of 4 seconds for the freight trains.

Table 29 | Technical minimum runtimes for Kr_int variation

	IC		Sprinter		Freight train	
	Technical minimum runtime	delta	Technical minimum runtime	delta	Technical minimum runtime	delta
Kr_int 0,9	00:24:04	0	00:32:04	0	00:36:16	+4s
Kr_int 1,0	00:24:04	0	00:32:04	0	00:36:12	0

The influence of factor Kr_int on the infrastructure occupation is presented in Table 30. The impact on the infrastructure occupation is limited with a maximum benefit of 0,7 percent point. The impact is more prominent in the infrastructure variant with reduced trackside train detection.

Table 30 | Infrastructure occupation, Kr_int 0,9 / 1,0

		Kr_int 0,9	Kr_int 1,0
ERTMS/ETCS L2		74,6%	74,3%
ERTMS/ETCS HL3	500m virtual subsections & existing trackside train detection	70,7%	70,4%
ERTMS/ETCS HL3	Virtual subsections up to 100m, existing trackside train detection	67,1%	66,7%
ERTMS/ETCS HL3	Virtual subsections up to 100m, reduced trackside train detection	72,4%	71,7%

6.4.2.2. Kv_int

The second integrated correction factor for lambda trains is Kv_int, the speed dependent correction factor. The default Kv_int value of 0,9 is compared to a conservative value (0,76) and a more optimistic value (1,0). This has a direct impact on the minimum technical runtimes, see Table 31. The influence on the minimum runtime of the freight trains is limited to a maximum deviation of 7 seconds.

Table 31 | Technical minimum runtimes for Kv_int variation

	IC		Sprinter		Freight train	
	Technical minimum runtime	delta	Technical minimum runtime	delta	Technical minimum runtime	delta
Kv_int 0,76	00:24:04	0	00:32:04	0	00:36:19	+7s
Kv_int 0,9	00:24:04	0	00:32:04	0	00:36:12	0
Kv_int 1,0	00:24:04	0	00:32:04	0	00:36:09	-3s

Variation of values for correction factor Kv_int does not result in very large changes of the infrastructure occupation, see Table 32. The maximum difference in infrastructure occupation between the most optimistic and most conservative value of Kv_int is 1,4%. This is the case for the ERTMS/ETCS HL3 variant with small VSS and existing TTD.

Table 32 | Infrastructure occupation, Kv_int 0,76 / 0,90 / 1,00

		Kv_int 0,76	Kv_int 0,9	Kv_int 1,0
ERTMS/ETCS L2		74,9%	74,3%	73,8%
ERTMS/ETCS HL3	500m virtual subsections & existing trackside train detection	70,9%	70,4%	70,0%
ERTMS/ETCS HL3	Virtual subsections up to 100m, existing trackside train detection	67,5%	66,7%	66,1%
ERTMS/ETCS HL3	Virtual subsections up to 100m, reduced trackside train detection	72,2%	71,7%	71,2%

6.4.2.3. Kt_int

The third integrated correction factor that is analysed is the brake build-up time correction factor Kt_int. The Dutch NVs prescribe a default value of 1,0. The NVs for integrated correction factor Kt_int of other countries are in between 0,82 (Network Rail, UK) and 1,3 (BaneNor, Norway).

Table 33 | Technical minimum runtimes for Kt_int variation

	IC		Sprinter		Freight train	
	Technical minimum runtime	delta	Technical minimum runtime	delta	Technical minimum runtime	delta
Kt_int 0,82	00:24:04	0	00:32:04	0	00:36:06	-6s
Kt_int 1,0	00:24:04	0	00:32:04	0	00:36:12	0
Kt_int 1,30	00:24:04	0	00:32:04	0	00:36:27	+15s

Table 33 contains the minimum runtimes for the different Kt_int values. The correction on the brake build-up time of lambda trains turns out to be the integrated correction factor with the largest impact on the runtimes of trains. The maximum runtime difference between the values can be as much as 21 seconds. Table 34 provides the infrastructure occupation for the different values of Kt_int. Although the impact on the minimum runtimes is the highest of the three investigated correction factors, the impact on the infrastructure occupation is not larger than the other factors. The maximum difference between the infrastructure occupation rates is 1,2%.

Table 34 | Infrastructure occupation, Kt_int 0,82 / 1,0 / 1,30

		Kt_int 0,82	Kt_int 1,0	Kt_int 1,30
ERTMS/ETCS L2		73,5%	74,5%	74,5%
ERTMS/ETCS HL3	500m virtual subsections & existing trackside train detection	69,8%	70,4%	70,9%
ERTMS/ETCS HL3	Virtual subsections up to 100m, existing trackside train detection	66,5%	66,7%	67,2%
ERTMS/ETCS HL3	Virtual subsections up to 100m, reduced trackside train detection	71,4%	71,7%	72,6%

The results of this sensitivity analysis show that the impact of the individual changes of the integrated correction factors to the minimum runtimes of the various trains is limited to a maximum deviation of 15 seconds compared to the default values. The impact on the infrastructure occupation is limited to 1,4% between the most optimistic value and the least optimistic value of the factors.

6.5. Capacity benefit usability

The capacity benefits that ERTMS/ETCS HL3 offers compared to the legacy signalling system NS'54/ATB-EG and ERTMS/ETCS L2 has to be collected in such a way that the benefits can be used for train service improvements. First the headway reduction of various train types is examined, followed by the application of the capacity benefits.

6.5.1. Headway reduction

ERTMS/ETCS HL3 offers reduced headways compared to both the legacy signalling system and ERTMS/ETCS L2. Four headway situations that are common on the corridor Utrecht – Den Bosch are examined. A fifth situation that is currently not applied in the regular timetable is added to this list: an IC following an IC. Figure 53 and the following list provide the 5 train following situations.

A. Sprinter train following an IC, critical headway at the start of the corridor;
B. IC following a Sprinter, critical headway at the end of the corridor;
C. IC following an IC, critical headway constant over the corridor;
D. Freight train following an IC, critical headway at the start of the corridor;
E. IC following a freight train, critical headway at the end of the corridor.

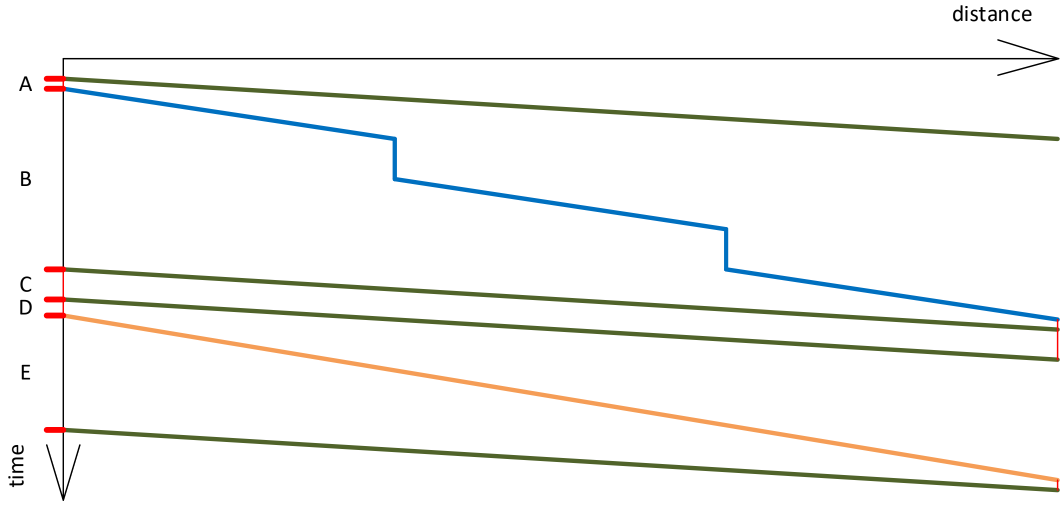

Figure 53 | Time distance graphs: Five common train following scenarios

Situations A&B occur from Houten Castellum to Geldermalsen, situation C can occur from Utrecht Centraal to Den Bosch and situations D&E between Utrecht Vaartsche Rijn and Geldermalsen.

Table 35 | Minimum headways under different signalling systems

	Variant	A: IC - Sprinter	B: Sprinter - IC	C1: IC – IC same platforms	C2: IC-IC diff. platforms	D: IC - Freight	E: Freight - IC
NS'54/ATB	1	00:01:45	00:05:01	00:04:14	00:02:17	00:02:17	00:06:35
ERTMS/ETCS L2	2	00:01:33	00:04:14	00:03:18	00:02:17	00:01:45	00:05:34
ERTMS/ETCS HL3	3	00:00:53	00:03:55	00:03:18	0:01:18	00:01:40	00:05:34
ERTMS/ETCS HL3	4	00:00:46	00:03:45	00:03:12	0:01:14	00:01:25	00:05:25
ERTMS/ETCS HL3	5	00:00:46	00:03:45	00:03:12	0:01:14	00:01:25	00:05:54

From the results in Table 35 can be concluded that the individual headways under ERTMS/ETCS HL3 can be reduced by 45 to 75 seconds compared to ERTMS/ETCS L2 and the legacy block signalling system. The biggest gains are in the reduced headways of a slow train (Sprinter and freight train) following an equipped IC. The headway when following a non-equipped freight train in the ERTMS/ETCS HL3-variant with reduced TTD is increased compared to ERTMS/ETCS L2, but the benefits of the reduced headways between all other (equipped) trains make up this loss. This makes that the capacity of all ERTMS/ETCS HL3 scenarios is on average better than ERTMS/ETCS L2.

The biggest constraint of IC-IC following is the platform scheduling at the stations. With both successive trains having a dwell at the same platform, the platform capacity will be the limiting factor. When there is a possibility to dwell close-following trains at different platforms at both the origin and destination, the headways can be reduced even more (column C2 in Table 35). When this is not feasible, other solution are required.

Optimizing the length of block sections to match the operational requirements and applying new technologies as flow dependent authorization at stations without platform alternatives is very useful for reducing headways. The block length or length of the virtual subsections should be adjusted to the expected train speeds or train speed differences to improve the headways of successive trains. By allowing an arriving train to enter an occupied platform block the platform headways can be reduced. The main condition for this solution is that the departing train has a MA of at least the full train length in rear of the platform and that this MA will not be withdrawn or shortened in any case.

6.5.2. Usage of additional capacity

The additional capacity created by ERTMS/ETCS HL3 can be used in several ways. In chapter 3 the capacity balance of ERTMS/ETCS L2 was compared with the balance of the legacy systems. Three scenarios have been introduced: increasing the frequency, increasing the average speed and increasing the stability. The same scenarios are used to create a similar capacity balance for ERTMS/ETCS HL3, see Figure 54.

Compared to ERTMS/ETCS L2 the train frequencies can be further increased, e.g. adding additional trains to the basic pattern. The balance allows for an increase of the average speed compared to ERTMS/ETCS L2 by reducing the travel times of the IC-trains whilst maintaining the existing trains services. A third option is to increase the stability of the train performance even more by adding more buffer between successive trains. The capacity balance for both ERTMS/ETCS L2 and HL3 is presented in Figure 54. The available capacity is represented by the length of the chord connecting the four axes.

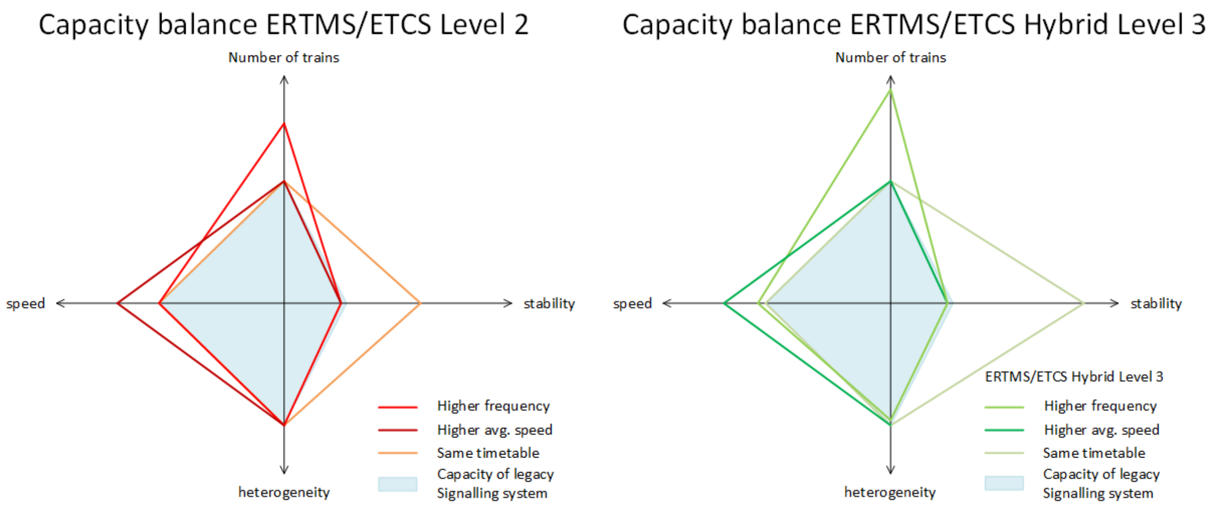

Figure 54 | Capacity balance ERTMS/ETCS Level 2 and ERTMS/ETCS Hybrid Level 3

An increase of the average speed when maintaining the original timetable does not support the ambitions laid down in OV Toekomstbeeld 2040 and does not facilitate service expansion. Moreover, this option is not feasible with the existing track infrastructure, as the maximum speed on most parts of the corridor is limited to 130 km/h. This speed is already driven by the IC trains between Utrecht and Den Bosch. The additional railway capacity offered by ERTMS/ETCS HL3 can be a trigger for upgrades to the railway tracks, enabling for higher speeds in the future.

Increasing stability by using the additional capacity as extra buffer time is also not facilitating service expansion. The stability has already been addressed in subsections 6.2 and 6.3 and will not be investigated any further. The third option is increasing the train frequencies. Additional trains can facilitate the expected demand growth. The possibility of running additional trains is analyzed in more detail in the next subsection, as it contributes to the ambitions of OV Toekomstbeeld 2040.

6.5.3. OV Toekomstbeeld 2040: 8 ICs/hour

The ambition for 2040 is to increase the frequencies of the intercity trains on main corridors from 6 to 8 ICs/hour. All other train services have to be continued with similar or improved frequencies as well. This requires a new pattern to include the additional trains and maintain a logical train order and reasonable headways. The additional 7th and 8th hourly ICs are integrated behind one of the other ICs with a 5 minute interval. This creates a 5-10-5-10-minute pattern for the ICs, maintaining larger timeslots for the freight trains with a overtake in Geldermalsen. Creating a 7,5-minute interval between all ICs turns out to be impossible given the existing track layout and routing, as a path for the freight trains requires more than this 7,5-minute gap. The details of the new pattern is presented in Table 36, while Figure 55 visualizes the hourly pattern.

The train paths are based on the technical minimum runtimes and an 8% runtime supplement. All platforms are allocated the same way as in the original timetable. The scheduled dwelltime of the freight trains in Geldermalsen is extended to 600 seconds to create the second part of the freight path (Gdm-Ht) in another 7,5-minute gap.

Table 36 | Extended simulated timetable: 8 ICs/hour

	Ut			Gdm			Ht
	Arrival	Departure	Track	Scheduled dwelltime [s]	Minimum dwelltime [s]	Track	Track
IC 1	:58	:00	18	-	-	505	6A
IC 2	:03	:05	18	-	-	505	6A
Freight	:07		15	600	120	506	705
SPR Gdm	:09:30	:07:30	21	120	42	4B	-
IC 3	:13	:15	18	-	-	505	6A
SPR Ht	:17:30	:19:30	21	450	42	4B	4A
IC 4	:18	:20	18	-	-	505	6A
SPR Htnc	:27:30	:29:30	21	-	-	-	-

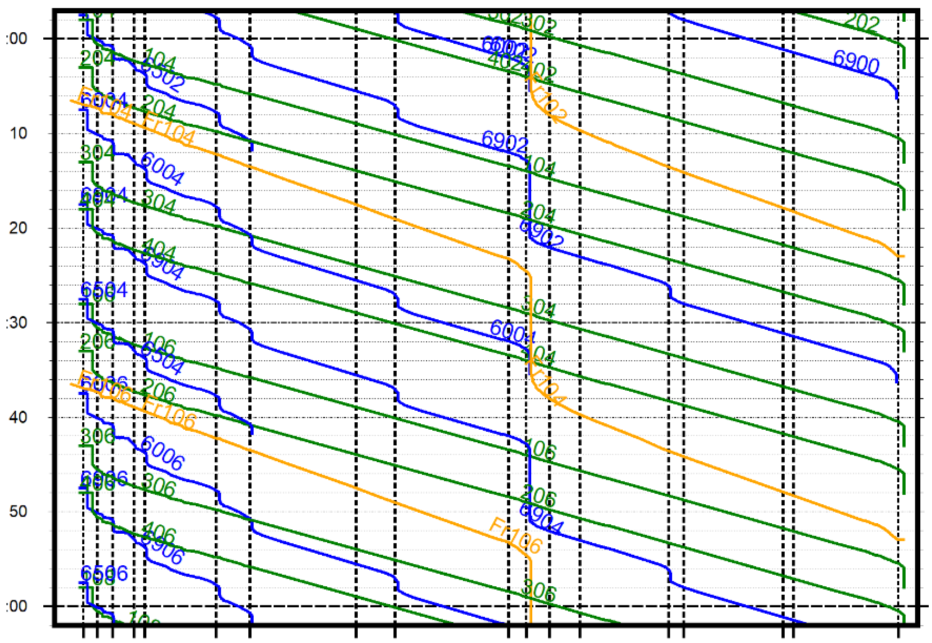

Figure 55 | Pattern of the extended simulated timetable: 8 ICs/hour

6.5.3.1. Capacity assessment of extended timetable

To assess the infrastructure occupation and the capacity consumption of the different block signalling systems for the extended timetable, this timetable is compressed according to UIC Leaflet 406. The results of the simulation and compression are included in Table 37 and visually presented in Figure 56. All blocking time diagrams are included in the Appendix A5. Without buffer time, the infrastructure occupation increases by 7,5 percentage points on average compared to the current timetable.

Table 37 | Infrastructure occupation, 8 ICs/hour

		Minimum Cycle Time	Infrastructure occupation	Infrastructure occupation
ERTMS/ETCS L2		00:49:34	2974 s	82,6%
ERTMS/ETCS HL3	500m virtual subsections & existing trackside train detection	00:46:34	2794 s	77,6%
ERTMS/ETCS HL3	Virtual subsections up to 100m, existing trackside train detection	00:43:52	2632 s	73,1%
ERTMS/ETCS HL3	Virtual subsections up to 100m, reduced trackside train detection	00:47:28	2848 s	79,1%

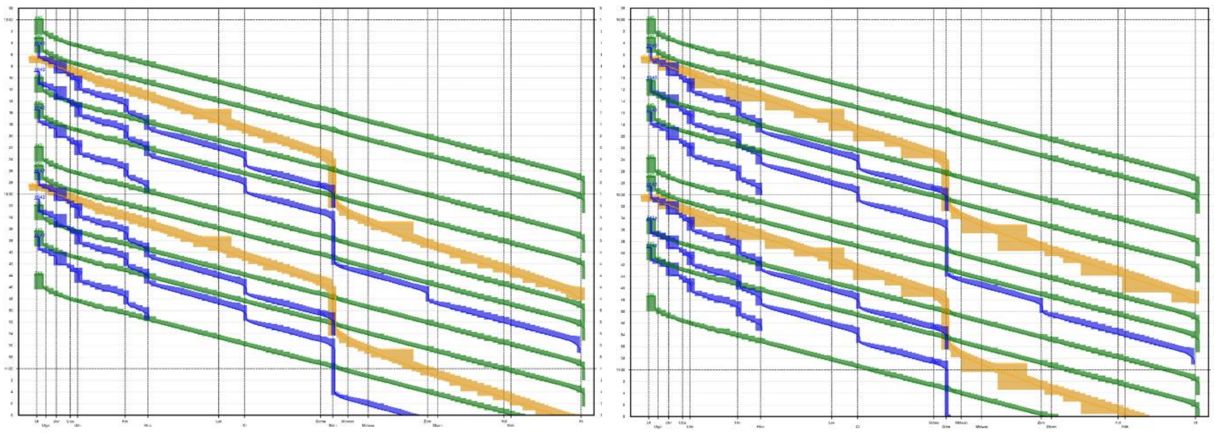

Figure 56 | Compressed extended timetables for HL3 with existing TTD (left) and HL3 with reduced TTD (right)

When including the buffer times (Table 38) this results in a capacity consumption of over 100% for some of the ERTMS/ETCS implementations. A timetable with unhindered train paths and a buffer of 60 seconds per train will theoretically not fit on the infrastructure. However, as can be concluded from the legacy signalling system with the existing timetable, bending the train paths of the ICs between Geldermalsen and Den Bosch allows a timetable with a capacity consumption of 104,0% to be executed. This means the minimum runtimes cannot be kept: the runtimes of these trains will increase.

