Operational transitions in railway infrastructure

Master thesis

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Preface

Terwijl de kinderen in mijn straat hun ongewoon lange schoolvrije periode gebruikten om de sloot voor mijn huis uit te baggeren, wat de buurt vervulde met een enorme moeraslucht, en visten naar rivierkreeftjes, die daar niet horen te zitten, zat ik op mijn kamer te schrijven aan mijn afstudeerrapport. Dag in, dag uit herhaalde dit tafereel zich. Soms had ik de neiging om me bij hen te voegen, zeker als de zinnen met moeite uit mijn vingers kwamen. Het feit dat dit rapport af is en voor u ligt, is daarom niet te danken aan mijn eigen kracht, maar door de gemeenschappelijke inspanning van velen die mij de afgelopen maanden ondersteund hebben.

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Samenvatting

Introductie en onderzoeksdoel

Technologische innovaties in de Nederlandse spoorwegsector, zoals ERTMS en 3kV tractie-energievoorziening (TEV), maken het mogelijk om de efficiëntie, effectiviteit en snelheid van het spoorwegsysteem de komende decennia te verhogen. De implementatie van nieuwe systemen als ERTMS en 3kV is een langdurig proces. De nieuwe systemen zullen daarom lange tijd naast de oude systemen (ATB-EG en 1.5kV) blijven bestaan. Tussen die oude en het nieuwe systemen zijn operationele transities nodig. Het aantal operationele transities zal de komende jaren daardoor toenemen.

Sommige van deze operationele transities blijken vatbaar voor verstoringen. Wanneer een operationele transitie mislukt, kan dit voor aanzienlijke vertragingen op het spoorwegnet zorgen. Vooral wanneer meerdere operationele transities dicht bij elkaar liggen of gelijktijdig plaatsvinden, is het risico van verstoringen bij een van deze transities aanzienlijk. Wanneer verschillende operationele transities worden gecombineerd, kan een verstoring in de ene transitie grote gevolgen hebben voor de andere operationele transitie die vlak naast de eerste transitie ligt. Operationele transities worden gedefinieerd door twee kenmerken. Ten eerste zijn het fysieke locaties in de spoorinfrastructuur. De locatie is dus nauwkeurig vast te stellen. Ten tweede vereist een operationele transitie dat de machinist moet schakelen tussen twee systemen of zijn/haar gedrag aanzienlijk moet veranderen.

Het doel van dit proefschrift is om het effect van operationele transities op de betrouwbaarheid van de treinexploitatie te onderzoeken. Het is vaak onduidelijk hoe groot de impact van operationele transities op de treindienst zijn. Dit proefschrift levert een bijdrage aan de wetenschappelijke literatuur door een aanzienlijk aantal operationele transitietypen te typeren en te onderzoeken. Dit onderzoekt geeft inzicht in de effecten van systeemtransities op de betrouwbaarheid van de treinexploitatie. Voor ProRail kan dit onderzoek bijdragen aan een beter begrip van operationele transities. Hieruit kunnen maatregelen worden genomen die de betrouwbaarheid van operationele transities vergroten om zo de punctualiteit van de treindienst toe te laten nemen.

Methodieken

Omdat er in de wetenschappelijke literatuur weinig bekend is over (operationele) transities in de spoorsector, wordt gebruik gemaakt van een verkennende onderzoeksmethode. Als onderzoeksmethode wordt de grounded theory-approach gebruikt. Hierbij worden theorieën gevormd op basis van patronen die uit de data naar voren komen. Bovendien wordt de ‘mixed methods approach’ toegepast om data te verzamelen. Zowel kwantitatieve als kwalitatieve databronnen worden gebruikt om deze patronen in operationele transities te ontdekken.

De eerste stap in het onderzoek is het identificeren van operationele transitietypes op het Nederlandse spoorwegnet. Op basis van de kenmerken van operationele transities, brainstorming en interviews zijn acht operationele transitietypes geïdentificeerd. Waar mogelijk zijn de locaties van deze transities vastgelegd.

Er zijn vier case studies uitgevoerd waarin verschillende typen operationele transities aan bod komen. In de eerste case study worden operationele transities op de HSL-Zuid, Betuweroute en Havenspoorlijn onderzocht aan de hand van informatie uit literatuur en uit interviews. In de tweede case study worden operationele transities op knooppunt Meteren onderzocht en de derde case study onderzoekt operationele transities bij Zaandam. Voor de tweede en derde case studies worden kwantitatieve methoden gebruikt. Twee deelvragen aan de orde bij deze drie case studies. Allereerst wordt onderzocht in hoeverre vertragingen ontstaan door de vastgestelde operationele transities. Ten

tweede wordt onderzocht wat de onderliggende oorzaken van mislukte operationele transities zijn. In de vierde en laatste case study wordt de rol van menselijke factoren bij het mislukken van operationele transities onderzocht. Interviews met machinisten en experts zijn gebruikt om de rol van human factors in vertragingen als gevolg van een mislukte ATB-EG-ERTMS transities te onderzoeken. Deze laatste case study is niet gericht op een specifieke locatie.