Table 38 | Capacity consumption, 8 IC'/hour

		Required buffer	Capacity consumption	Capacity consumption
ERTMS/ETCS L2		840 s	3814 s	105,9%
ERTMS/ETCS HL3	500m virtual subsections & existing trackside train detection	840 s	3634 s	100,9%
ERTMS/ETCS HL3	Virtual subsections up to 100m, existing trackside train detection	840 s	3472 s	96,4%
ERTMS/ETCS HL3	Virtual subsections up to 100m, reduced trackside train detection	840 s	3688 s	102,4%

Limiting factor in the extended timetable are the platform working at both end stations. The occupation of the platforms is limiting the headways between successive ICs. Allocating different platforms for the short-following IC-trains at both Utrecht Centraal and Den Bosch allows for a further timetable expansion. The headways can be reduced by another 2 minutes per additional IC, bringing down the infrastructure occupation with 236 seconds and reducing the capacity consumption (including 60 seconds buffer time) to 89,9% (ERTMS/ETCS HL3 with existing trackside train detection) or 95,9% (ERTMS/ETCS HL3 with reduced trackside train detection). This makes 8 ICs per hour a feasible timetable growth.

As discussed before, the default buffer time of 60 seconds is a rather arbitrary engineering choice. As ERTMS/ETCS uses train data to calculate the braking curves, the blocking times can be predicted much more accurate, even during the (early) timetabling processes. Instead of a fixed buffer time of 60 seconds, a buffer proportional to the infrastructure occupation time or a flexible buffer according to the train types could be a better measure.

6.5.4. ERTMS/ETCS Hybrid Level 3 in relation to other innovations

By introducing other innovations next to installing ERTMS/ETCS HL3 the railway capacity can be further increased. ProRail is investigating the benefits of 3kV DC traction power supply, physically unbundling of different train types and Automatic Train Operations (ATO).

Introducing 3kV DC traction to the legacy signalling system can result in a capacity benefit up to 4,3%, depending on the corridor and rolling stock characteristics (Reijnen, 2017). The unbundling aspect of the 'Innovations of the future' introduces more homogeneity on the railway tracks. The infrastructure will be separated by use. In general, more homogeneity can result in a decrease of the capacity consumption. Installing ATO reduces the impact of human factors, making the rides between two stations more consistent over time and narrowing down the train path envelope, thereby reducing capacity consumption. On the Thameslink corridor ATO aims at a service increase from 18 trains per hour when driving manually to 24 trains per hour with ATO.

The combination of these four railway innovations could lead to a more efficient use of the railway tracks, resulting in more railway capacity. This additional capacity can be used to answer the demand growth and offer more train paths to the different operators.

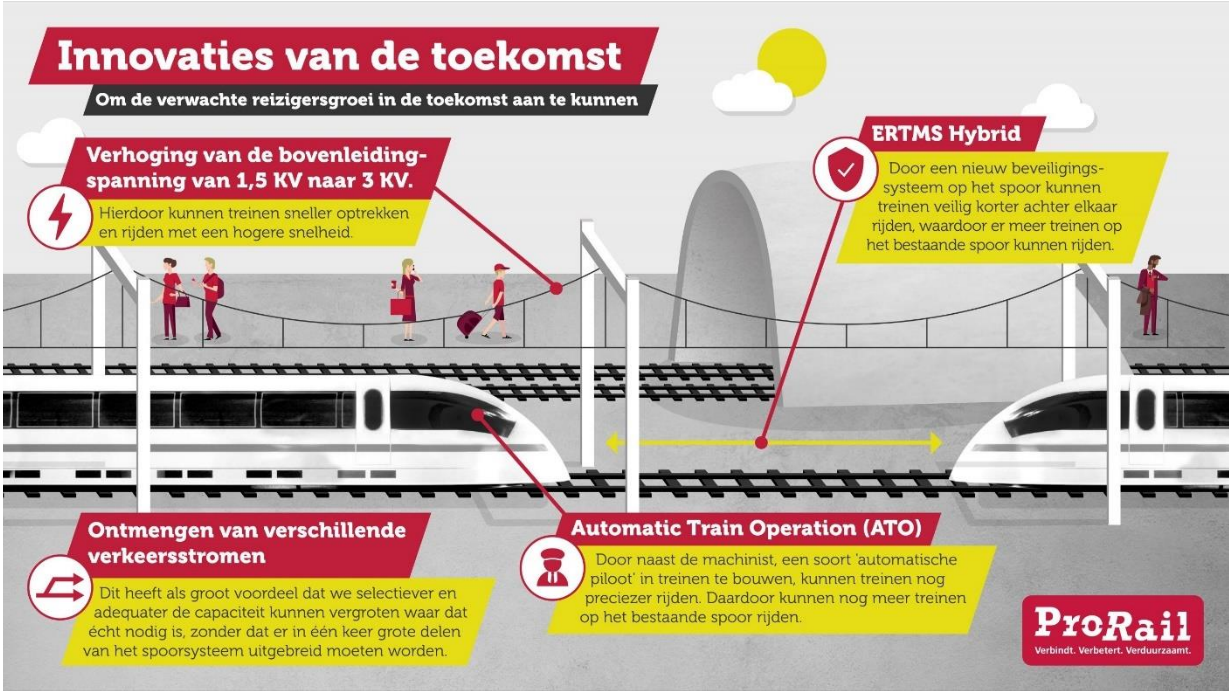

Figure 57 | Future innovations to facilitate railway growth: 3kV, ATO, ERTMS/ETCS and unbundling (ProRail, 2019)

7. Reduction of trackside equipment

This chapter goes into more details on the required trackside assets and the system and component reliability. The general principles of ERTMS/ETCS Level 2 and ERTMS/ETCS Hybrid Level 3 have been introduced before, and will not be repeated.

7.1. Projection of trackside train detection

The implementation differences between ERTMS/ETCS L2 and ERTMS/ETCS HL3 are principally in the block reservation (the amount of short blocks), the block release and trackside train detection. Due to the Train Integrity Monitoring system onboard of the passenger trains, the amount of required trackside train detection can be reduced drastically. The other ERTMS/ETCS trackside and onboard assets are comparable between the levels.

The principles of both the track circuits and the axle counter trackside train detection systems have already been introduced in Chapter 3. This section provides the projection and the performance of both systems on the existing rail infrastructure.

7.1.1. Track circuits

Track circuits are in use all over the Dutch infrastructure network. Most common are the track circuits of General Railway Systems, commonly known as GRS track circuits. The section length of GRS track circuits is limited, as noise in the signal increases with the section length. Regular section length lies between 20 and 1000m. Junctions, crossovers and level-crossings set an even higher demand to the length and amount of sections. The requirements to the sections near junctions, crossovers and level-crossings are included below in Figure 58. Junctions require at least four sections. Crossovers require seven sections, while level-crossings require three sections (ProRail, 2012).

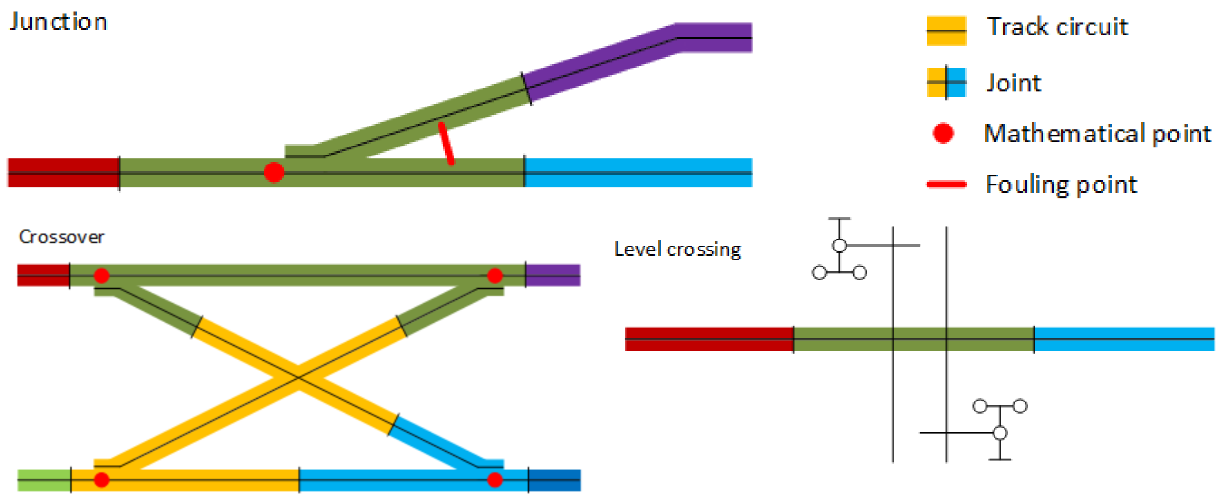

Figure 58 | Projection of track circuits on junctions, crossovers and level-crossings (ProRail, 2012)

Train detection via track circuits is a vulnerable system that encounters several problems. Light and modern rolling stock is not always detected correctly as the contact surface of the wheels with the track is very small and the running characteristics of this rolling stock are positive, thus not cleaning the track. Another problem is the monoculture of the rolling stock, with all the train services over the days being carried out with the same type of rolling stock.

Old trains and wheels used to clean the tracks thanks to their running characteristics. Other problems regarding the train detection using track circuits are the formation of layers of insulating rust on little used tracks and (in autumn) the formation of a thin insulating layer on the tracks by falling leaves from surrounding trees. Both these problems are not directly related to the implementation of ERTMS/ETCS but should be solved somehow.

7.1.2. Axle counters

Axle counters as train detection system are in use in the Netherlands on several corridors, but not in combination with NS'54/ATB-EG signalling and train protection. The combination of axle counters and ERTMS/ETCS is already in use at the HSL-Zuid. The length of sections between axle counter can be much longer than track circuits, with regular section length between 20 and 10.000m. Train detection based on axle counters does not encounter the problems of track circuits. Modern light rolling stock with optimal running characteristics is still detected correctly, in contradiction to the track circuits.

However, axle counters can require a reset when failures or errors in the counting processes occur. New safety relevant procedures will have to be developed for the reset. As axle counters are a form of spot detection, they do require an initialisation. This means the sections have to start occupied or the sections requires a sweeping action to determine that the track is actually free.

The requirements for axle counter-based train detection are different from the requirement to track circuits. For the same three track sections as in the previous subsection (junctions, crossovers and level-crossings) the minimum amount of required trackside train detection is provided in Figure 59. At a junction at least 3 axle counter units are required, a crossover requires 12 detection units for optimal independent track utilization and a level crossing requires 4 detection units per track (ProRail, 2018d).

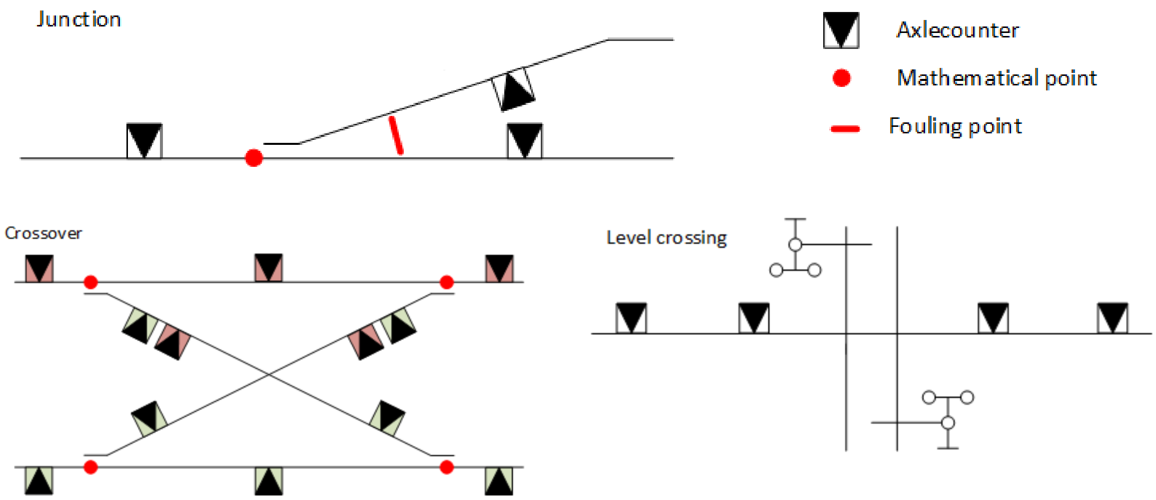

Figure 59 | Projection of track circuits on junctions, crossovers and level-crossings (ProRail, 2018d)

7.2. Component reliability

The reliability of individual components is expressed in the number of Train Depleting Irregularities (TDIs). A TDI is a irregularity that leads to a delay of at least 3 minutes for at least one train. It is an indicator used by ProRail for classifying infrastructure (un)availability. Several other indicators on The reliability of the various relevant components has been checked from the available database of nuisances and infrastructure failures (ProRail, 2019b).

Over the year 2018, a total of 10.136 TDIs were recorded. This total breaks down in the systems that were harmed (Rail systems, Train protection systems, ICT, unknown) and the causes of the TDIs (technical cause, process error, third parties, weather, unknown).

The category Rail systems includes components as e.g. tracks, junctions, civil constructions and the power supply components. The category Train protection systems contains ATP-systems, signalling systems, and several variants of train detection systems. The relevant assets for this study are collected in the category ‘Train protection systems’, with 2.098 TDIs (20,7%). The break down figure of TDIs in this category are presented in Figure 60.

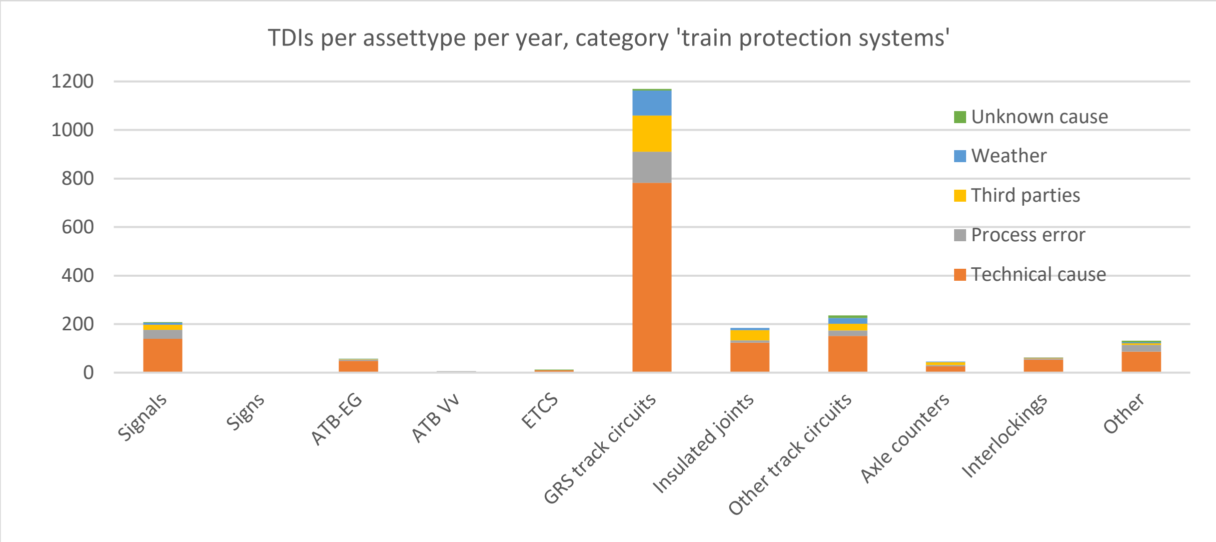

Figure 60 | Break down of the 2018 TDIs in the category ‘Train protection systems’ (ProRail, 2019b)

7.2.1. Signalling & train protection components

Signals and their supportive LED-speed indicators, (static) signs and components of ATB-EG and ATB Vv are all components that are in use on most of the existing main line corridors. Issues that have been registered regarding these aspects include erroneous signalling aspects, defective signal lights, defective signs and erroneous ATB-EG and ATB Vv signals. ERTMS/ETCS is currently in use on small parts of the network only with new components, resulting in less registered defects. Defects on the ETCS trackside signalling system, problems with the required Eurobalises and balisegroups and defects of the virtual subsections are separated in three subcategories. The reliability of the individual signalling & train protection components is included in Table 39. Trackside train detection systems are considered in the next subsection.

Table 39 | Asset reliability, signalling & train protection components

	Amount of asset	Number of irregularities, 2018	TDI per year
Signals	12.000	208	0,017 per signal
Signs	>100.000	2	0,000 per sign
ATB-EG, blocks	12.000	58	0,005 per block
Signals with ATB Vv	3.000	6	0,002 per signal equipped with ATB Vv
ETCS, blocks	750	6	0,008 per block
ETCS, BGs	2.150	6	0,003 per BG
ETCS, VSSs	-	-	0,002 per VSS (estimation)

As the approach with VSSs is a new solution to be introduced with ERTMS/ETCS HL3, no reference systems are yet available, thus the failure rate is unknown. The VSSs are a digital configuration without any trackside equipment. The failure rate will most probably be smaller than ERTMS/ETCS block sections with trackside train detection. Therefore the failure rate of VSSs is estimated to be 25% of the failure rate of the physical ERTMS/ETCS blocks. This is an conservative failure rate.

7.2.2. Trackside train detection

An analysis of the performance of GRS track circuits leads to two components in this trackside train detection system that are most vulnerable to underperformance: the track circuits themselves and the insulated joints between track sections. GRS problems considered are erroneous detected trains, broken track circuits, and broken relays. A section with GRS track circuits leads to 0,071 TDI per year, while the required insulated joints lead to another 0,007 TDI per joint per year.

Registered issues with axle counters include erroneous evaluations and broken power supplies. Performance-wise corridors equipped with axle counters lead to an increase in performance compared to GRS track circuits. On average a section equipped with axle counters leads to 0,039 TDI per year. When the amount of trackside train detection remains the same, the unavailability of the track caused by failures in train detection can be reduced by up to 50%. Table 40 provides an overview of the reliability of the trackside train detection components.

Table 40 | Asset reliability, train detection components

	Amount of asset	Number of irregularities, 2018	TDI per year
Sections with GRS track circuits	16.500	1169	0,071 per section
Insulated joints	26.400	184	0,007 per joint
Axle counters	1.200	46	0,039 per axle counter unit

7.3. Infrastructure implementation

In the simulated infrastructure variants (Section 5.5) there is no distinction in the type of trackside train detection. The type of TTD is not relevant for the capacity of a corridor. However, the type of TTD is relevant for the implementation costs and system reliability.

The legacy signalling system is equipped with track circuits and the accompanying insulated joints. This is the reference for the asset analysis. ERTMS/ETCS allows for the use of both track circuits and axle counters. ERTMS/ETCS L2 uses the same amount of trackside train detection as the legacy system. The three different HL3 infrastructure variants have differences in the amount of (virtual) blocks and the amount of trackside train detection.

In the last of the ERTMS/ETCS HL3 infrastructure variants the trackside train detection is limited to the minimum required locations. Junctions, crossovers and level-crossing are the only location where TTD is present. Due to the limitation of the section length when using GRS track circuits, this variant can only be obtained by implementing axle counters. The following infrastructural variants are analysed:

- NS'54/ATB-EG, existing trackside train detection locations, GRS track circuits;
- ERTMS/ETCS Level 2, existing trackside train detection locations with GRS track circuits;
- ERTMS/ETCS Level 2, existing trackside train detection locations with axle counters;
- ERTMS/ETCS Hybrid Level 3, medium virtual subsections (500m), existing trackside train detection locations with GRS track circuits;
- ERTMS/ETCS Hybrid Level 3, medium virtual subsections (500m), existing trackside train detection locations with axle counters;
- ERTMS/ETCS Hybrid Level 3, small virtual subsections (up to 100m), existing trackside train detection locations with GRS track circuits;
- ERTMS/ETCS Hybrid Level 3, small virtual subsections (up to 100m), existing trackside train detection locations with axle counters;
- ERTMS/ETCS Hybrid Level 3, small virtual subsections (up to 100m), reduced trackside train detection with axle counters.

The projection of ERTMS/ETCS L2 and HL3 on the corridor Utrecht – Den Bosch is based on the valid OBE-drawings and the relevant valid Engineering Rules. Appendix A1 provides a list of the used OBE-drawings. Appendix A2 visually provides an overview of the different infrastructure models, with the modelled (virtual) blocks and the trackside train detection. The number of infrastructure components for equipping all tracks on the corridor is provided in Table 41.

Table 41 | Infrastructure components per variant, Utrecht - Den Bosch

	NS54/ATB-EG track circuits	ETCS L2 | track circuits	ETCS L2 | axle counters	ETCS HL3 | track circuits 500m VSS, existing TTD	ETCS HL3 | axle counters 500m VSS, existing TTD	ETCS HL3 | track circuits 100m VSS, existing TTD	ETCS HL3 | axle counters 100m VSS, existing TTD	ETCS HL3 | axle counters 100m VSS, reduced TTD
ATB-EG, blocks	508	0	0	0	0	0	0	0
Signals	300	0	0	0	0	0	0	0
Signals with ATB Vv	160	0	0	0	0	0	0	0
H/L signals	20	20	20	20	20	20	20	20
Signs	144	0	0	0	0	0	0	0
Sections (track circuits)	504	504	0	504	0	504	0	0
Insulated joints	806	806	0	806	0	806	0	0
ETCS, blocks	0	508	508	508	508	508	508	408
ETCS, VSSs	0	0	0	300	300	750	750	850
ETCS, BGs	0	508	508	508	508	508	508	508
SMBs	0	300	300	520	520	872	872	872
Axle counters	0	0	806	0	806	0	806	574

7.4. System reliability & availability

Combining the reliability & (un)availability of components with the number of components per infrastructural variant leads to the total system availability. This is expressed in the number of TDIs per year. Figure 61 provides an overview of the expected yearly TDIs for the corridor Utrecht – Den Bosch in the category 'Train Protection systems'. The breakdown of the yearly TDIs into the individual components is included in Table 42.

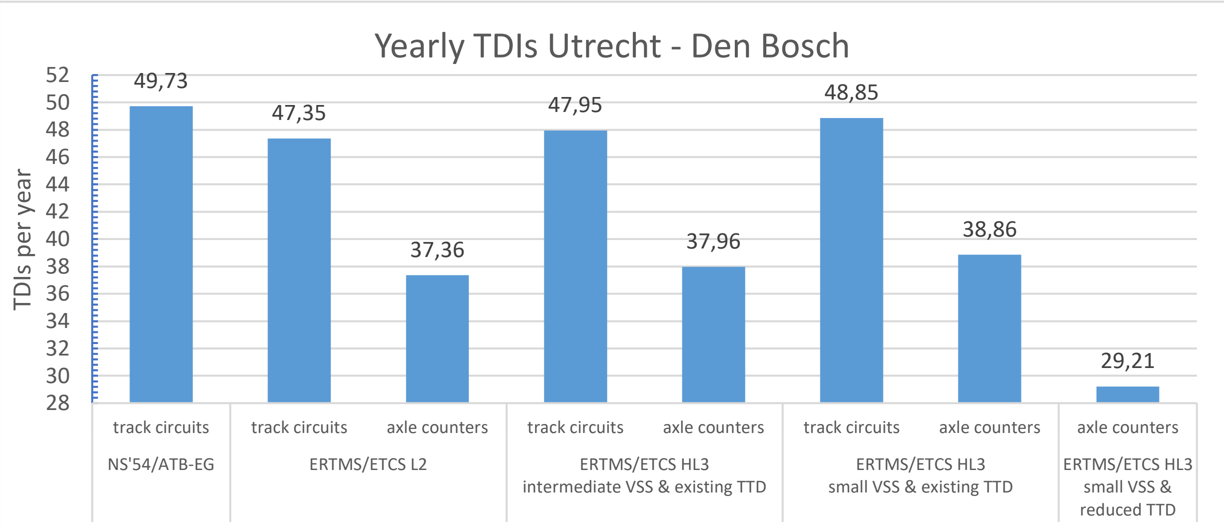

Figure 61 | Yearly TDIs Utrecht - Den Bosch, category 'Train Protection systems'

The existing configuration of the corridor results in almost 50 TDIs per year in the category 'Train Protection systems'. Over 80% of these TDIs are the result of the trackside train detection: the GRS track circuits and the insulated joints. Leaving the existing TTD in place in all other variants results in the TTD-related TDIs being transferred to the other infrastructural variants.

Introducing ERTMS/ETCS L2 in combination with the existing trackside train detection results in a slightly lower track unavailability. The ERTMS/ETCS hardware has a better reliability than the NS'54 signals and ATB-EG components, resulting in fewer yearly TDIs. By creating short virtual subsections (ERTMS/ETCS

HL3) the amount of ETCS blocks remains the same while a lot of new digital subsections are created. The expected reliability of the VSSs results in only a slight increase of the yearly TDIs on the corridor. The number of balisegroups does not increase with the creation of VSSs, as not every VSS needs a BG for position referencing. Strictly seen that is a deviation from the Engineering Rules ERTMS (ProRail, 2015) but locating a BG every VSS would be very cumbersome and is not required for operations.

When transferring to axle counters, the unavailability of the different ERTMS/ETCS drops drastically. The difference in unavailability is approximately 10 TDIs per year on this corridor between GRS track circuits and axle counter trackside train detection. The infrastructural variant of ERTMS/ETCS HL3 with small VSS and axle counters on all existing TTD-locations results in 21,8% less yearly TDIs on this corridor than the existing configuration. By reducing the trackside train detection to the bare minimum the number of yearly TDIs can be reduced by over 40% compared to the legacy system, and by 38% compared to ERTMS/ETCS L2 signalling with track circuits. Table 42 provides the build-up of the TDIs of the different infrastructure variants.

Not included in the TDIs is the ability of the ERTMS/ETCS HL3 variants to mitigate false errors in the counting system. When the evaluation of a section between two axle counters reports a difference in the number of axles that have passed, this count can be corrected when the last train that has passed was a train equipped with a TIMS. As most of the trains on this corridor will be TIMS-equipped, a lot of the TDIs related to axle counters can be mitigated.

Table 42 | Breakdown of the expected yearly TDIs, category 'Train Protection systems'

	NS54/ATB-EG track circuits	ETCS L2 | track circuits	ETCS L2 | axle counters	ETCS HL3 | track circuits 500m VSS, existing TTD	ETCS HL3 | axle counters 500m VSS, existing TTD	ETCS HL3 | track circuits 100m VSS, existing TTD	ETCS HL3 | axle counters 100m VSS, existing TTD	ETCS HL3 | axle counters 100m VSS, reduced TTD
ATB-EG, blocks	2,54	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Signals	5,10	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Signals with ATB Vv	0,32	0,00	0,00	0,00	0,00	0,00	0,00	0,00
H/L signals	0,34	0,34	0,34	0,34	0,34	0,34	0,34	0,34
Signs	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Sections (track circuits)	35,78	35,78	0,00	35,78	0,00	35,78	0,00	0,00
Insulated joints	5,64	5,64	0,00	5,64	0,00	5,64	0,00	0,00
ETCS, blocks	0,00	4,06	4,06	4,06	4,06	4,06	4,06	3,26
ETCS, VSSs	0,00	0,00	0,00	0,60	0,60	1,50	1,50	1,70
ETCS, BGs	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
SMBs	0,00	0,00	31,43	0,00	31,434	0,00	31,43	22,39
Axle counters	0,00	1,52	1,52	1,52	1,52	1,52	1,52	1,52
Total	**49,73**	**47,35**	**37,36**	**47,95**	**37,96**	**48,85**	**38,86**	**29,21**
	100%	**95,2%**	**75,1%**	**96,4%**	**76,3%**	**98,2%**	**78,2%**	**58,7%**

8. Conclusions & recommendations

This chapter provides the conclusions that can be drawn from this report. Secondly, recommendations regarding (further research on) ERTMS/ETCS Hybrid Level 3 implementation will be made. The research questions that have been stated in Section 1.4 will be answered in a logical order. The main findings of the theoretical approach and the results of the case study will lead to the answer to the main research question in section 8.1. Section 8.2 provides recommendations on ERTMS/ETCS Hybrid Level 3 implementation and recommendations for future research.

8.1. Conclusions

The four sub-questions that have been stated in section 1.4 will be answered in logical order.

Theoretical advantages of ERTMS/ETCS Hybrid Level 3

"What are the advantages in terms of capacity and asset reduction of ERTMS/ETCS Hybrid Level 3 over ERTMS/ETCS Level 2 and NS'54/ATB?"

With the introduction of ERTMS/ETCS, the technical minimum runtime can be reduced by train dependent, block independent, route dependent and speed dependent braking. This allows the train to start braking not earlier than required for the specific track/train combination, independent from the block section boundaries, for a specific route with reduced braking distances at lower speeds.

By creating shorter blocks (independent of trackside train detection) all trains running under ERTMS/ETCS can reduce the approach part of the blocking time. As the block occupation process is divided in smaller steps in distance with a minimum of 100m, the system allows a train to follow closer to the preceding train.

Trains equipped with a Train Integrity Monitoring System report the completeness of the train. The train and the trackside are aware of the location of both the front end and the rear end of the train. This feature allows for short following by releasing the (virtual) blocks based on position report information and integrity confirmation. Trackside train detection is still required for the protection of danger points (junctions and level-crossings) and for releasing the infrastructure of non-TIMS equipped trains.

Unfortunately not all trains can already be equipped with a TIMS. For these trains, mostly trains with a varying composition and length (e.g. freight trains), the remaining trackside train detection provides the integrity confirmation. With most trains reporting their location and integrity via GSM-R, the amount of trackside train detection can be reduced without limiting railway capacity too much. This remaining trackside train detection also provides additional safety by detecting unauthorized movements of unconnected trains and provides fast recovery from degraded scenarios.

ERTMS/ETCS Hybrid Level 3 implementation

"How can ERTMS/ETCS Hybrid Level 3 be implemented on the Dutch railway network in terms of infrastructure and operations according to the Engineering Rules ERTMS or how should they be adjusted to match them?"

ERTMS/ETCS Hybrid Level 3 fits in the Engineering Rules ERTMS - OVS60040. The principles of ERTMS/ETCS Hybrid Level 3 with virtual blocks do not differ too much from ERTMS/ETCS Level 2, except for the block release of trains equipped with onboard Train Integrity Monitoring. The release mechanism based on position reports and integrity confirmation is not specifically mentioned in the Engineering Rules. This block release mechanism should be included in the Dutch Engineering Rules ERTMS.

For short following near stations and junctions, the optimal block length at very low speeds might fall short of the minimum length of 100m. With the tendency of removing junctions and increasing the entry speed of stations, the section length will still be adequate.

Around existing special locations as phase breaks, sections breaks, level transition areas, steep slopes in tunnels and towards bridges and near platforms the placement of stop marker boards can be limited by those elements. Special elements can result in large headways between successive (freight) trains as optimal short blocks might not be possible. The issues that arise are not safety relevant, but create operational risks that should be mitigated. Maintaining the existing procedures or solving the issues in the traffic control systems using flow dependent authorisation, train dependent authorisations based on the train classification or other solutions to reduce headways of these trains can be a solution.

Moreover, the concept of ERTMS/ETCS Hybrid Level 3 signalling and train protection is in the first place a safety system – the capacity benefits of ERTMS/ETCS Hybrid Level 3 should be additional. Implementation of the system should guarantee safe train operations. Traffic management and operations regarding special trains that require specific solutions can also be solved in other systems than the safety system, such as the European Traffic Management Layer (ETML) to be developed or the legacy national traffic management systems. The Dutch Engineering Rules ERTMS are not directly limiting ERTMS/ETCS Hybrid Level 3 implementation.

Impact on capacity consumption

"What is the impact of ERTMS/ETCS Hybrid Level 3 on the capacity consumption of the Dutch railway network and how is this affected by non-integer trains?"

The technical minimum runtimes of all trains decrease by the implementation of ERTMS/ETCS. This decrease is independent from the implemented ERTMS/ETCS level. Running the 2019 timetable on five different infrastructure variants (NS'54/ATB-EG, ERTMS/ETCS Level 2 and three different ERTMS/ETCS Hybrid Level 3 projections) with all unhindered train paths provides an overview of the capacity benefits of ERTMS/ETCS Hybrid Level 3 compared to ERTMS/ETCS Level 2 and the legacy signalling system.

With the current NS'54/ATB-EG signalling and train protection systems, the infrastructure is used to a level beyond the theoretical maximum. Compressing the timetable results in 84% infrastructure occupation, which is more than the UIC-proposed infrastructure occupation rate of 75%. Adding a 60 second buffer between each of the scheduled paths results in over 100% capacity consumption, which implies that it is theoretically impossible to rub the 2019 timetable on the existing infrastructure. By bending train paths, partially reducing the train speeds, the capacity consumption can decrease to under 100%. However, bending the train paths negatively influences the running times of trains.

Changing to ERTMS/ETCS Level 2 without a change in block layout and train detection locations results in almost 10 percent point reduction of the infrastructure occupation. Adding the buffer time results in a capacity consumption of 90,9%, which makes this a feasible signalling system given the 2019 timetable and existing infrastructure. This is still well above the 75% proposal of maximum infrastructure occupation.

An optimal projection of ERTMS/ETCS Hybrid Level 3 gives a further reduction of infrastructure occupation. By decreasing the block length at critical parts of the corridor to 100m the infrastructure occupation drops to 66,7% on this corridor. This results in a feasible, robust and stable timetable with the infrastructure occupation rate under the 75% proposal. In a scenario with reduced trackside train detection (only junctions, crossovers and level-crossings being equipped with trackside train detection) trains without onboard Train Integrity Monitoring create a large headway to the following train. However, the infrastructure occupation (71,7%) and capacity consumption (88,8%) with the same timetable is still better than the ERTMS/ETCS Level 2 projection. The resulting infrastructure occupation is still under the 75% proposal.

Reduction of trackside train detection

"What is the impact from ERTMS/ETCS Hybrid Level 3 on the signalling system by reducing track side equipment along the Dutch railway network?"

The implementation of ERTMS/ETCS does not require a specific type of trackside train detection. The GRS track circuits that are currently in use on most of the corridors equipped with NS'54/ATB-EG do face problems with the detection of rolling stock, that could be solved by implementing axle counters.

Three of the five infrastructural variants have been analysed for both GRS track circuits and axle counter implementation. As the legacy signalling system is the reference, axle counters have not been implemented here. The variant of ERTMS/ETCS Hybrid Level 3 with minimized trackside train detection (junctions, crossovers and level-crossings) is only analysed for axle counters, as the length of the individual sections exceeds the maximum possible length to be covered by GRS track circuits.

In 2018, just over 10.000 Train Depleting Irregularities were registered. Almost 2.100 of them are caused by the signalling system and the various trackside train detection systems. On the corridor Utrecht – Den Bosch, over 80% of the train protection related irregularities is accountable to the trackside train detection, the GRS track circuits and the accompanying insulated joints. Removing these and replace the train detection by axle counters is very beneficial for track reliability, reducing up to 20% of the related Train Depleting Irregularities.

Shorter blocks logically implies an increase in the amount of blocks. This comes with an increase of the track unavailability, as ERTMS/ETCS blocks and virtual subsections both have a non-zero failure rate. As not each of the short blocks requires a balisegroup, the unavailability caused by failures of the balisegroups does not increase with the block-increment.

ERTMS/ETCS Hybrid Level 3 with small subsections and trackside train detection based on axle counters reduces the number of yearly Train Depleting Irregularities by over 20% compared to the legacy signalling system. When reducing the trackside train detection to the minimum and transferring to axle counters, a TDI-reduction of over 40% compared to NS'54/ATB-EG is possible. ERTMS/ETCS L2 with axle counters will result in a reduction of 25%. The track unavailability with reduced trackside train detection is better than ERTMS/ETCS Level 2 with axle counters.

Moreover, ERTMS/ETCS Hybrid Level 3 uses both position reports and trackside train detection. Errors of the trackside train detection can be mitigated by the integrity information of a train that has just passed.

Contribution of ERTMS/ETCS Hybrid Level 3 to the Dutch railway system

The main research question of this thesis is the following:

"What is the contribution of ERTMS/ETCS Hybrid Level 3 over ERTMS/ETCS Level 2 and the NS'54/ATB-EG legacy signalling system to the Dutch railway system in terms of capacity increase and reduction of trackside equipment?"

ERTMS/ETCS Hybrid Level 3 is a new and promising signalling concept. The virtual block principle fits in the engineering rules on ERTMS with only minor modifications. The engineering rules should be adjusted to allow the block-release mechanism based on trainside information. The system allows for an easy and flexible configuration. By creating short blocks and the use of onboard train integrity monitoring, ERTMS/ETCS Hybrid Level 3 allows close-following. The concept of ERTMS/ETCS Hybrid Level 3 combines trackside train detection and position reports to deliver an optimal performance and mitigates operational risks in degraded situations.

Engineering corridors in such a way that the length of the critical blocks sections can be reduced to minimum sizes of approximately 100m allows for very short headways. The headways between trains can be reduced by 45 to 75 seconds compared to NS'54/ATB-EG. This results in large capacity benefits: the infrastructure occupation on the corridor drops from 84% to 66,7%. Realising the required short blocks while maintaining the full trackside train detection will decrease reliability.

ERTMS/ETCS Hybrid Level 3 allows for a substantial reduction in trackside train detection compared to ERTMS/ETCS Level 2 and the legacy signalling system, while still providing a capacity improvement. Minimising the detection and at the same time changing from GRS track circuits to axle counters, the number of instances of Train Depleting Irregularities can be reduced by over 40% compared to the legacy system with GRS track circuits.

The reduced capacity consumption compared to the legacy signalling system can be used to run a 7^{th} and 8^{th} hourly IC, which is in line with the ambitions of ProRail. By maintaining the existing trackside train detection and creating small blocks at critical parts of the corridor, these trains can be merged in the timetable by some margin. For the option with reduced track side train detection the capacity consumption exceeds the 100%. It is theoretically impossible to fit the additional trains including a 60 second buffer to all trains within the hour. However, the existing practical situation of NS'54/ATB-EG with a theoretical capacity consumption of 104% shows that it is possible to run timetable of over 100% capacity consumption by bending train paths.

The exact balance of required railway capacity and required amount of track side train detection is up to ProRail. This study has indicated the opportunities of ERTMS/ETCS Hybrid Level 3 on both the capacity effects and possibilities for asset reduction. Compared to ERTMS/ETCS Level 2, ERTMS/ETCS Hybrid Level 3 offers more capacity (66,7% vs 74,3%), improved robustness (less secondary delays), reduced assets and track unavailability (up to 25% reduction of unavailability) and more flexibility for implementation and adaptation.

8.2. Recommendations

Two types of recommendations will be provided in this section. Subsection 8.2.1. covers recommendations on the implementation of ERTMS/ETCS Hybrid Level 3, while 8.2.2. includes recommendations on future research.

8.2.1. Implementation of ERTMS/ETCS Hybrid Level 3

The concept of ERTMS/ETCS Hybrid Level 3 is capable of handling different types of trains. Both rolling stock with and without onboard Train Integrity Monitoring can be dealt with. On corridors with only few junctions and level-crossing but regular freight paths, the lack of integrity confirmation of the freight trains is limiting the headways and thereby railway capacity. This decreases the possibility of reducing trackside train detection. A solution for onboard monitoring and confirming the integrity of these trains is still required for optimal use of the infrastructure and a further reduction in trackside equipment and track unavailability.

Differences in braking behaviour of the rolling stock will lead to small deviations in both the minimum runtimes as well as the infrastructure occupation and capacity consumption. By changing the integrated correction factors of the ERTMS/ETCS braking curves the runtimes of the individual trains and the capacity consumption can be tightened. By adjusting the Dutch National Values, the accumulated effects of the individual changes can result in just that bit additional capacity.

For optimal capacity benefits, ERTMS/ETCS Hybrid Level 3 should be implemented with small virtual subsections near junctions and other critical locations. The amount of trackside train detection should be maintained at least as-is to minimize the impact of trains without onboard Train Integrity Monitoring. The Integrated Correction Factors could be tuned to provide optimal braking performance. Of the investigated correction factors and values, the combination of gamma-braking based on Confidence Level 4 and lambda-braking with Kr_int of 1,0, Kv_int of 1,0 and Kt_int of 0,82 provides the best running times for the individual trains and the least infrastructure occupation.

A small set of default rolling stock for all trains has been modelled in this thesis. The rolling stock has been selected for its relevance on the corridor and the fact that the characteristics regarding train acceleration and braking are known very well. To fully benefit from the ERTMS/ETCS braking curves for runtime and capacity calculations it is highly recommended to model the specific rolling stock and simulate the individual behaviour. This detailed procedure can help optimize the distribution of capacity.

Lastly, the implementation of ERTMS/ETCS Hybrid Level 3 should go hand-in-hand with other infrastructural projects on the corridors to result in an integrated solution. Separately working on new signalling systems and e.g. overhead wiring will result in a suboptimal product for one of the systems.

8.2.2. Future research

Not all opportunities of ERTMS/ETCS Hybrid Level 3 have been discussed in this thesis. For instance, the layout and projection of ERTMS/ETCS Hybrid Level 3 in stations and on railway yards is not included. As ERTMS/ETCS Hybrid Level 3 allows much shorter headways between successive trains, the platforms and yards will be the most restrictive infrastructure parts in the future.

The valid Engineering Rules do not allow for splitting platform blocks into smaller virtual subsections. Solutions are required to optimize this infrastructure. ProRail can think of very small virtual blocks (<100m) on yards, allowing multiple trains on a single platform when the platform length is sufficient, or flow-dependent authorization where the arriving train is already granted authority into a block that has not yet been released by the departing train. Future research on these topics could improve the process of projecting ERTMS/ETCS Hybrid Level 3 on relevant corridors.

Another interesting topic for future research is the development of an algorithm for calculating the optimal sizes of the virtual subsections. The basic work on some of the ERTMS/ETCS Level 2 implementations as well as these ERTMS/ETCS Hybrid Level 3 implementations have been engineered based on basic calculations on the speed profiles of the different trains and the Engineering Rules ERTMS. A dedicated algorithm will be useful for mass-implementation of ERTMS/ETCS Hybrid Level 3.

This thesis provides results on capacity and track unavailability for two options on the amount of trackside train detection. Optimal implementation will depend on different characteristics of the tracks and the expected traffic. A clear procedure for deciding on the optimum amount of trackside train detection should be developed for future implementation of ERTMS/ETCS Hybrid Level 3.