Identificatie van operationele transitie types

In totaal zijn acht soorten operationele transities zijn geïdentificeerd. Er zijn zes typen operationele transities geïdentificeerd die 'permanent' van aard zijn. Ze maken deel uit van de spoorweginfrastructuur en kunnen niet gemakkelijk worden gewijzigd (Tabel 1). Verder zijn er twee soorten tijdelijke operationele transities. Deze operationele transities zijn voor een beperkte tijd aanwezig. De locatie van deze transities is ook variabel (Tabel 2).

Tabel 1 Permanente operationele transitietypes

TRANSITIE TYPES	BESCHRIJVING
TRACTIE ENERGIEVOORZIENING (TEV)	TEV-transities zijn noodzakelijk wanneer twee verschillende TEV-systemen worden gebruikt. Treinen hebben de juiste apparatuur nodig om beide TEV-systemen aan te kunnen. De bestuurder is verantwoordelijk voor het overschakelen tussen beide TEV-systemen. Fasescheidingen komen voor op 25kV railsecties om stromen te scheiden die niet in fase zijn. De machinist moet hier de pantograaf te laten zaken.
AUTOMATISCHE TREINBEVEILIGING (ATP)	In Nederland worden meerdere ATP systemen gebruikt: ATB-EG, ATB-NG en ETCS. Transities tussen deze systemen worden automatisch uitgevoerd door het ATP system in de trein. De machinist dient deze transities te bevestigen.
BEWEEGBARE BRUGGEN	Verschillende soorten bruggen vereisen verschillende handelingen van de machinist. Sommige bruggen kunnen zonder operationele beperkingen worden gepasseerd, terwijl voor andere bruggen, bijvoorbeeld bruggen zonder bovenleiding, de machinist tractie moet uitschakelen.
VERTICAAL ALIGNEMENT	Het verticale spooralignement kan veranderen bij bruggen, tunnels, fly-overs, dive-unders en het (natuurlijke) terrein waarop de spoorlijn is gebouwd. Steile hellingen veroorzaken grote veranderingen in de treinsnelheid. De machinist moet zich hiervan bewust zijn en anticiperen op de aanwezigheid van hellingen in de spoortracé.
VERKEERSLEIDINGS-POSTEN	Het Nederlandse spoorwegnet wordt aangestuurd door Verkeersleidings-posten (VL-post) die problemen en conflicten op het spoor oplossen. Wanneer conflicten niet op tijd door treindienstleiders (trdl) worden afgehandeld, kunnen treinen gele en rode seinen tegenkomen, die de trein afremmen. De overdracht van treinen tussen de Primaire Procesleidingsgebieden (PPLG's) van verschillende trdl's en tussen VL-posten kan eveneens vertragingen veroorzaken
NIET CENTRAAL BEDIENDE GEBIEDEN	Op enkele rangeerterreinen en emplacementen worden wissels niet aangestuurd door trdl's, maar door rangeerders of machinisten. De trdl begeleidt de acties van het rijdende personeel, maar de trdl kan niet ingrijpen. Transities van niet-centraal naar centraal bediende gebieden worden aangegeven met borden of seinen.

Tabel 2 Tijdelijke operationele transitietypes

TRANSITIE TYPES	BESCHRIJVING
TIJDELIJKE SNELHEIDS-BEPERKINGEN (TSB)	TSB's worden ingesteld wanneer rijden op volle snelheid op een bepaalde baanvak als onveilig wordt beschouwd, hetzij vanwege een slechte of slecht functionerende infrastructuur, hetzij vanwege onderhoudswerkzaamheden om de onderhoudsploeg te beschermen
AANWIJZINGEN VAN TRDL	Aanwijzingen worden door trdl's opgelegd als er op of langs een spoorlijn gevaarlijke situaties zijn, zoals mensen of grote dieren die langs het spoor lopen, of open vuur vlakbij de spoorlijn.

Case study: HSL, Betuweroute and Havenspoorlijn

Een case study is uitgevoerd naar operationele transities op de HSL-Zuid, de Betuweroute en de Havenspoorlijn. Hiervoor zijn literatuur en interviews als bronnen gebruikt. In totaal zijn er op deze spoorlijnen vier typen operationele transities aanwezig: ATP-systeem transities, TEV-transities, veranderingen in het verticale spooralignement en transities tussen VL-posten. Op meerdere locaties worden deze vier transitietypes gecombineerd. Op de HSL-Zuid stranden treinen vaak in de neutrale secties die de twee TEV-systemen (1,5 kV DC en 25 kV AC) van elkaar scheiden. Deze strandingen komen vaak voor wanneer treinen niet in staat zijn om de neutrale sectie met voldoende snelheid te passeren. Aangezien de neutrale secties bovenop een viaduct liggen, moeten treinen een voldoende hoge snelheid van minimaal 40 km/u hebben om de 600 meter lange neutrale secties te passeren. Wanneer een ATP-systeem transitie mislukt en een trein geen verbinding met de RBC tot stand kan brengen, ontvangt de trein geen Movement Authority (MA), remt af en komt tot stilstand bij zijn End of Authority (EoA). Wanneer een trein moet wachten op een andere trein of wanneer een pad te laat wordt ingesteld door de trdl, moet de trein eveneens snelheid minderen. Wanneer deze snelheidsreducties gebeuren vlak voor neutrale secties of op steile hellingen, kan dit ervoor zorgen dat treinen stil komen te staan en niet meer verder kunnen.