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Appendices

A1 – List of valid OBE-drawings

A2 – Infrastructure models in RailSys

A3 – Compressed Blocking Time Diagrams

A4 – 30 minute perturbation, delay propagation

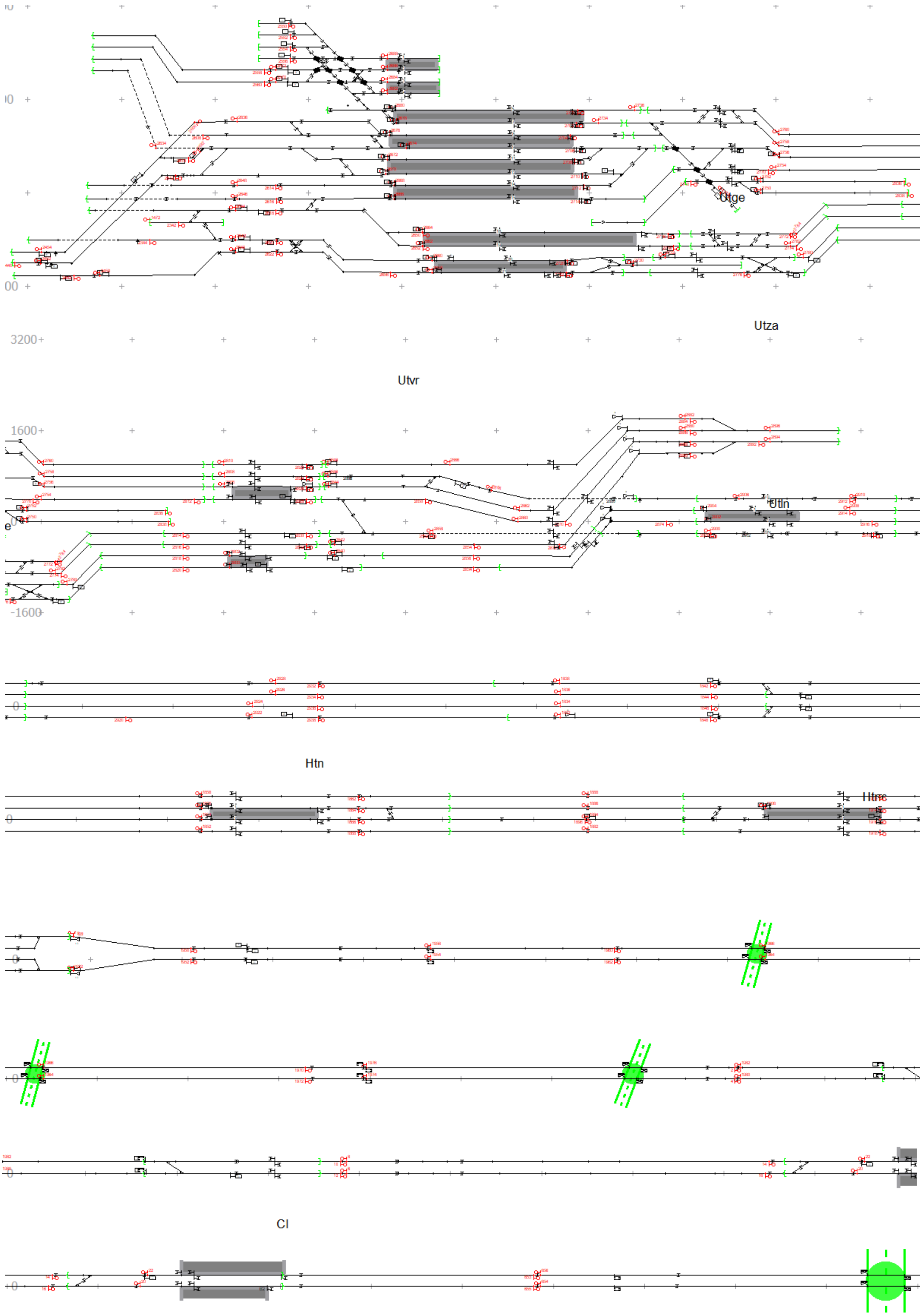
A5 – Compressed Blocking Time Diagrams, additional ICs

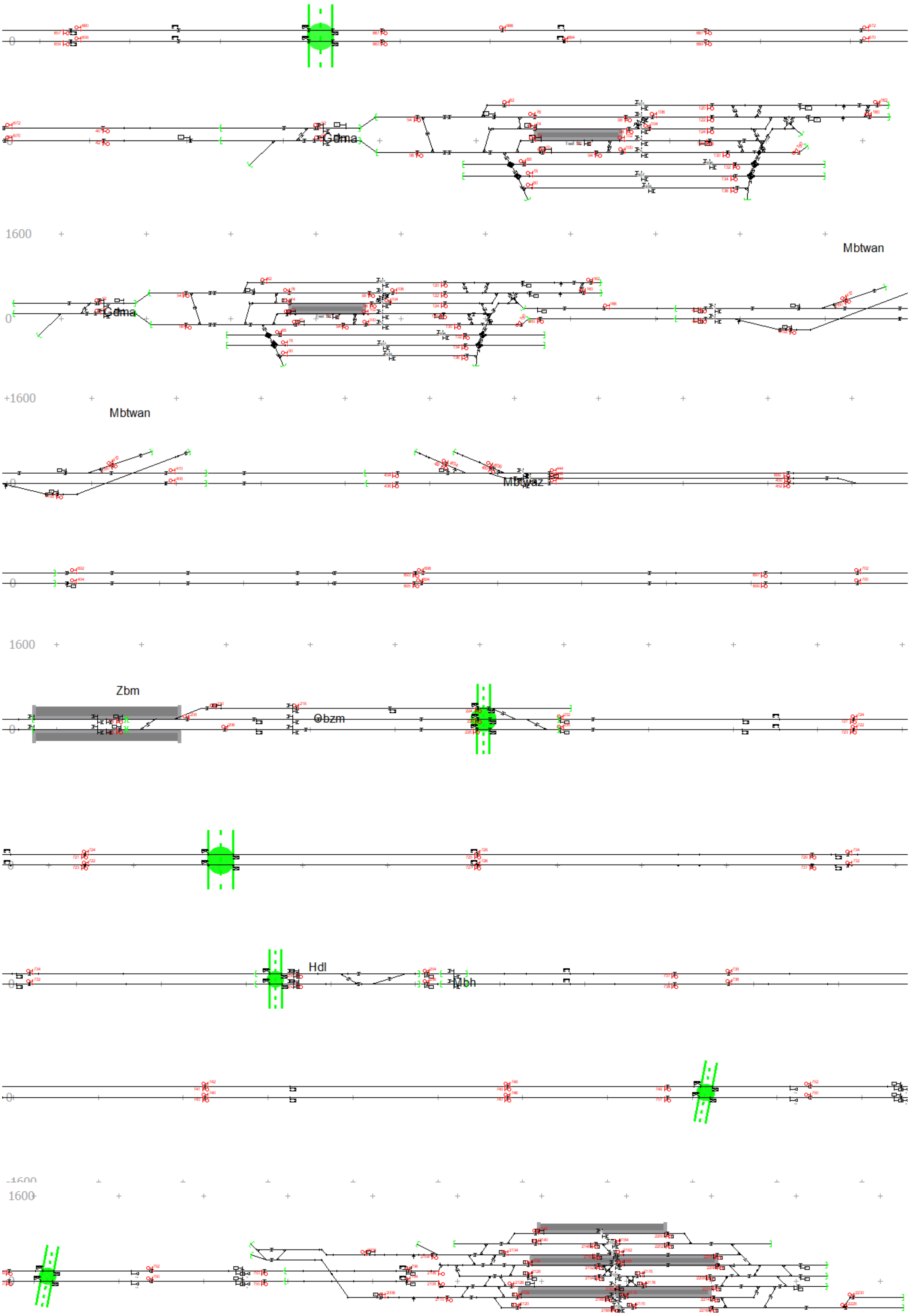
A1.1. List of valid OBE-drawings

This appendix provides a list of the valid OBE-drawing on which the infrastructure model of RailSys is based.

Drawing	Area	Date
000885431-I	Utrecht Centraal Noordzijde	03-12-2018
000885490-F	Utrecht Centraal Zuidzijde	14-10-2017
000885519-D	Lunetten	14-10-2017
000885359-M	Houten	15-12-2017
000885360-I	Houten	19-10-2017
000885361-L	Culemborg	19-10-2017
000200078-AQ	Geldermalsen	07-03-2018
000885225-AE	Meteren Aansl	26-06-2018
000885226-L	Meteren Aansl-Zaltbommel	19-10-2017
000200082-AB	Zaltbommel	19-10-2017
000200083-AB	Hedel	19-10-2017
000201978-AN	’s-Hertogenbosch	14-12-2018
000201971-AC	’s-Hertogenbosch	14-12-2018

A2.1. NS'54/ATB-EG

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1600
Mbtwan
Gdma
+1600
Mbtwan
Mbtwaz
1600
Zbm
Obzm
Hdl
Mbh
1600

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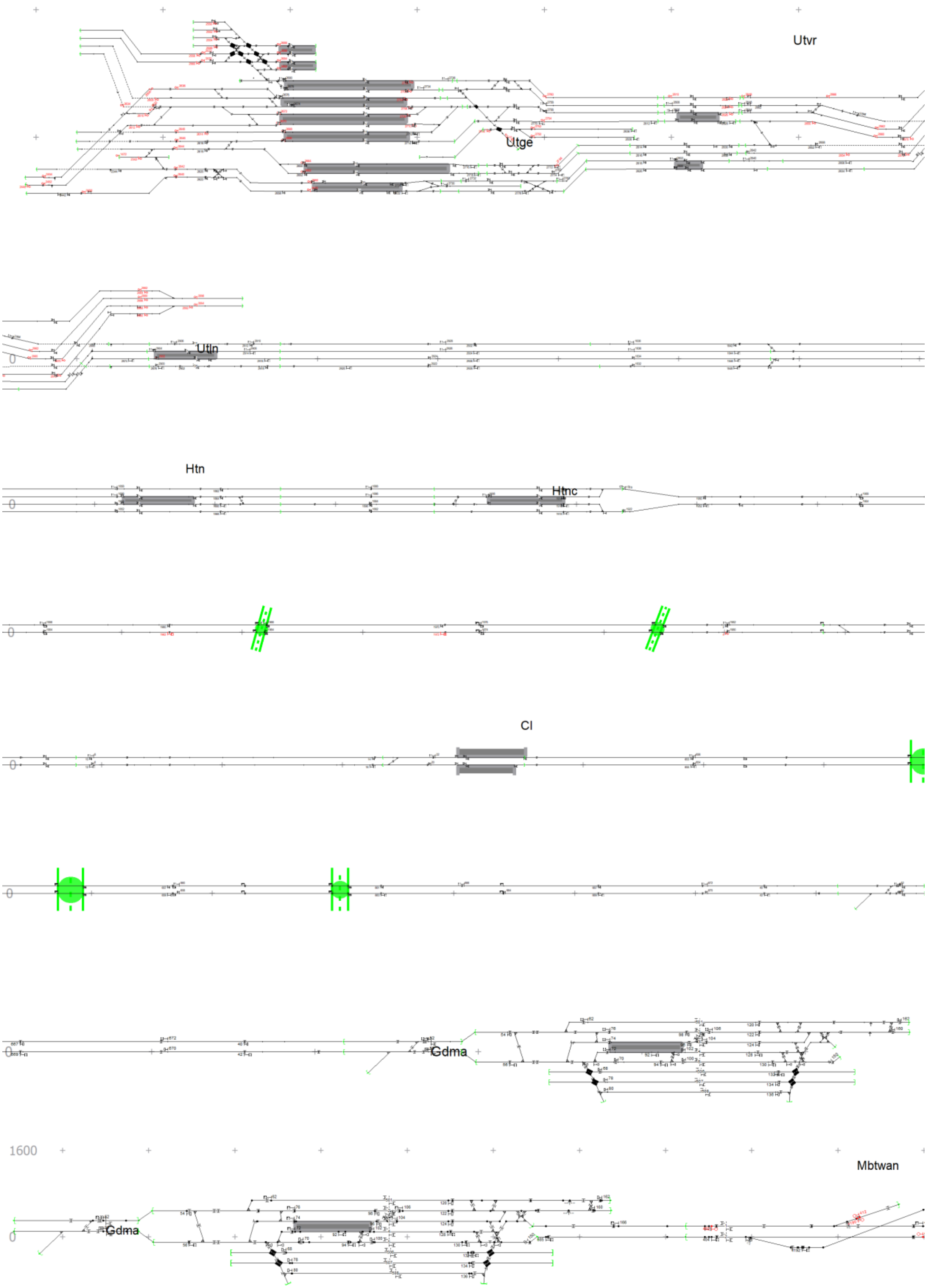

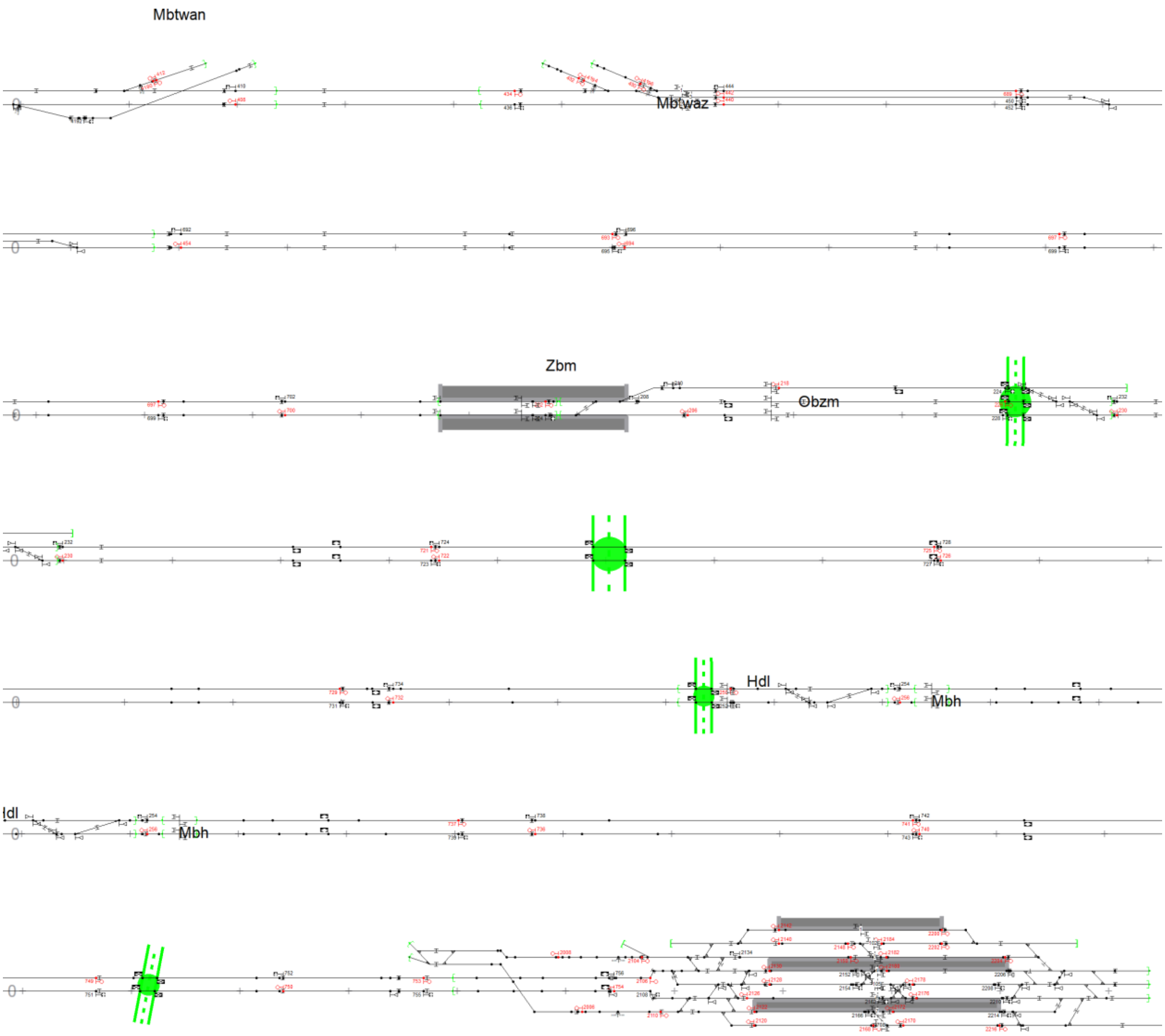
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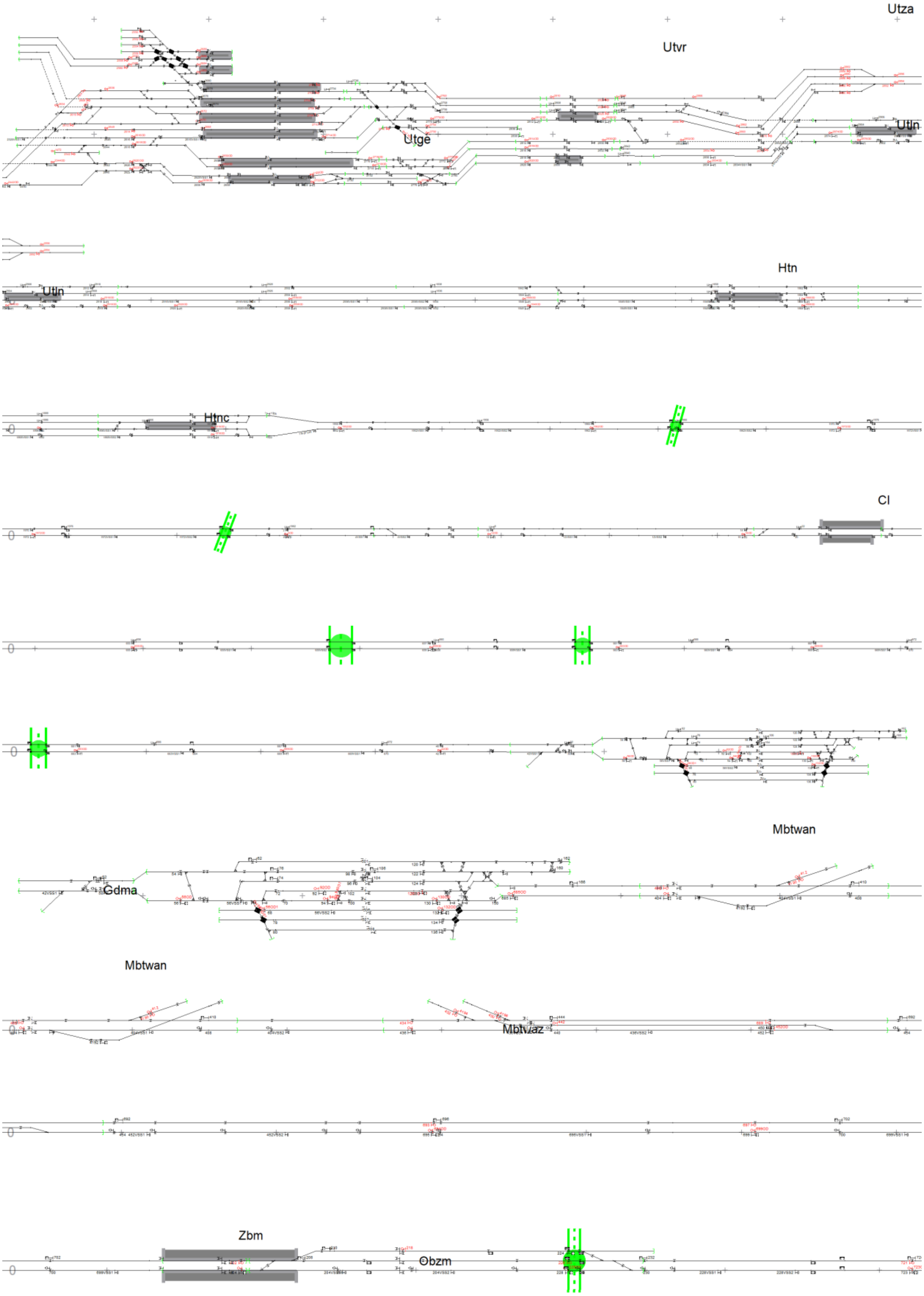
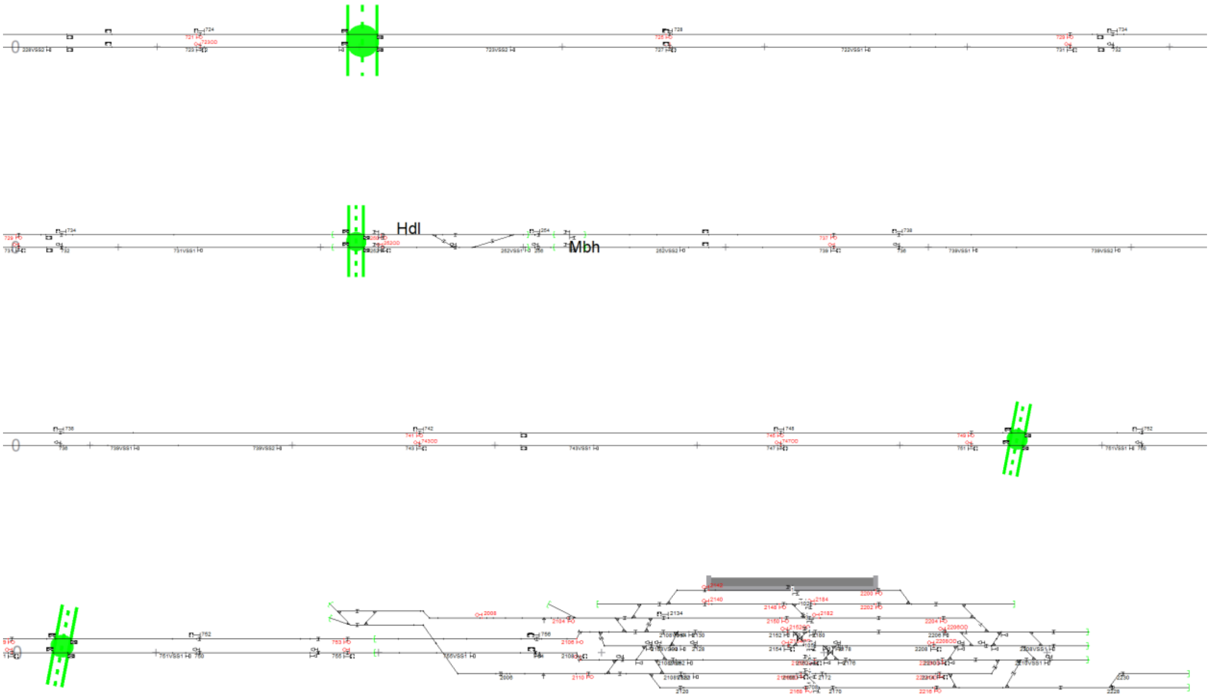
Mbtwaz
Zbm
Obzm
Hdl
Mbh
Hdl
Mbh

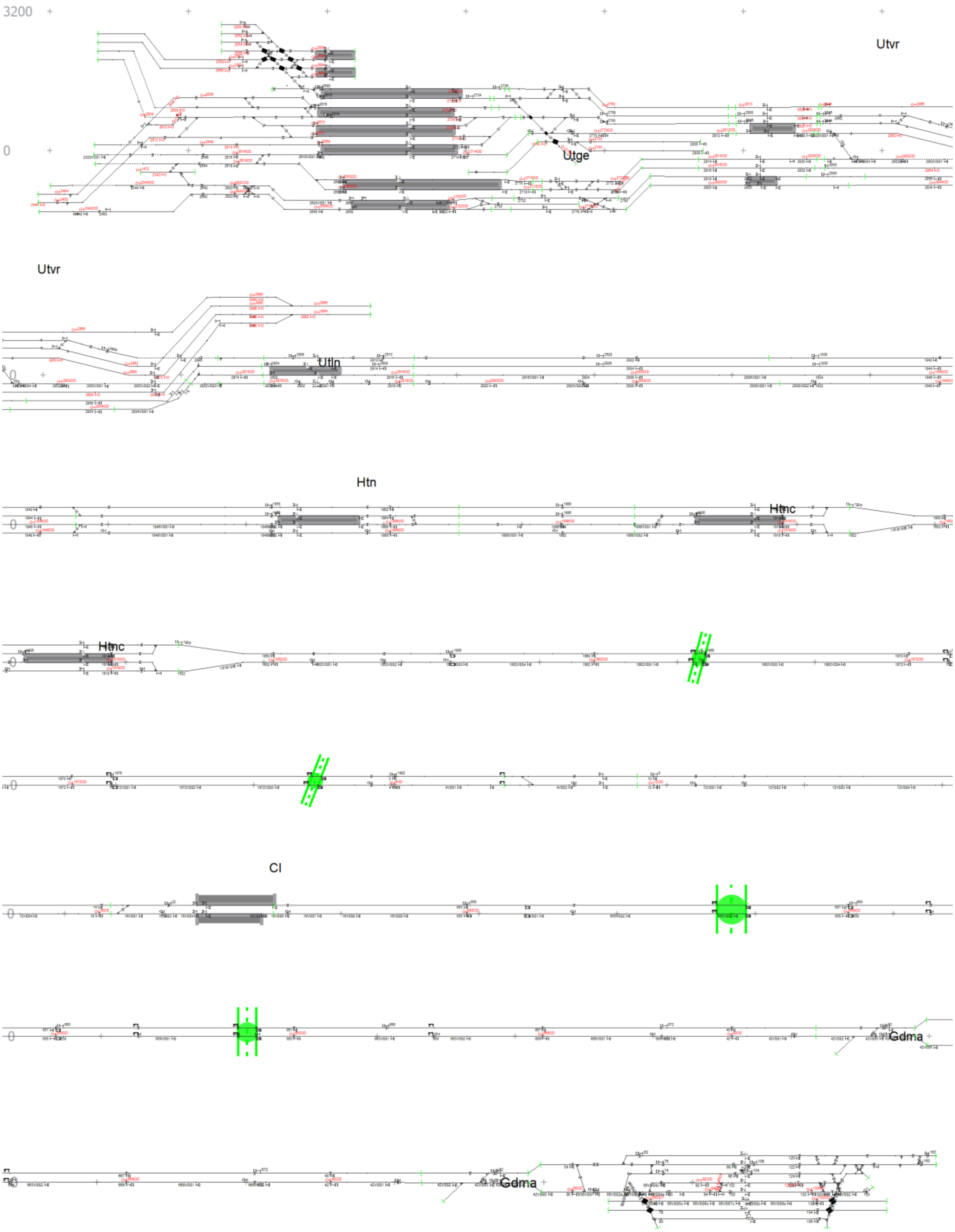
A2.3. ERTMS/ETCS HL3, intermediate VSS

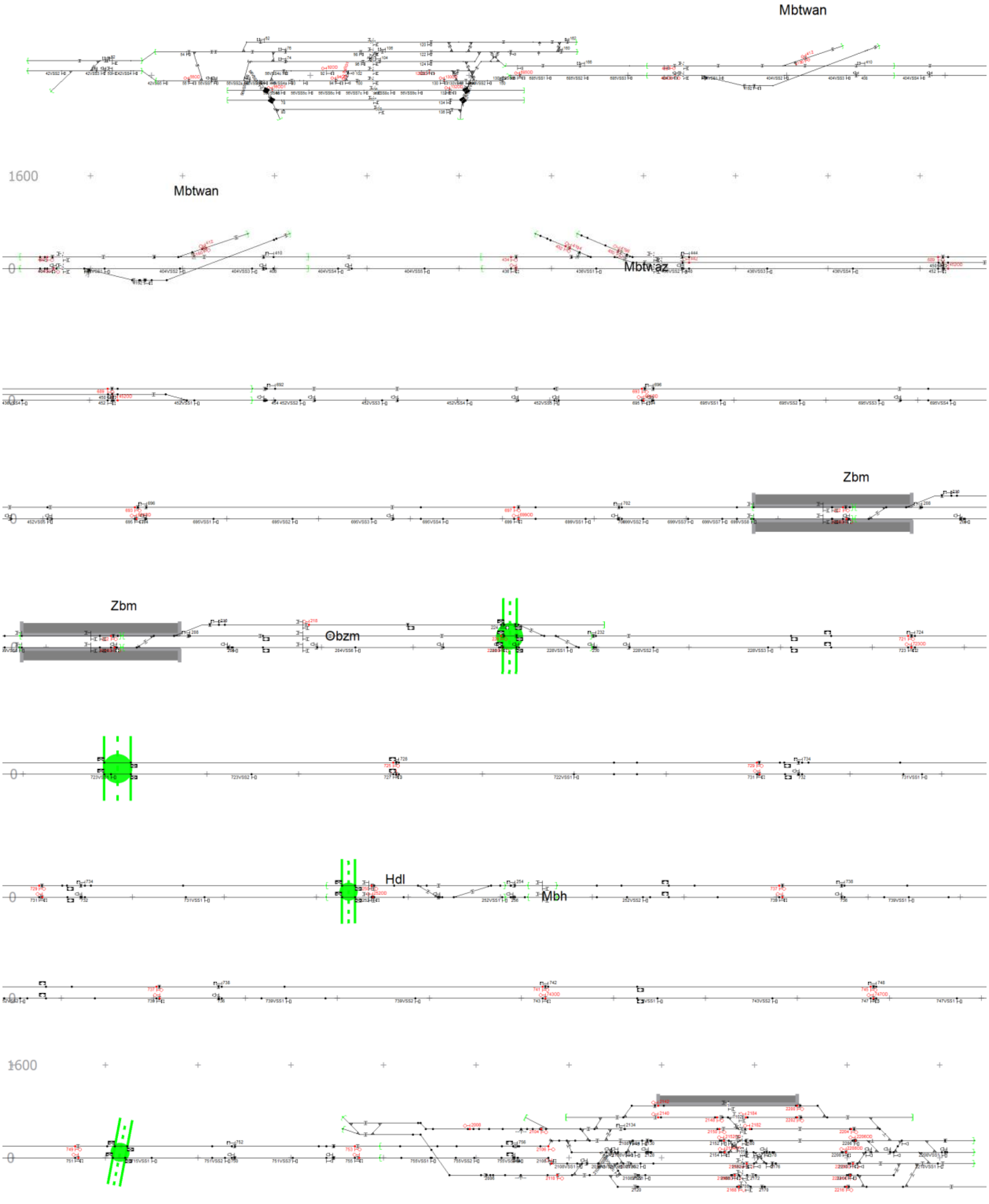



Hdl
Mbh

A2.4. ERTMS/ETCS HL3, small VSS

The (reduced) trackside train reduction is not very clear in this overview. In variant 2, all existing insulated joints work as trackside train detection. In variant 3, all around junctions, crossovers and level-crossings trackside train detection is present. All other existing TTD is removed.

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1600
Mbtwan
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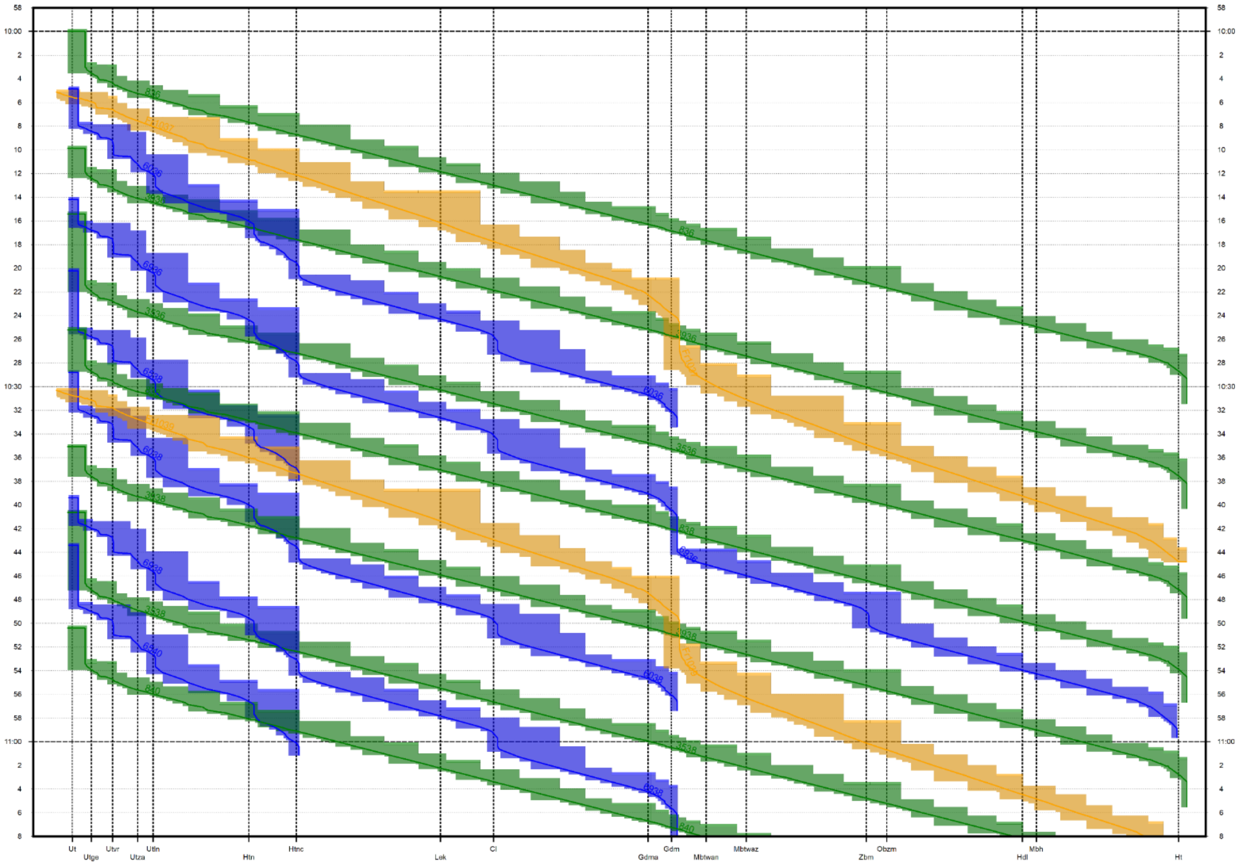
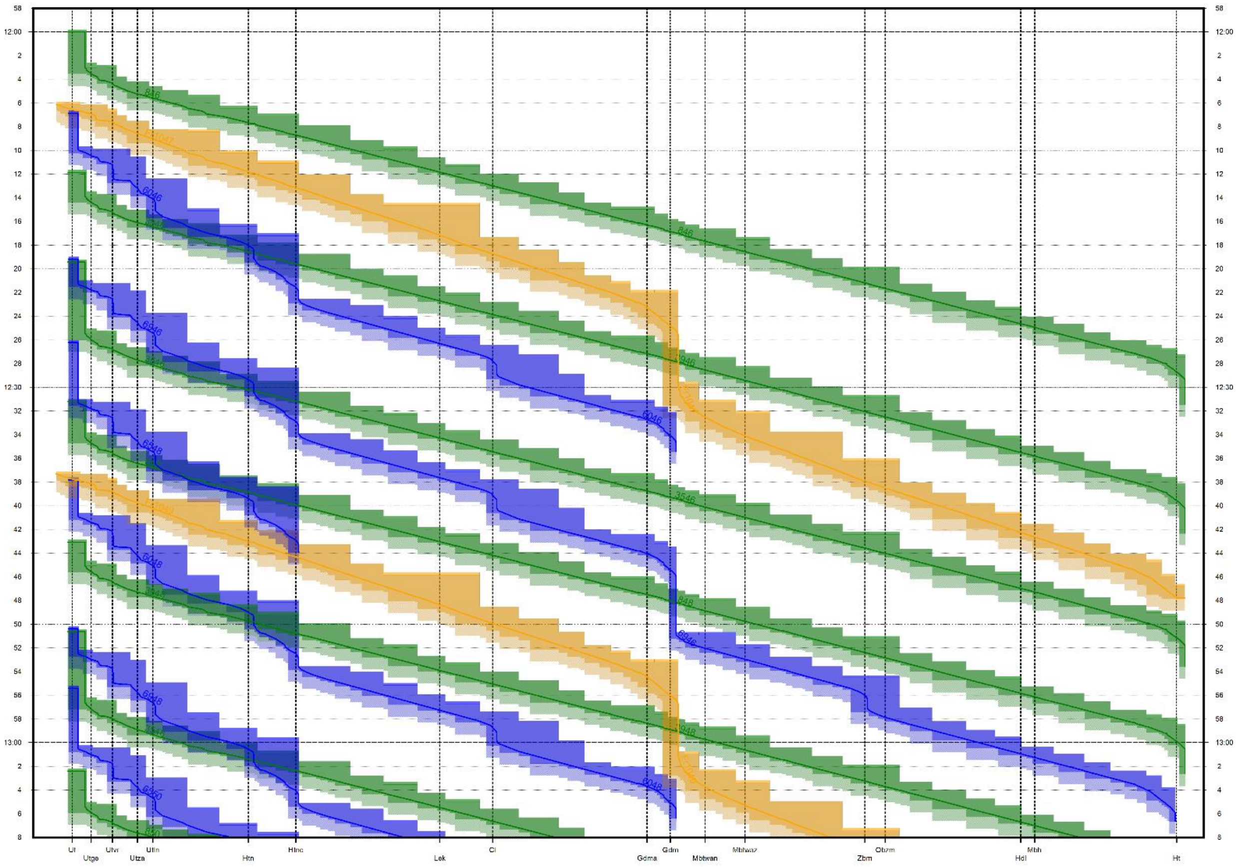
Zbm
Zbm
Obzm
Hdl
Mbh
1600

A3.1.1. NS'54/ATB-EG



A3.1.2. NS'54/ATB-EG + buffer



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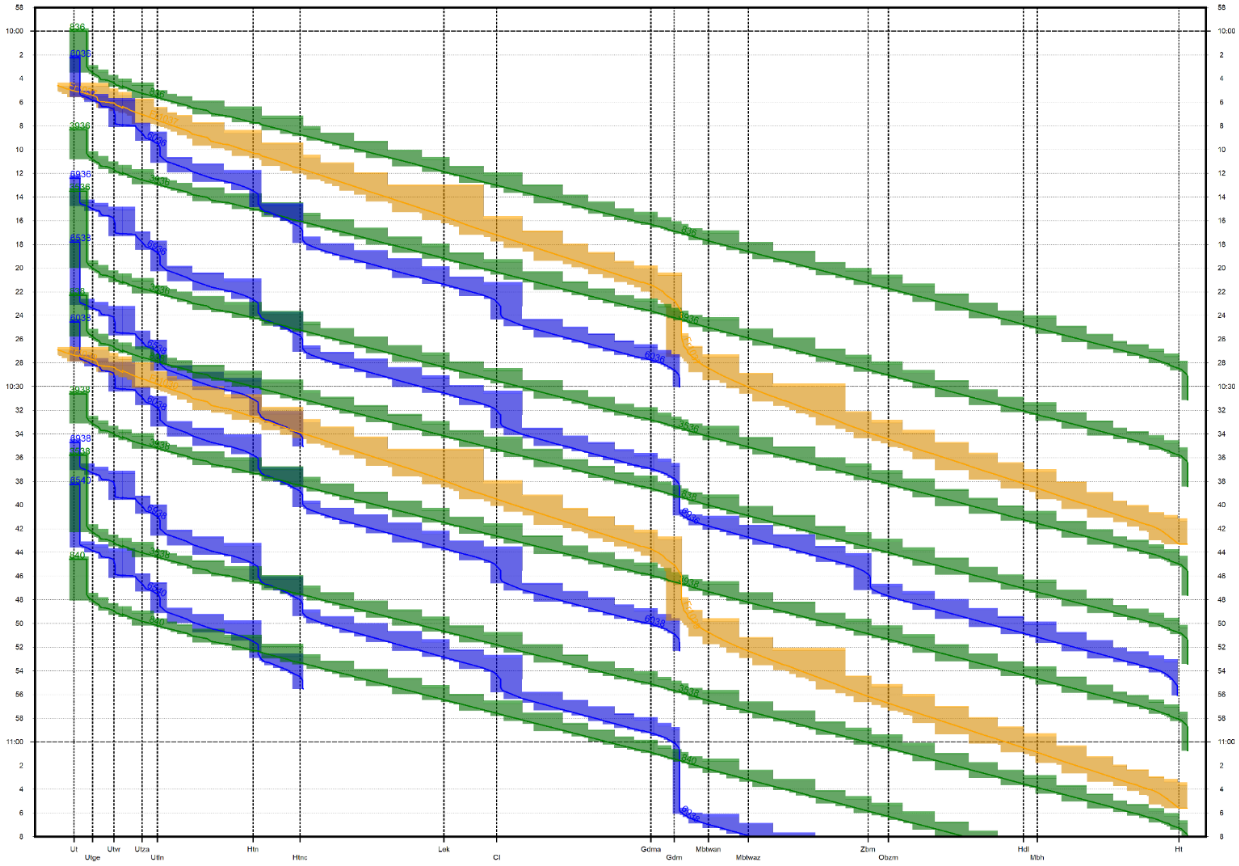
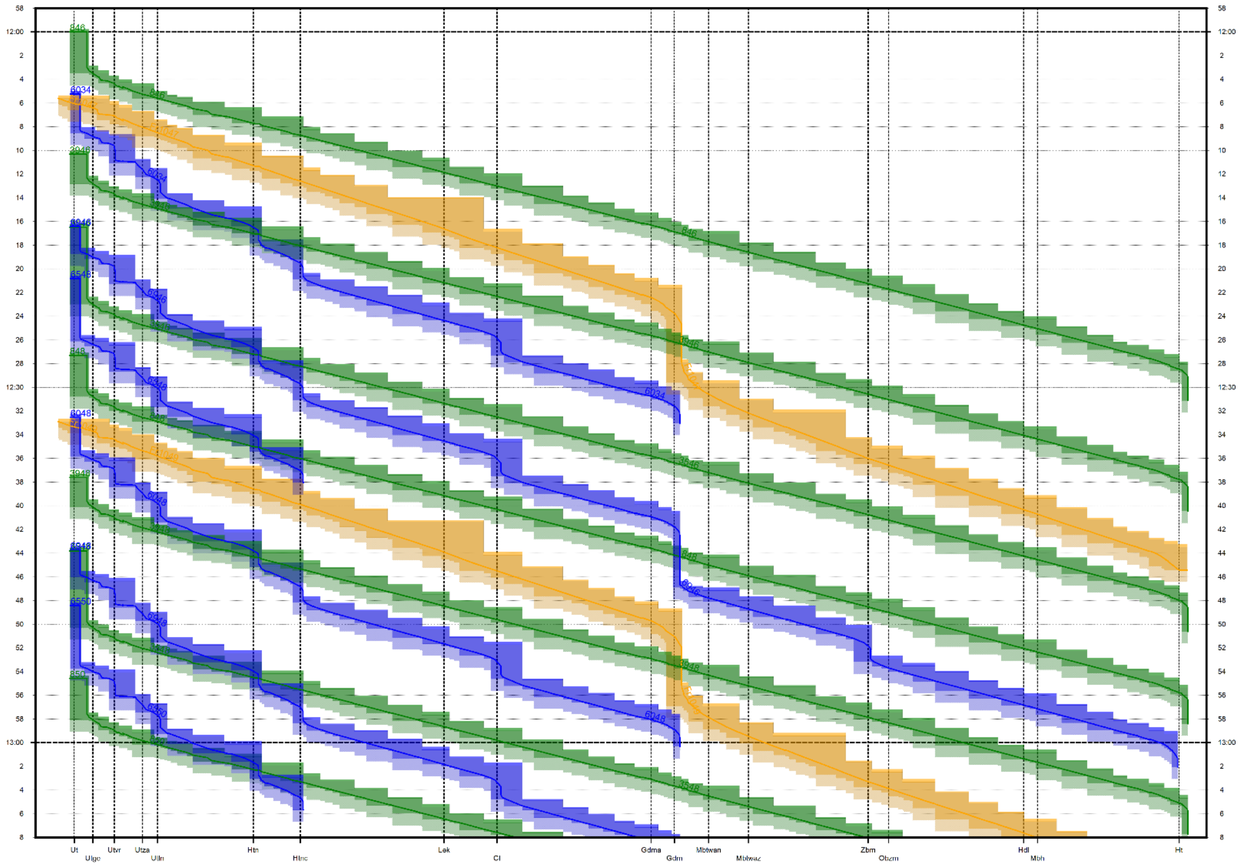
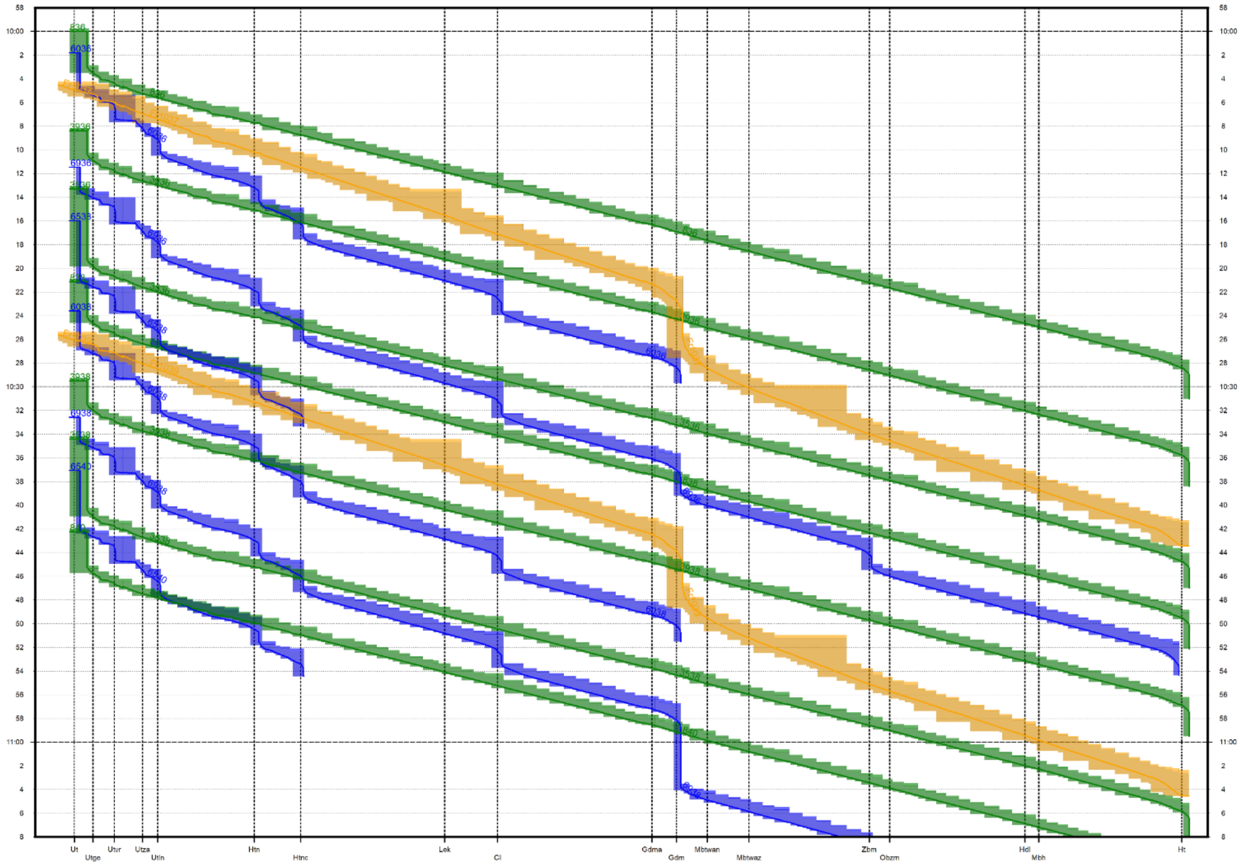