Neutrale secties veroorzaken bij de Betuweroute en Havenspoorlijn soortgelijke problemen als op de HSL-Zuid. Opwaartse hellingen zijn bij deze beide spoorlijnen echter een groter probleem dan bij de HSL-Zuid. Op het tracé van de Betuweroute en Havenspoorlijn zijn meerdere diepe tunnels met steile hellingen aanwezig. Het is voor de goederentreinen die daar rijden belangrijk om met de juiste snelheid de tunnel in te gaan, omdat goederentreinen zwaar zijn en de locomotief niet in staat is om een trein op een steile opwaartse helling op snelheid te krijgen. Als de inrijsnelheid van de tunnel te laag is, heeft de trein mogelijk niet genoeg kinetische energie om de andere kant van de tunnel te bereiken. Als de treinsnelheid te hoog is, zal de trein onderin de tunnel te snel rijden en zal ETCS een remming uitvoeren. Wanneer een goederentrein gele of rode seinen of zijn EoA nadert in de buurt van een opwaartse helling, bijvoorbeeld als gevolg van een vertraagde rijweginstelling door de trdl of als gevolg van ander kruisend verkeer, zal dit de kans op een stranding van de trein aanmerkelijk vergroten. De trein kan dan namelijk niet met voldoende snelheid tegen de helling oprijden, of tijdens het oprijden van de helling gedwongen wordt te remmen.

Ten slotte, het onderzoek naar operationele transities op deze drie spoorlijnen heeft aangetoond dat kenmerken van specifieke type treinen en locomotieven de kans op een mislukte transitie kan vergroten. Vanwege treintechniek of software duurt het lang voordat sommige transities zijn voltooid. In andere gevallen is de communicatie tussen de trein en de infrastructuur niet optimaal, wat een succesvolle transities eveneens kan belemmeren.

Case study: Meteren knooppunt

Bij knooppunt Meteren sluit de Betuweroute aan op de spoorlijn Utrecht - Den Bosch (A2-corridor) in noordelijke en zuidelijke richting. Beide verbindingsbogen maken het mogelijk dat treinen die vanuit het noorden en het zuiden komen, doorrijden richting de Duitse grens bij Zevenaar en vice versa. Op deze verbindingsbogen zijn vier typen operationele transities aanwezig: transities in ATP-systeem (ATB-EG naar ERTMS Level 2), TEV (1,5 kV DC tot 25 kV AC), transities in het spooralignement en transities tussen VL-posten; de A2-corridor wordt aangestuurd door het VL-post Utrecht, terwijl zowel de Betuweroute als de Havenspoorlijn aangestuurd worden door het VL-post Kijfhoek. Tot slot bevat één van deze verbindingsbogen een fly-over met steile hellingen.

De frequentie en duur van vertragingen op de verbindingsbogen blijken een stuk hoger te zijn dan op baanvakken zonder operationele transities. Tussen de 6% en 36% van alle treinen op de verbindingsbogen is vertraagd. De gemiddelde vertragingstijd per trein, de totale vertragingstijd van alle treinen gedeeld door het aantal gepasseerde treinen, varieert tussen 70 en 120 seconden. Daarentegen is de vertragingskans op ‘normale’ baanvakken zonder transities doorgaans 1% of minder en de gemiddelde vertragingstijd per trein 2 - 5 seconden. Niet alle vertragingen worden veroorzaakt door mislukte transities. Vooral op verbindingsbogen die gebruikt worden door het treinverkeer dat de A2-corridor oprijdt, wordt de meeste vertragingen veroorzaakt doordat treinen moeten wachten voordat ze de A2-corridor op kunnen rijden. Doordat de A2-corridor veel wordt gebruikt door reizigersverkeer, is er weinig ruimte voor intakkende goederentreinen. In totaal ondervindt gemiddeld 4% tot 5% van alle treinen vertragingen als gevolg van operationele transities bij Meteren. Hiervan wordt ongeveer driekwart veroorzaakt door een te laat ingestelde rijweg. Een kwart van deze van de treinen heeft problemen bij de transitie van ATB naar ERTMS en wordt daardoor vertraagd.

Hoewel een kleine minderheid van het aantal vertragingen wordt veroorzaakt door de aanwezigheid van operationele transities, wordt ongeveer de helft van de totale vertragingstijd (de som van alle vertragingstijden opgeteld) veroorzaakt door mislukte transities. Ruim een kwart van de vertragingstijd wordt veroorzaakt door ETCS-gerelateerde storingen. In de meeste gevallen kon geen verbinding worden gecreëerd tussen de on-board ETCS unit en de RBC. Werkproces-gerelateerde vertragingen, vertragingen die kunnen worden toegeschreven aan handelingen van de machinist of trdl, lagen ten grondslag aan ruim 20% van de vertragingstijd. Te laat ingestelde rijwegen waren binnen deze categorie de voornaamste oorzaken voor vertragingen.

Bij mislukte ATB-ETCS transities komen treinen vaak volledig stil te staan en bij te laat ingestelde rijwegen worden treinen sterk afgeremd doordat ze gele en rode seinen tegenkomen of hun EoA naderen. Deze mislukte transities zijn verantwoordelijk voor zo’n aanzienlijk aandeel in de totale vertragingstijd, doordat treinen die dit soort mislukte transities meemaken vaak tot stilstand komen in de neutrale sectie van de TEV-transitie, of stranden doordat ze niet voldoende snelheid kunnen maken om de aanwezige heuvels te beklimmen. Vaak leidt dit tot een vertraging van één of meerdere uren en een verstoringen van de gehele treindienst ter plekke.

De case study van Meteren toont aan dat de meeste vertragingstijd wordt veroorzaakt doordat treinen stranden in neutrale secties, of op steile hellingen. Vooral voor goederentreinen geldt dat steile hellingen een gevaar voor strandingen oplevert, mits ze deze met onvoldoende snelheid oprijden.

Case study: Zaandam

Een tweede kwantitatieve case study wordt uitgevoerd op Zaandam, waar meerdere typen operationele transities aanwezig zijn. Er bevindt zich een draaibrug zonder bovenleiding ten noorden van station Zaandam aan de spoorlijn Zaandam naar Enkhuizen. Verder ligt er een grote tunnel, de

Hemtunnel, met 25 ‰-steile hellingen ten zuiden van station Zaandam. Tenslotte is er op het station van Zaandam zelf een rangeerterrein aanwezig in het NCBG-gebied, dus in Zaandam is een transitie tussen CBG en NCBG aanwezig.

In tegenstelling tot de case study van Meteren werd geen duidelijke toename in het aantal vertragingen of in de gemiddelde vertragingstijd waargenomen als gevolg van de aanwezigheid van operationele transities. Bij de Zaanbrug was een lichte toename van de vertragingsfrequentie en -duur waar te nemen, maar op basis van deze resultaten is het moeilijk te concluderen dat de Zaanbrug vertragingen veroorzaakt als gevolg van de bovenleidingvrije sectie op de brug. Bij de Hemtunnel is de frequentie en ernst van vertragingen zelfs lager dan gemiddeld. Ten slotte is het niet mogelijk om vertragingen bij de overgang van CBG naar NCBG te meten. Er is geen treindetectie in NCBG's, wat betekent dat treinbewegingen hier niet kunnen worden geregistreerd.

Een analyse van de vertragingsoorzaken werd uitgevoerd om te onderzoeken of er structurele oorzaken zijn voor vertragingen. De meeste vertragingstijd bij de Zaanbrug werd veroorzaakt door vertragingen zonder enige duidelijke verbinding met de aanwezigheid van de brug over de Zaan. Een enkele keer strandde een trein in het bovenleidingvrije deel van de brug en kon niet meer verder rijden zonder assistentie. Voor deze specifieke gebeurtenis is geen duidelijke oorzaak gevonden, noch zijn er structurele factoren gevonden die de Zaanbrug vatbaar lijken te maken voor vertragingen en verstoringen.

De Hemtunnel, aan de zuidkant van station Zaandam, is voorzien van X/G-seinen, die zorgen voor een volledig treinpad door de gehele tunnel voor zware treinen, zoals goederentreinen. Door dit signaleringssysteem komen goederentreinen geen gele of rode seinen tegen in de tunnel en is de kans klein dat een goederentrein in de tunnel tot stilstand komt en strandt. Mede hierdoor is er slechts één goederentrein gestrand in de Hemtunnel in 2019. Het gebrek aan gestrande treinen in de Hemtunnel wordt gedeeltelijk veroorzaakt door het X/G-regime dat wordt gebruikt voor de tunnel. Een andere oorzaak voor de weinige strandingen is het feit dat ATB-EG een verlaagde snelheidslimiet van 40km/u superviseert aan het begin van de tunnel. Het is daardoor niet mogelijk om te snel de tunnel in te rijden. De maximum snelheid voor goederentreinen, die normaal tussen de 80km/h en 100 km/h ligt, wordt echter niet door ATB-EG gesuperviseerd. Verder leidt een te hoge snelheid onderin de tunnel leidt niet direct tot een ATB-ingreep, doordat de normale baanvaksnelheid wordt gehandhaafd en niet de maximum snelheid van de goederentrein.

De case study van Zaandam toont aan dat enkelvoudige transities niet lijken te leiden tot een toename in het aantal vertragingen of in de totale vertragingstijd. Zeker wanneer er voorzorgsmaatregelen worden genomen om te voorkomen dat treinen stil komen te staan, zoals met het X/G-regime in de Hemtunnel, kan het risico op gestrande treinen en daarmee grote verstoringen in de treindienst op een acceptabel niveau worden gehouden.

Case study: human factors in mislukte ATP-transities

In de vierde en laatste case study wordt de rol van menselijke bij transities tussen ATP systemen onderzocht. Er zijn drie fasen te onderscheiden waarin menselijke factoren een rol spelen.