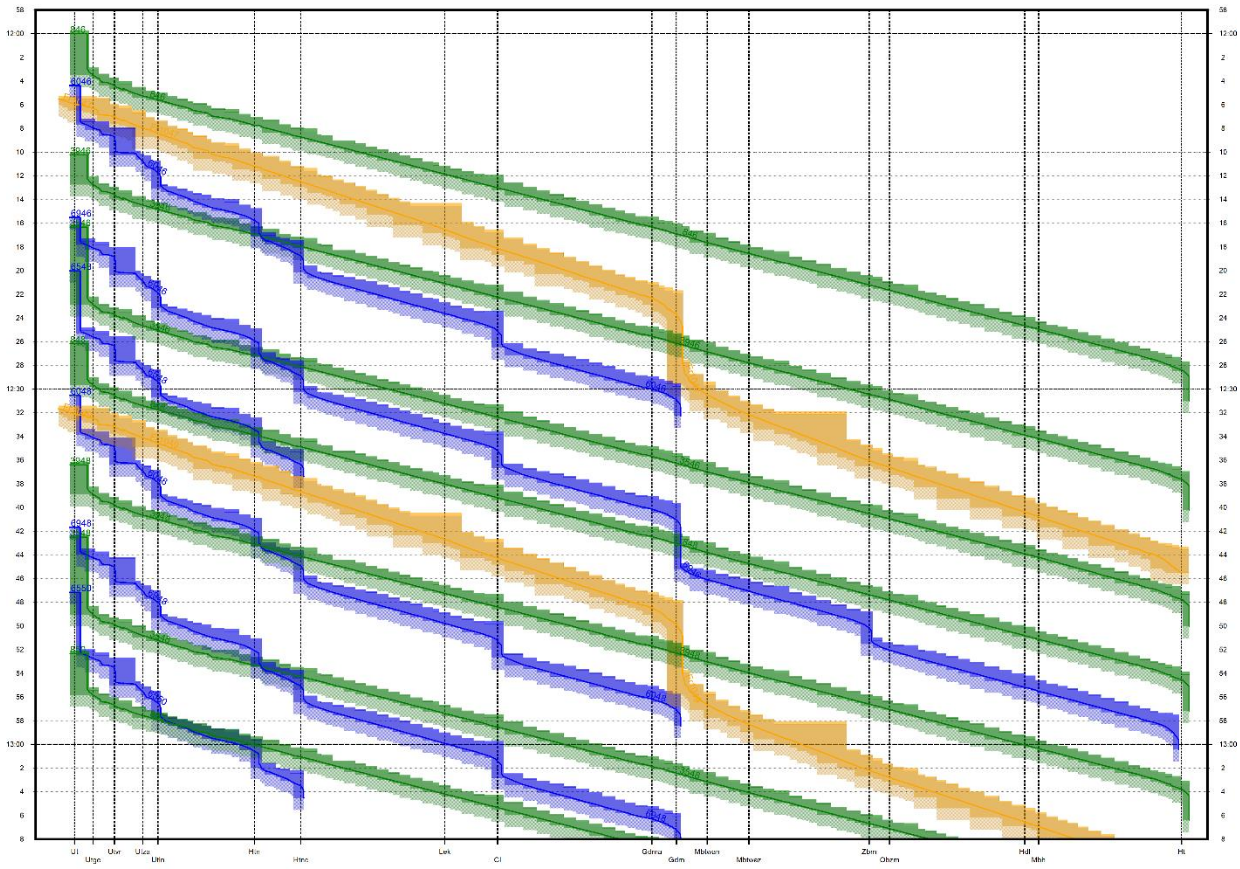
A3.2.2. ERTMS/ETCS L2 + buffer



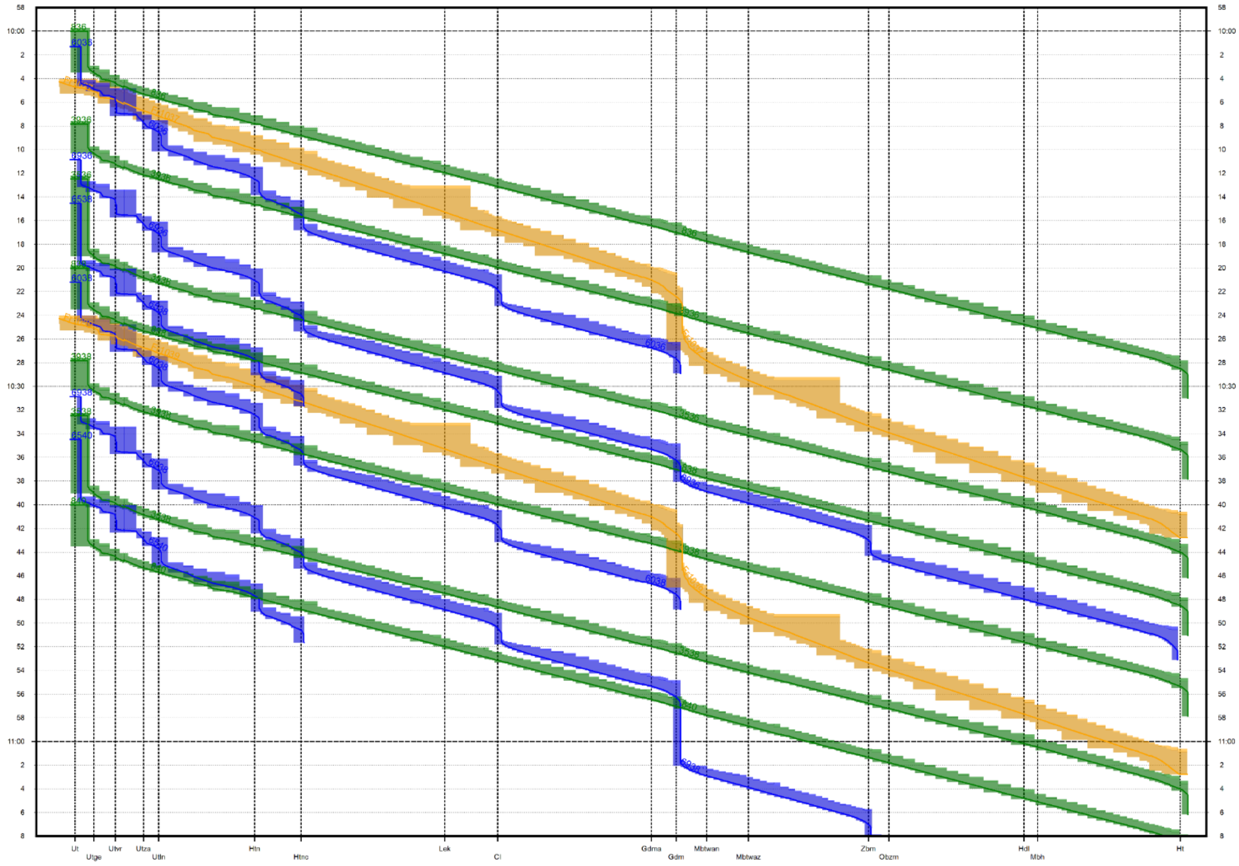
A3.3.1. ERTMS/ETCS HL3, intermediate VSS



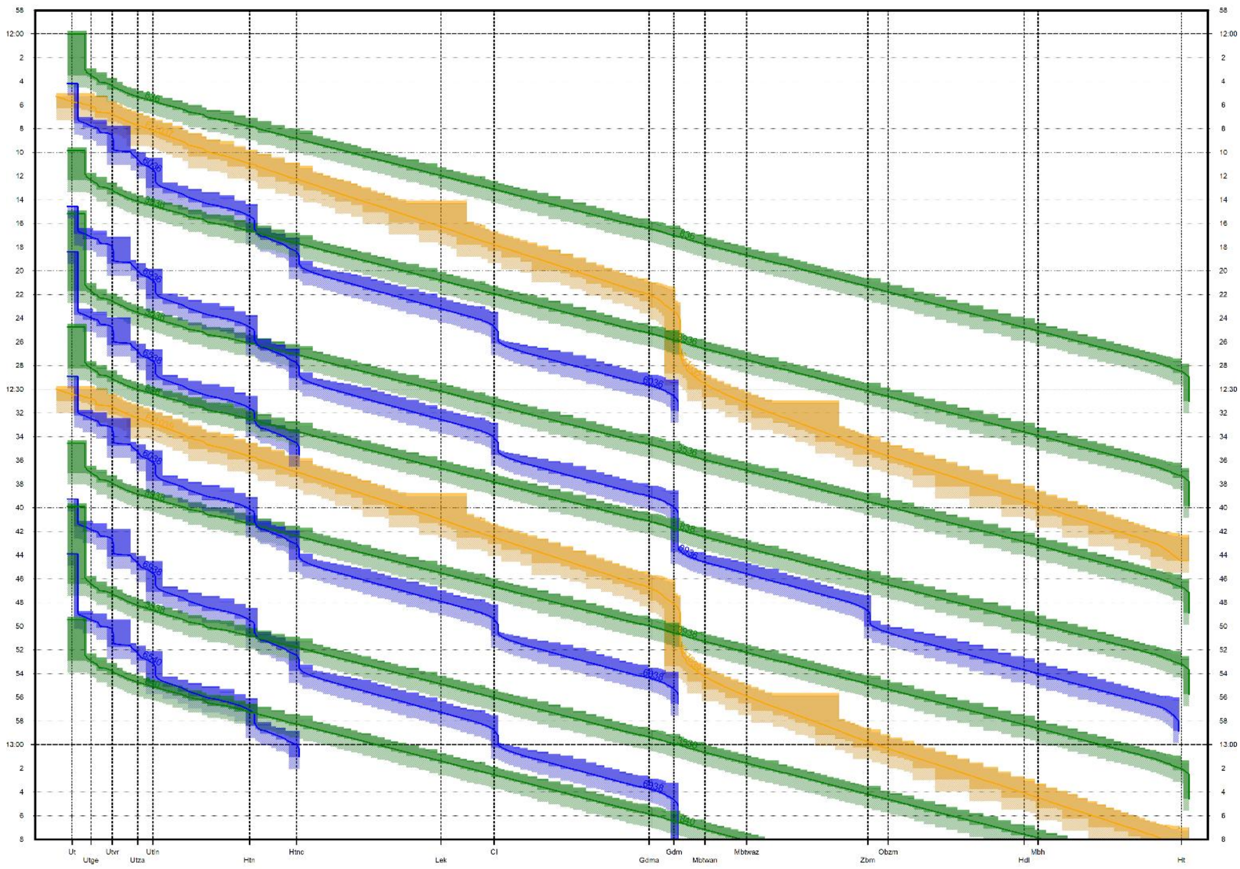
A3.3.2. ERTMS/ETCS HL3 + buffer, intermediate VSS



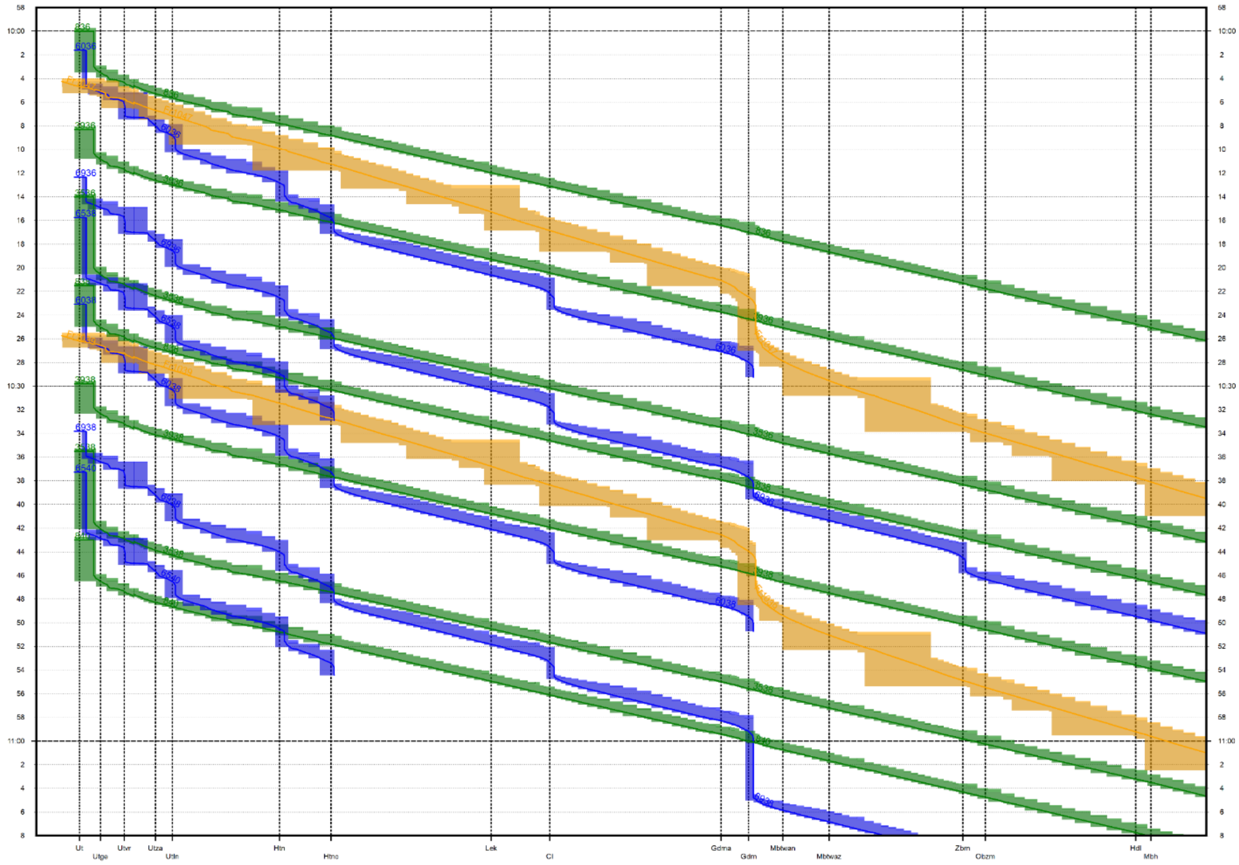
A3.4.1. ERTMS/ETCS HL3, small VSS



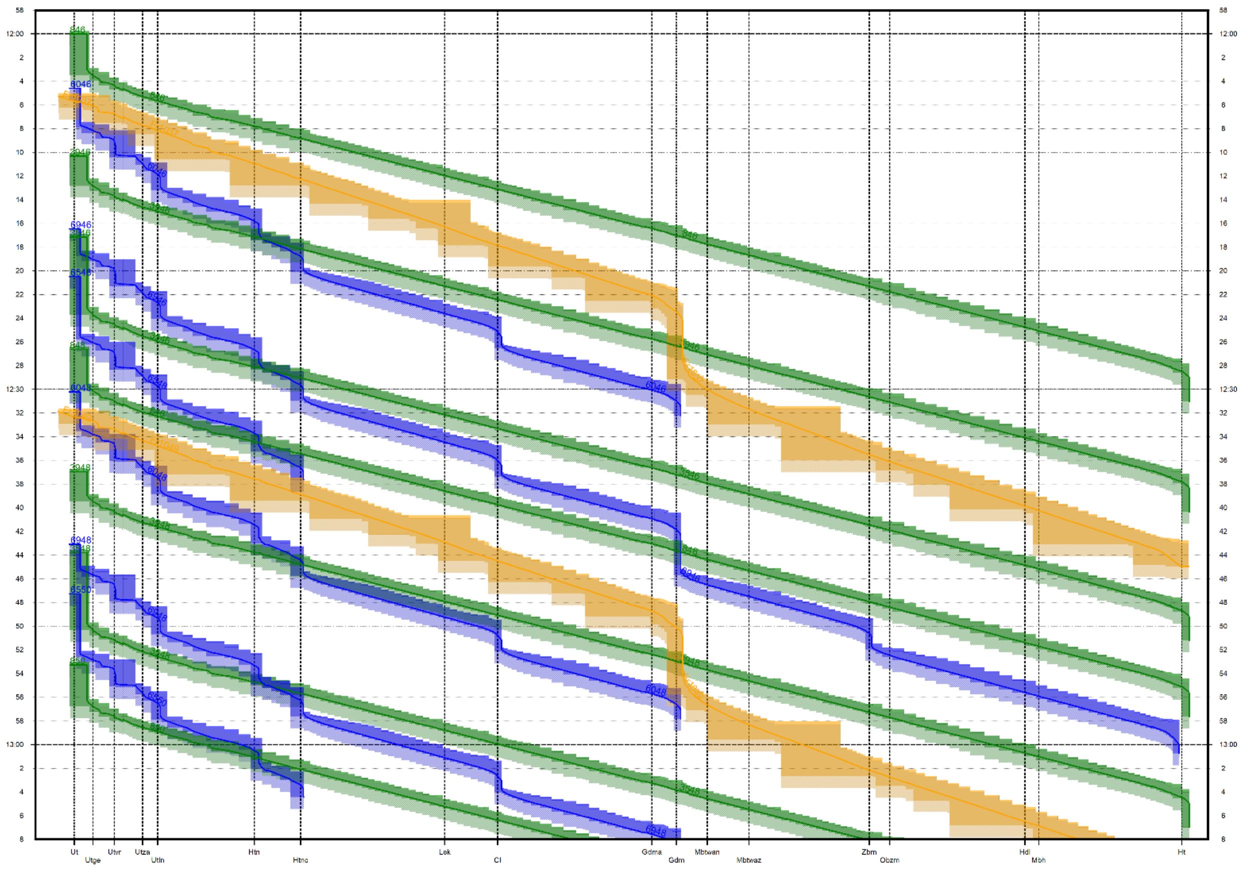
A3.4.2. ERTMS/ETCS HL3 + buffer, small VSS