Voorafgaand aan de transitie kan de machinist anticiperend bepaalde acties en voorzorgsmaatregelen nemen die het risico op een mislukte transitie verkleinen of elimineren. Sommige specifieke storingen komen regelmatig voor op een specifieke locatie, onder specifieke omstandigheden en vaak bij een specifiek type materieel. Wanneer hetzelfde type storing vaak voorkomt, proberen machinisten deze storingen te voorkomen. Deze 'workarounds’ voorkomen dat aan bepaalde voorwaarden wordt voldaan, waardoor transities mislukken. Een voorbeeld van zo’n workaround is dat machinisten voor een transitie snelheid minderen. Terwijl er bij normale snelheid wel een fout optreedt tijdens de transitie, gebeurd dit niet bij gereduceerde snelheid. Vaak is er geen logisch verband tussen de gebruikte workaround en het al dan niet mislukken van transities. Voor machinisten is het vaak onduidelijk waarom deze workarounds transitiefouten voorkomen. Ze weten alleen dat specifieke transitiefouten kunnen worden voorkomen door voorafgaand aan de transitie bepaalde, ogenschijnlijk ongerelateerde, acties te ondernemen.

Tijdens de daadwerkelijke operationele transitie is de rol van de machinist beperkt tot het erkennen van de transitie. De on-board ETCS units van verschillende typen treinen werken niet allemaal hetzelfde. Zo vragen sommige typen ETCS units wel een erkenning tijdens een transitie van ATB naar ETCS, terwijl andere ETCS units dit niet van de machinist vragen. Dit kan verwarring bij machinisten veroorzaken wanneer in de komende jaren meer spoorlijnen worden uitgerust met ETCS en meer treintypes worden uitgerust met (verschillend werkende) ETCS-units aan boord.

Bij een transitiefout is de machinist vaak niet op de hoogte van de precieze oorzaak van de storing. De ETCS-unit aan boord geeft de machinist via de DMI weinig informatie over de oorzaak van de storing. NS heeft een speciale helpdesk om machinisten op de HSL-Zuid te helpen. De helpdeskmedewerkers hebben toegang tot real-time informatie van de ETCS unit in de trein. Die informatie kan de helpdeskmedewerkers ondersteunen bij het diagnosticeren van de oorzaken van storingen. Aangezien de oorzaak van transitiefouten vaak onbekend is, kan de bestuurder geen individuele problemen oplossen en wordt de hele ETCS-unit vaak gereset door de machinist om alle problemen in één keer op te lossen, wat een tijdrovend proces is. Tijdsdruk om verder te rijden verhindert vaak dat machinisten de exacte oorzaken van storingen onderzoeken. Sommige machinisten ervaren stress als een transitie mislukt, wat de kans vergroot dat ze meer fouten maken tijdens het oplossen van mislukte transities.

Concluderend, het bestuderen van de workarounds die gebruikt worden door machinisten kan helpen om locaties op te sporen waar veel transities mislukken om die vervolgens op te lossen. Verder is het gebrek aan standaardisatie van on-board ETCS units een mogelijke bron van verwarring voor machinisten die tot meer gemaakte fouten kan leiden. Ten slotte kunnen mislukte ATP-systeem transities sneller worden opgelost als de machinist meer informatie ter beschikking en hij deze informatie goed kan gebruiken.

Conclusie en aanbevelingen

Een enkele operationele transitie heeft weinig invloed op de betrouwbaarheid van de treinexploitatie. De frequentie en duur van vertragingen is niet significant hoger bij enkelvoudige operationele transities in vergelijking met een situatie zonder operationele transities. Wanneer meerdere transities worden gecombineerd, worden de frequentie en ernst van vertragingen en verstoringen aanzienlijk verhoogd. De mate waarin transities vertragingen veroorzaken, is sterk afhankelijk van de configuratie en combinatie van verschillende operationele transitietypen. Sommige transitietypen, zoals TEV-transities, bovenleidingvrije bruggen en stijgende hellingen, kunnen treinen laten stranden wanneer treinen daar tot stilstand komen. Andere soorten transities, zoals de transitie tussen VL-posten en tussen ATP systemen, kunnen een trein afremmen of tot stilstand brengen. Het combineren van transities uit beide groepen verhoogt de frequentie en de duur van vertragingen aanzienlijk.

Gebaseerd op de conclusies van dit onderzoek worden er verschillende aanbevelingen gedaan.

- Er wordt aangeraden om TEV-transities, bovenleidingsloze bruggen en steile hellingen niet te combineren met andere operationele transities, aangezien deze drie operationele transitietypen het meest kwetsbaar zijn voor verstoringen.

- Transities moeten zoveel mogelijk worden gestandaardiseerd, zowel de infrastructuur als de treinapparatuur. Op dit moment zijn er nog veel verschillen in de lokale uitvoering van infrastructuur en in de bediening van de verschillende typen materieel. Dit kan tot onnodige verwarring leiden bij machinisten en zo de kans op fouten vergroten.
- Er wordt geadviseerd om de interactie tussen trein en infrastructuur te verbeteren en om betrouwbaarheid van transities als criterium te stellen bij aanschaf van nieuwe treinen.
- In navolging van eerder advies gedaan door ProRail en NS, wordt aangeraden om bij de uitrol van ERTMS en 3kV, de transities tussen de oude en nieuwe systemen niet te combineren, daar dit deze combinatie van transities tot frequente en langdurige vertragingen kan leiden.
- Er wordt aangeraden om bij kwetsbare punten meer gebruik te maken van volledige treinpaden, zoals dit het geval is bij diepe tunnels waar een X/G-regime wordt gehanteerd.
- Tijdens mislukte transities dienen machinisten beter geïnformeerd te worden over de oorzaken voor het mislukken van de transitie. Verder moeten zij in staat zijn om die informatie te interpreteren en op basis van die informatie te kunnen handelen.

Omdat dit onderzoek exploratief van aard is, is het raadzaam om meer case studies uit te voeren om een beter begrip te krijgen van de relatie tussen operationele transitie(s) (combinaties) en de betrouwbaarheid van treinoperaties. Ook wordt geadviseerd om te onderzoeken of meer kenmerken in de spoorweginfrastructuur kunnen worden geïdentificeerd als operationele overgangen. De gebruikte methodologie was ongeschikt voor CBG/NCBG-overgangen en niet optimaal voor tijdelijke snelheidsbeperkingen en lastgevingen. Om deze transitietypen te onderzoeken, zijn andere benaderingen nodig.

Summary

Introduction and research goal

Technological innovations in the Dutch railway sector, such as ERTMS and the 3kV power supply system make it possible to increase the efficiency, effectivity and speed of the railway system in the upcoming decades. The implementation of systems such as ERTMS and 3kV is a lengthy process. The new systems will therefore operate alongside the old systems (ATB-EG and 1.5kV) for a long period of time. Between the old and the new system, operational transitions are required. The number of operational will therefore increase in the coming years.

Some of these transitions from one system to another system turn out to be prone to failures and disruptions. When an operational transition fails, this can cause considerable delays on the railway network. Especially when multiple operational transitions are close together and occur nearly simultaneously, the risk of failures in one of these transitions is present. When operational transitions are combined, a failure in one transition can have large effects on another operational transition that is about to take place. Operational transitions are defined by two characteristics. Firstly, they are physical locations in the rail infrastructure. Secondly, operational transition require the driver to switch between two systems, or to change his/her behaviour significantly.

The aim of this thesis is to investigate the effect of operational transitions on the reliability of train operations. The magnitude of the impact of operational transitions on the reliability of train operations is often unclear. This thesis contributes to scientific literature by examining a sizable number of operational transition types and providing an initial insight into the effect of these transitions on railway operations. For society in general and for ProRail in particular, the findings of this research can contribute to a better understanding of operational transitions. Using the acquired knowledge, ProRail can take measures that increase the reliability of operational transition passages, thereby increasing the punctuality of train services.

Methodology

As little is known in scientific literature on (operational) transitions in the railway sector, an exploratory research method is used. As a work process, grounded theory approach is used, whereby theories are formed based on patterns that emerge from the data. Furthermore, a mixed methods approach is applied for data gathering. Both quantitative and qualitative data sources are used to discover these patterns in operational transitions.

The first step in the research is the identification of operational transition types on the Dutch railway network. Based on the definition of operational transitions, brainstorming and interviews, eight operational transition types have been identified. When possible, the locations of these transitions have been recorded.

Four case studies have been conducted that cover different types of operational transitions. The first case study investigates operational transitions at the HSL-Zuid, Betuweroute and Havenspoorlijn, using literature and interview data. The second case study investigates operational transitions at Meteren junction and the third case study investigates transition at Zaandam. Quantitative methods will be used for the second and third case study. With these three case studies, two sub questions are covered. First, it is investigated to what extent delays emerge from the operational transitions that have been identified. Second, it is investigated what the underlying causes for failed operational transitions are. In the fourth and final case study, the role of human factors in the failure of operational transitions is investigated. Interviews with trains drivers and experts have been used to investigate the role of

human factors in delays caused by a failed ATB-EG to ERTMS transition. This last case study does not focus on a specific location.

Identification of operational transition types

In total, eight different types of operational transitions have been identified that fit the definition of an operational transition. Six transition types have been identified that are 'permanent' in nature. They are a part of the railway infrastructure and cannot be changed easily (Table 1). Furthermore, there are two types of temporary operational transitions. These operational transitions are present for a limited amount of time. The location of these transitions is also variable (Table 2).

Table 1 Permanent operational transition types

TRANSITION TYPES	DESCRIPTION
POWER SUPPLY SYSTEM	Power supply system transitions are necessary when two different power supply systems are used. Trains require equipment to use both power supply systems. The driver is responsible for conducting the transition between both systems. Phase separations occur on 25kV track sections to separate currents which are not in phase. Here, the train driver should lower the pantograph.
AUTOMATIC TRAIN PROTECTION SYSTEM (ATP)	Multiple train protection systems are used in the Netherlands: ATB-EG, ATB-NG and ETCS. Transitions between these systems are performed automatically by the on-board ATP system. The driver must acknowledge these transitions.
MOVEABLE BRIDGES	Different types of bridges require different actions to be undertaken by the driver. Some bridges, like catenary-free bridges, can only be passed when no traction is applied. Other moveable bridges do not have this restriction.
VERTICAL TRACK ALIGNMENT	Vertical track alignment can change at bridges, tunnels, fly-overs, dive-unders and the (natural) terrain on which the track is built. Steep gradients cause changes in train speed. The train driver should be aware of this and anticipate the presence of gradients in the line.
TRAIN TRAFFIC CONTROL DISPATCHING (DISPATCHING CENTRE)	The Dutch railway network is controlled by dispatching centres that solve real-time problems and conflicts. When conflicts are not handled by dispatchers in time, trains will encounter yellow and red signals, causing trains to slow down. The handover between dispatchers and between dispatching centres can cause delays.
NON-CENTRALLY CONTROLLED AREA'S (CBG/NCBG)	On some sidings and emplacements, switches are not controlled by dispatchers, but by shunters or train drivers. The dispatcher directs the actions of driving personnel, but he/she cannot intervene. Transitions from non-centrally to centrally controlled areas are indicated by signs or signals.