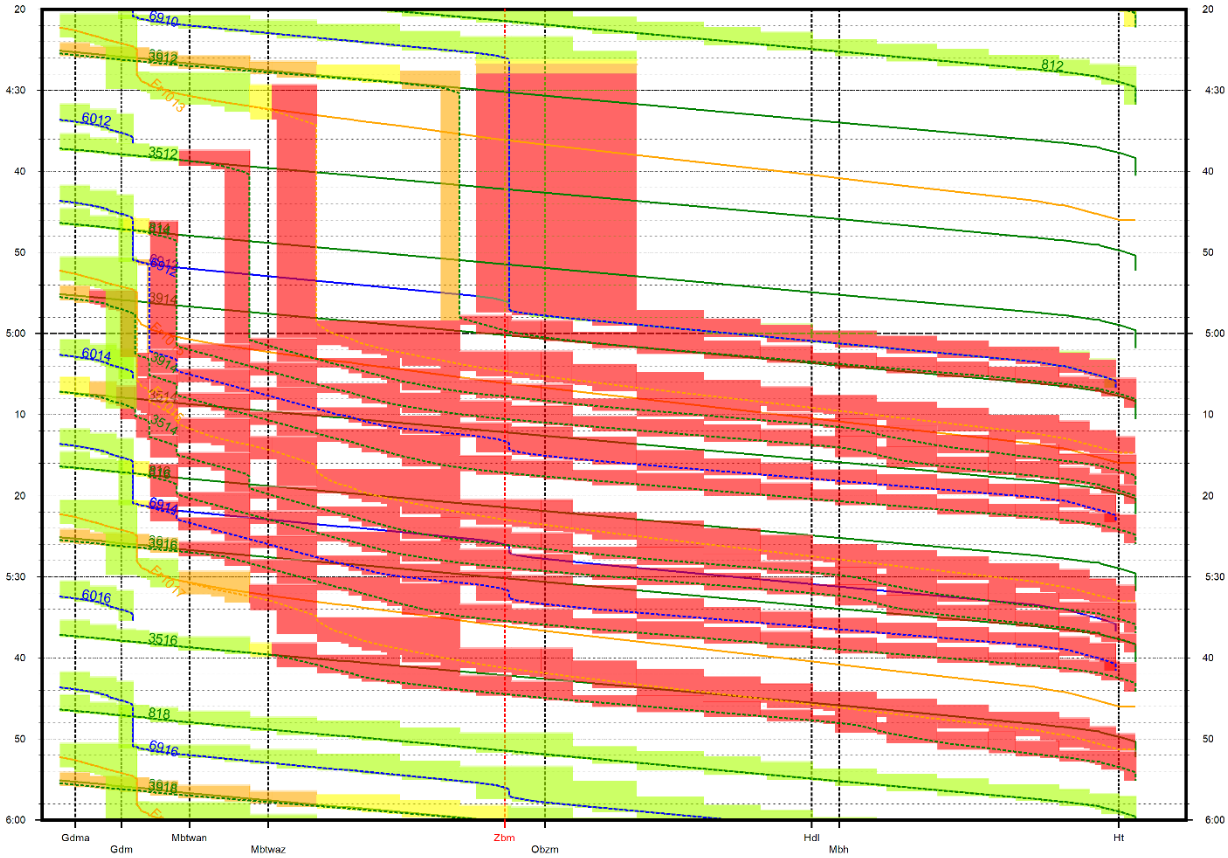
A3.5.1. ERTMS/ETCS HL3, small VSS, reduced TTD



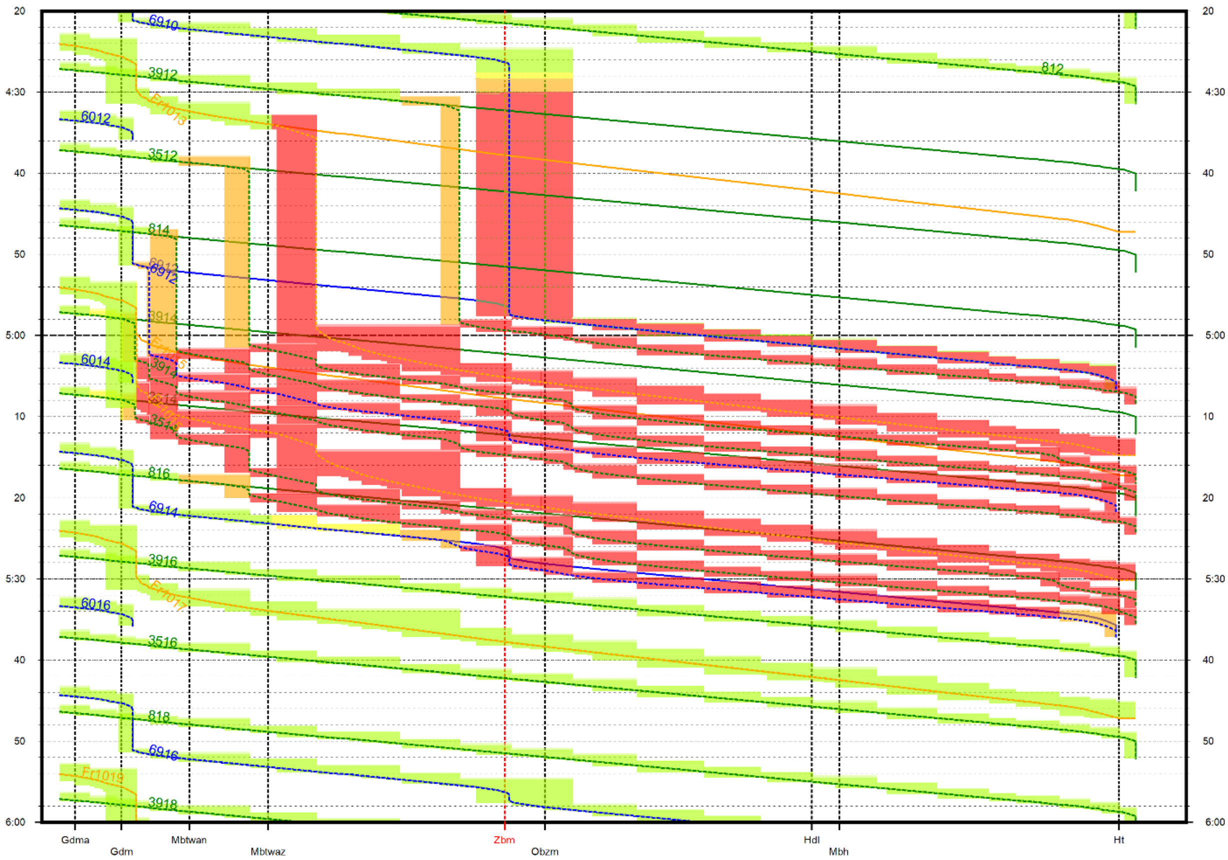
A3.5.2. ERTMS/ETCS HL3 + buffer, small VSS, reduced TTD