Table 2 Temporary systems requiring operational transitions

TRANSITION TYPES	DESCRIPTION
TEMPORARY SPEED RESTRICTIONS	TSRs are imposed when full-speed driving is deemed unsafe, either because of degraded or malfunctioning infrastructure, or because of maintenance works in order to protect the maintenance crew
DISPATCHER MANDATE	Mandates are imposed by the dispatcher on certain line sections when a dangerous situation exists along the line, like people or large animals along the line, or a fire close to the line.

Case study: HSL, Betuweroute and Havenspoorlijn

A literature study and interviews have been used to conduct a case study on operational transitions at the HSL-Zuid, the Betuweroute and the Havenspoorlijn. In total, four types of operational transitions are present on these railway lines: ATP system transitions, power supply system transitions, changes in vertical track alignment and transitions in dispatching centres. At multiple locations, these four transitions types are combined. At the HSL-Zuid, trains frequently get stranded in the neutral section that separates the two power supply systems (1.5kV DC and 25kV AC). These strandings often occur when trains are not able to pass the neutral section with sufficient speed. As the neutral section is location on top of a fly-over, trains should have a sufficiently high speed of at least 40 km/h to pass the 600 meter long neutral section. When an ATP system transition fails and the train is unable to create a connection with the RBC, the train won’t receive a movement authority (MA). Subsequently, the train will slow down and eventually stop at the End of its Authority (EoA). When a train is held by another train or when route setting occurs to late, train will have to slow down and stop as well. When these forced speed reductions occur right in front of neutral sections or on a steep upward slope, this can cause trains to strand.

At the Betuweroute and Havenspoorlijn, neutral sections cause similar problems as at the HSL-Zuid. Upward slopes are, however, more of a problem at these railway lines than at the HSL-Zuid. Several deep tunnels with steep slopes are present at the Betuweroute and Havenspoorlijn. For freight trains, entering the tunnel at the right speed is important, as freight trains are heavy and locomotive are not capable of getting a train up to speed on a steep upward slope. If the entry speed is too low, the train may not have enough energy to make it up the other side of the tunnel. If the train speed is too high, the train will overspeed at the bottom of the tunnel and ETCS will apply the train brake. When a freight train encounters restrictive signals or its EoA in the vicinity of an upward slope, for instance as a result of delayed route setting or as a result of other traffic, this will increase the possibility of a train stranding, as the train may not climb up the upward slope at the right speed or may be forced to brake during the ascend up the slope.

Finally, the study of operational transitions at these three railway lines has shown that characteristics of specific trains and locomotives increase the probability of a failed transition. Due to train mechanics or software, some transitions take a long period of time to complete. In other instances, communication between the train and the infrastructure is suboptimal, hindering a successful transition.

Case study: Meteren junction

At Meteren junction, the Betuweroute connects to the railway line Utrecht – Den Bosch (A2-corridor) in the northern and southern direction. Both connecting arches enable trains coming from the north and south to continue toward the German border at Zevenaar. On these connecting arches, four types of operational transitions are present: transitions in ATP system (ATB-EG to ERTMS Level 2), power supply system (1.5kV DC to 25kV AC), changes in vertical track alignment and transitions between dispatching centres. Whereas the A2-corridor is controlled by the dispatching centre Utrecht, the Betuweroute as well as the Havenspoorlijn are controlled by the dispatching centre Kijfhoek. Finally, one of these connecting arches contains a fly-over with steep inclines.

The frequency and severity of delays on the connecting arches turn out to be a lot higher than on track sections without any operational transitions. Between 6% and 36% of all trains on the four connecting arches is delayed. The average delay time per train, the total delay time of all trains divided by the number of passed trains, varies between 70 and 120 seconds. In contrast, the delay probability on ‘normal’ track sections without transitions typically is 1% or less and the average delay time per train

2 – 5 seconds. Not all delays, however, are caused by failed transitions. Especially on connecting arches for train traffic entering the A2-corridor, most delays are caused by trains that have to wait before entering the A2-corridor. As the A2-corridor is heavily used by passenger traffic, there is little space for trains to enter the A2-corridor. In total, 4% to 5% of all trains experience delays as a result of operational transitions at Meteren. Most of these delays are caused by delayed route setting. Of these delay, three quarter is caused by delayed route setting. The remaining quarter of trains are delayed as the result of a failed transition from ATB to ERTMS.

Although a small minority of the number of delays is caused by the presence of operational transitions, approximately half of the total delay time (the sum of all delay times) is caused by failed transitions. More than a quarter of the delay time is caused by ETCS-related faults. In most cases a connection could not be established between the on-board ETCS unit and the RBC. Work process-related delays, delays that can be attributed to actions of the driver or dispatcher, were at the basis for more than 20% of the delay time. Route setting delays were the main causes of delays in this category.