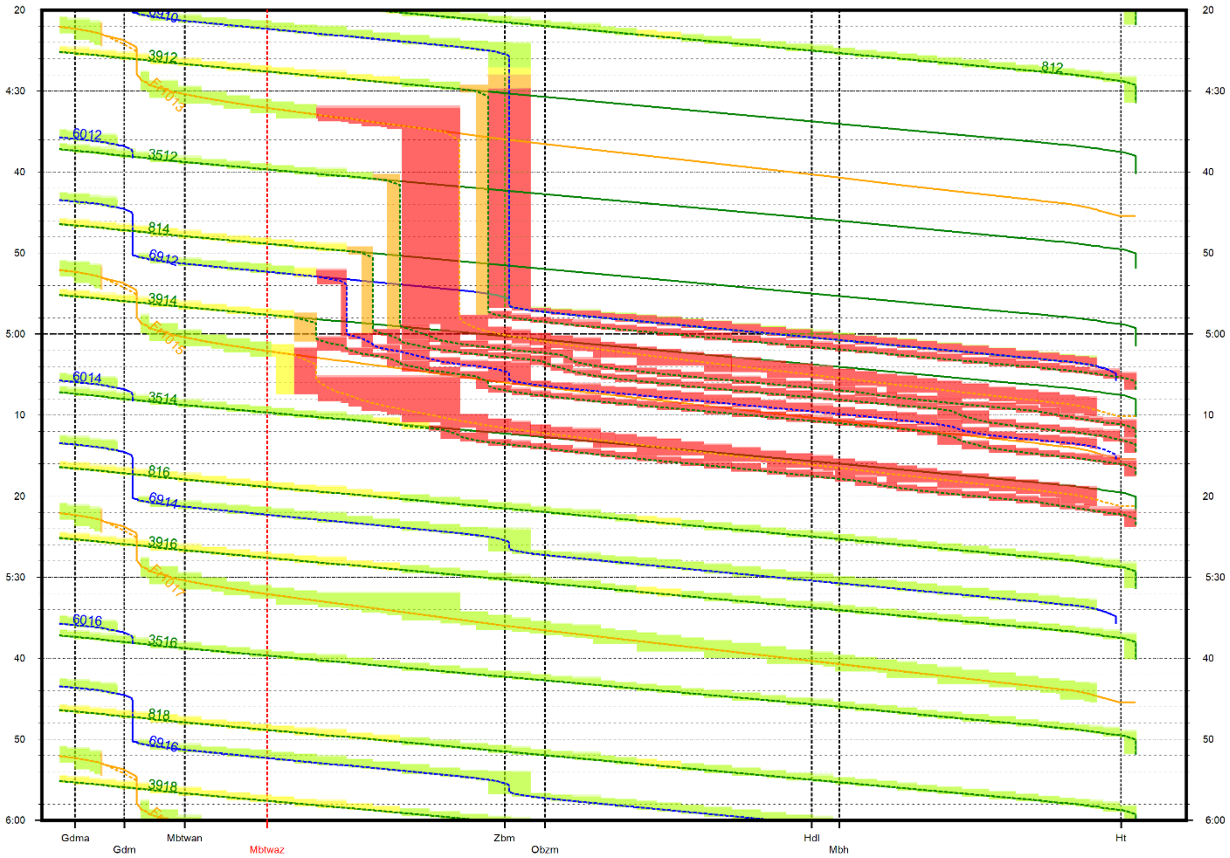
A4.1. NS’54/ATB-EG



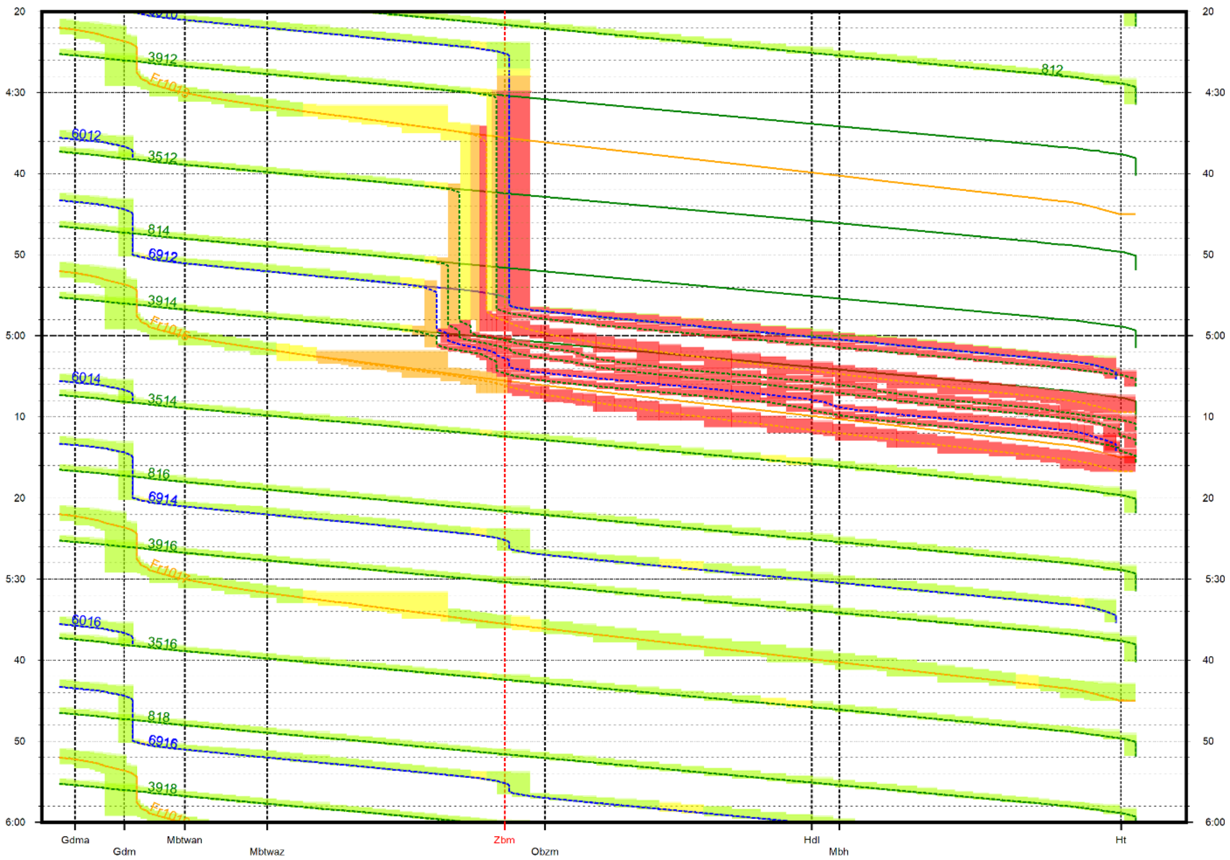
A4.2. ERTMS/ETCS L2



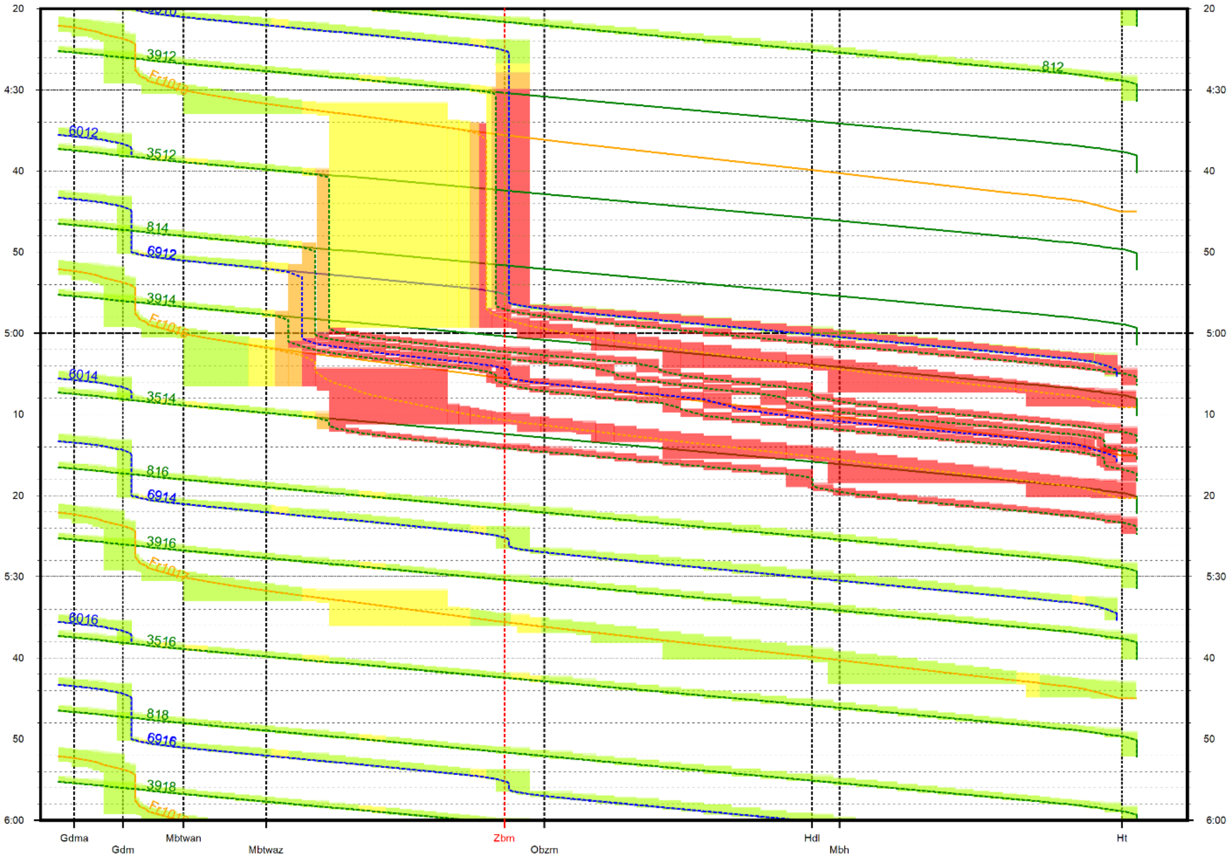
A4.3. ERTMS/ETCS HL3, intermediate VSS



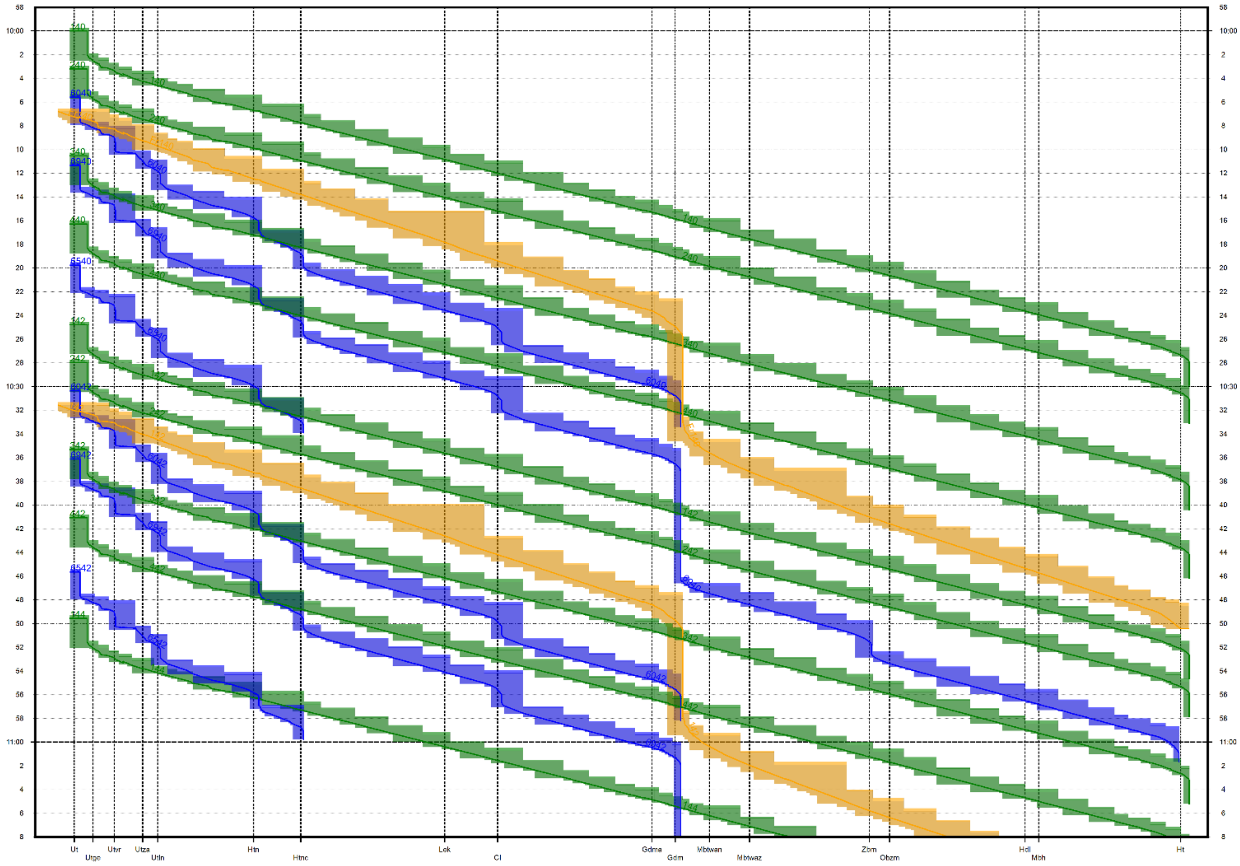
A4.4. ERTMS/ETCS HL3, small VSS



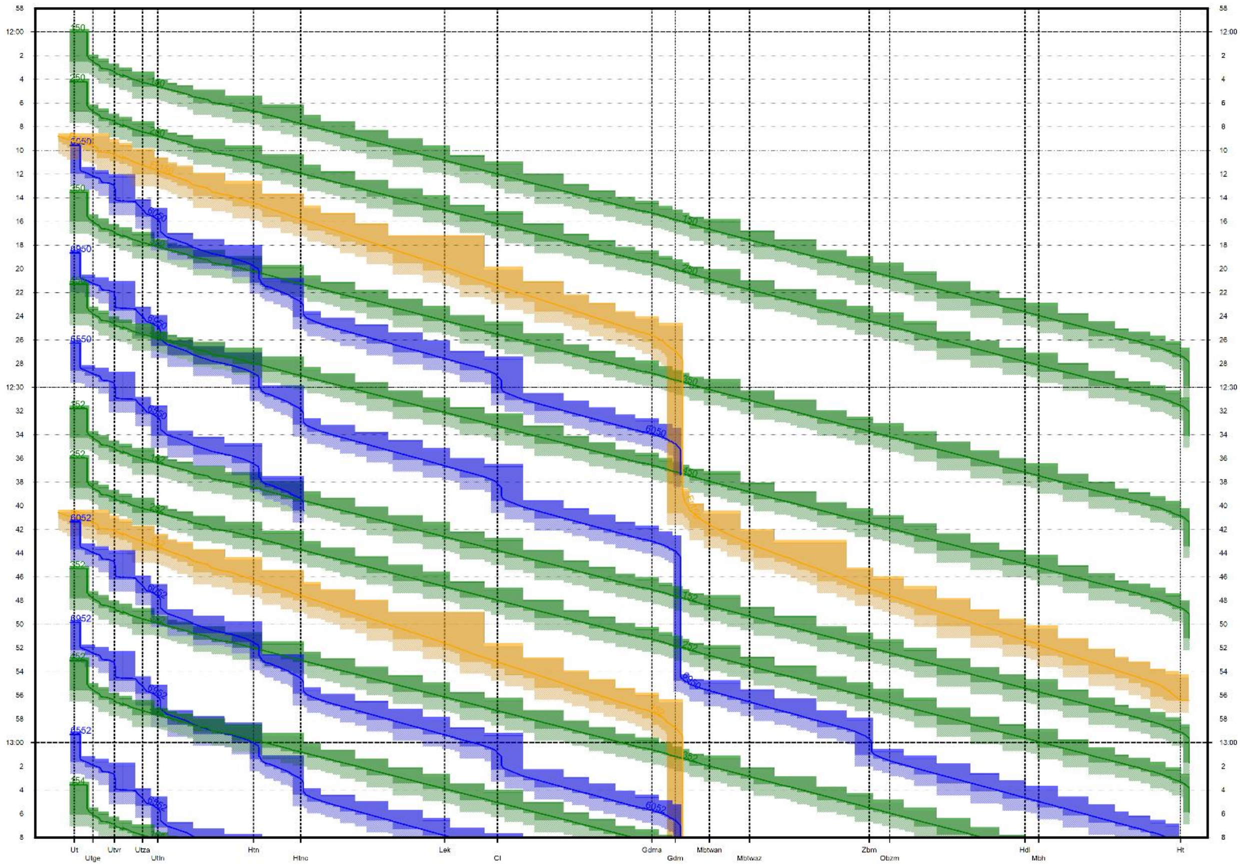
A4.5. ERTMS/ETCS HL3, small VSS, reduced TTD



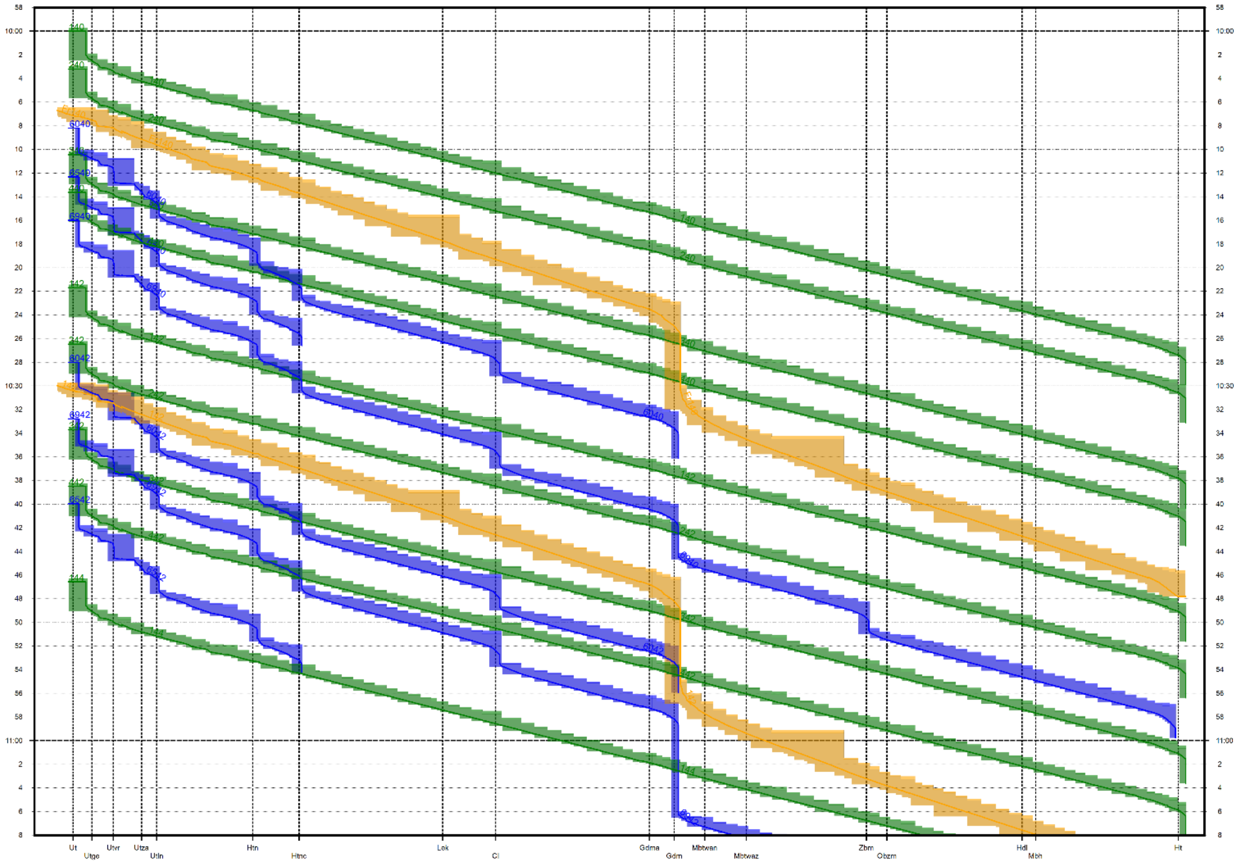
A5.1.1. ERTMS/ETCS L2, additional ICs



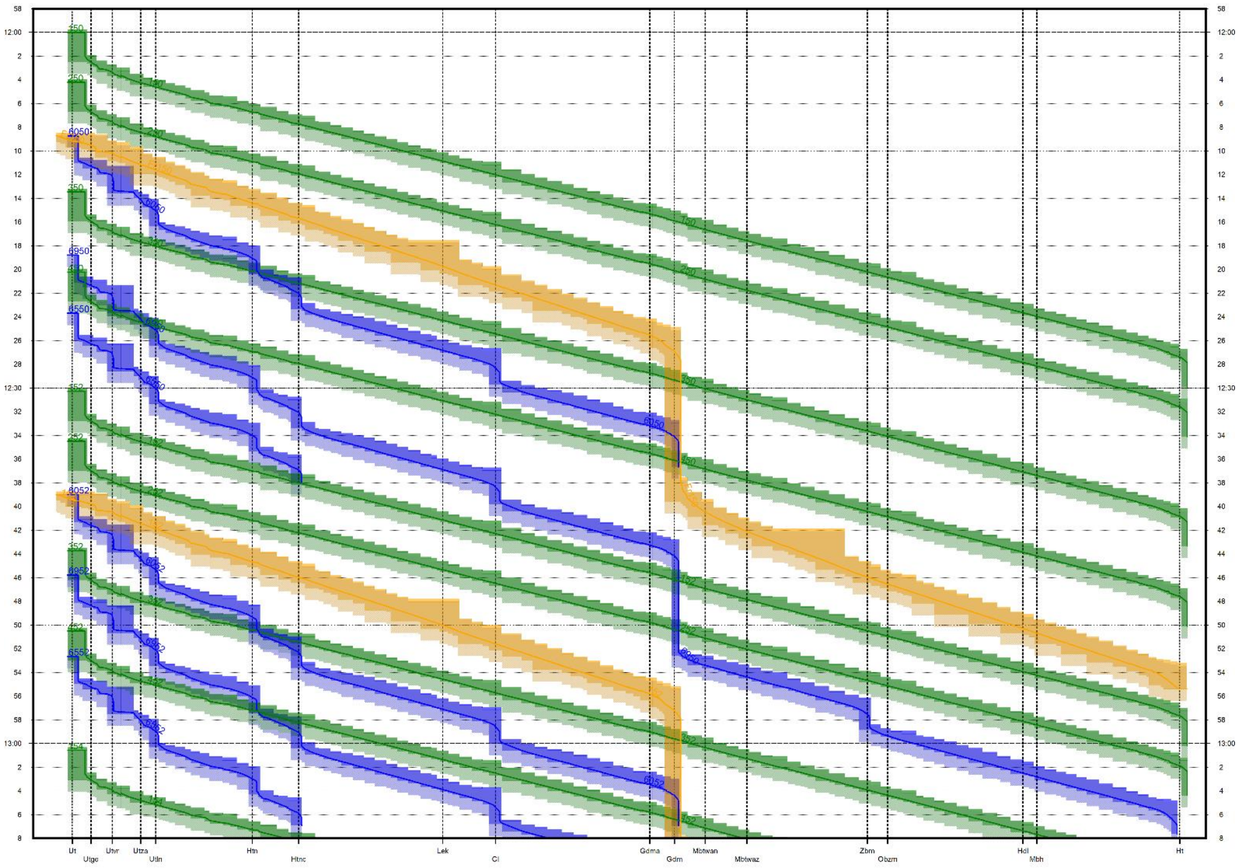
A5.1.2. ERTMS/ETCS L2 + buffer, additional ICs



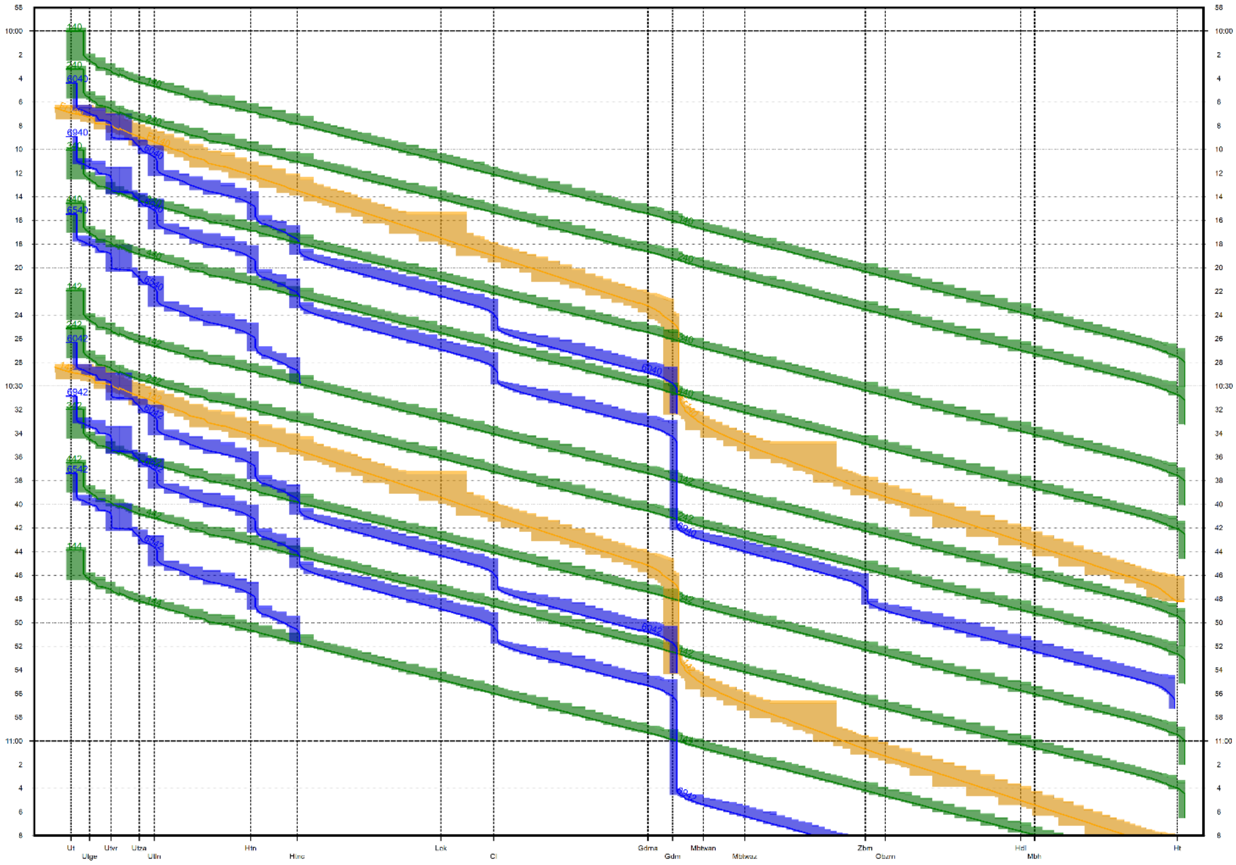
A5.2.1. ERTMS/ETCS HL3, additional ICs, intermediate VSS



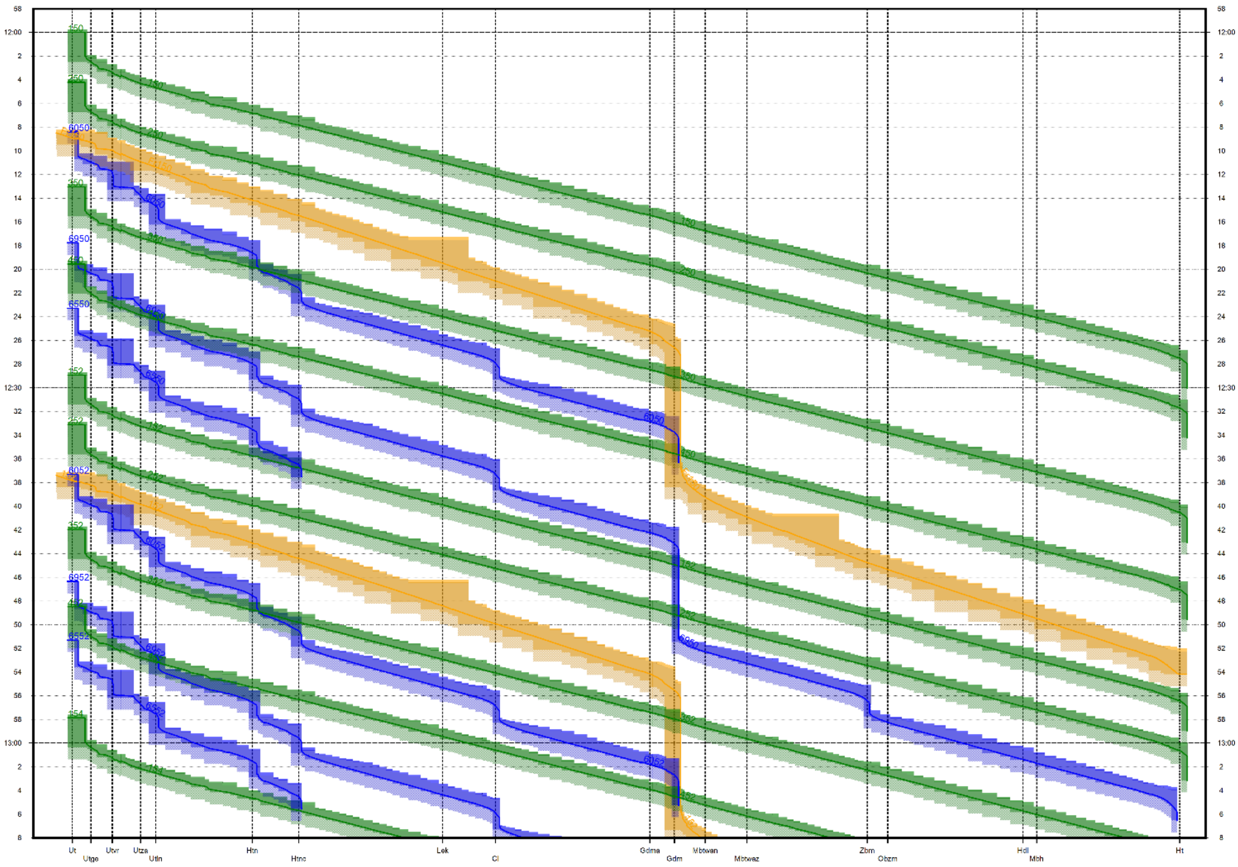
A5.2.2. ERTMS/ETCS HL3 + buffer, additional ICs, intermediate VSS



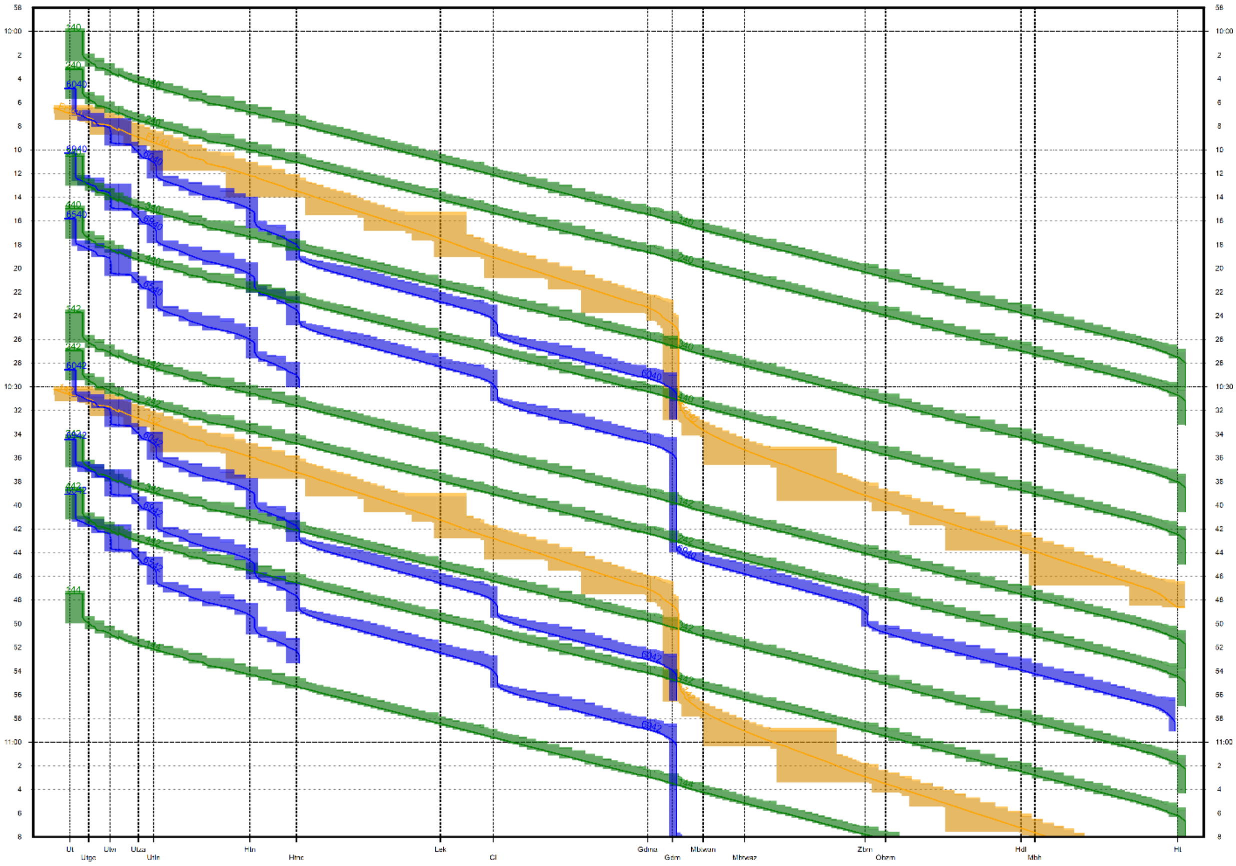
A5.3.1. ERTMS/ETCS HL3, additional ICs, small VSS



A5.3.2. ERTMS/ETCS HL3 + buffer, additional ICs, small VSS



A5.4.1. ERTMS/ETCS HL3, additional ICs, small VSS, reduced TTD



A5.4.2. ERTMS/ETCS HL3 + buffer, additional ICs, small VSS, reduced TTD