Failed ATB-ETCS transitions often cause trains to come to a complete standstill and route setting delays cause trains to slow down severely because they encounter yellow and red signals or near their End-of-Authority (EoA). These failed transitions are responsible for such a significant share of the total delay time, because trains experiencing these types of failed transitions often come to a stop in the neutral section of the TEV transition, or they cannot reach a sufficiently high speed to negotiate the upward slopes and strand as a result. This often leads to a delay of one or more hours and disruptions to the entire train service on site.

The Meteren case study demonstrates that most of total delay time is caused by trains stranding in neutral sections, or on steep slopes. Especially for freight trains, steep slopes pose a risk of strandings, when they approach them with insufficient speed.

Case study: Zaandam

A second quantitative case study is conducted on Zaandam, where multiple operational transition types are present. Firstly, a swing bridge without catenary is located north of Zaandam station on the Zaandam to Enkhuizen railway line. Secondly, a large tunnel, the Hem tunnel, with 25‰ steep inclines is located south of Zaandam station. Thirdly, at Zaandam station, a shunting yard is present which is in a NCBG area, so a transition between CBG and NCBG is present at Zaandam as well.

In contrast to the Meteren junction case study, no clear increase in delay frequency or delay severity was observed as a result of the presence of operational transitions. At the Zaan bridge, a slight increase in delay frequency and severity could be observed, but based on these results, it’s hard to conclude that the Zaan bridge causes delays as a result of the catenary-free section. At the Hem tunnel, the frequency and severity of delays is even lower than average. Finally, it is not possible to measure delays at the CBG to NCBG transition. There is no train detection in NCBGs, which means that train movements cannot be recorded.

An analysis of the delay causes is conducted to investigate if there are structural causes underlying delays. At the Zaan bridge, most delay time was caused by delays without any apparent connection to the presence of the bridge over the river Zaan. On one occasion, a train stranded in the catenary-free section of the bridge and was unable to move without assistance. No clear cause has been found for this specific event, nor have any structural factors been found that make the Zaan bridge susceptible to delays and disruptions.

The Hem tunnel, at the southern end of Zaandam station, is equipped with X/G-signals, which ensure a continuous train path throughout the entire tunnel for heavy trains, such as freight trains. Due to this signalling system, freight trains will not encounter yellow or red signals in the tunnel, reducing the probability of a freight train coming to a stop inside the tunnel and being unable to get out of the tunnel without assistance. As a result, only one freight train stranded in the Hem tunnel in 2019. The lack of stranded trains in the Hem tunnel is partially caused by the X/G-regime used for the tunnel. Another cause for the low number of strandings is the lowered entry speed limit of 40 km/h for freight trains, which is supervised by ATB-EG. It is therefore not possible to enter the tunnel too quickly. The maximum speed for freight trains, which is normally between 80 km/h and 100 km/h, is not supervised by ATB-EG. Furthermore, too high a speed at the bottom of the tunnel does not immediately lead to an ATB intervention, because the normal track section speed is maintained and not the maximum speed of the freight train.

The Zaandam case study shows that single transitions do not appear to lead to an increase in the number of delays or in the total delay time. Certainly when precautionary measures are taken to prevent trains from coming to a standstill, such as with the X/G regime in the Hem Tunnel, the risk of stranded trains and thus major disruptions in the train service can be kept at an acceptable level.

Case study: human factors in failed ATP system transitions

In the fourth case study, the role of human factors in ATP-transition failures are examined. Three stages can be distinguished in which human factors play a role of importance.

Prior to the transition, the train driver can anticipate on upcoming transitions and take certain actions and precautions that reduce or eliminate the risk of a failed transition. Some specific failures occur regularly on a specific location, under specific conditions and often with specific rolling stock. When the same type of failure occurs frequently, train drivers try to come up with means to prevent these failures from happening. These 'Workarounds' prevent that certain conditions are being met that cause transitions to fail. An example of such a workaround is that train drivers reduce the train speed during an ATP system transition. While a failure would likely occur at normal speed, the failure does not occur at reduced speed. Often, there is no logical connection between the used workaround and the transitions failures. For train drivers, it is often unclear why these workarounds prevent transition failures et al. They only know that specific failures can be prevented by taking certain, seemingly unrelated, actions prior to the transition.

During the actual operational transition, the role of the train driver is limited to acknowledging the transition. As operating principles of the on-board ETCS units of train differ slightly per train type, acknowledgement is not always required, depending on the train type. This may cause confusion to train drivers, when, in future years, more railway lines are equipped with ETCS and more train types are equipped with (differently operating) on-board ETCS units.

When a transition failure occurs, the train driver is often unaware of the precise cause of the failure. The on-board ETCS unit provides little information via the DMI on the failure cause to the driver. NS has a dedicated helpdesk to help drivers on the HSL-Zuid. The helpdesk staff have access to real-time data This information can support the helpdesk staff in diagnosing the causes for failures. As the cause of transition failures is often unknown, the driver is not able to solve individual problems and will reset the entire ETCS-unit to solve all problems at once, which is a time-consuming process. Time pressure often prevents train drivers from examining the exact causes of failures. Some train drivers experience stress when a transition has failed, which can increase the possibility that they make more mistakes while recovering from failed transitions.

In conclusion, studying the workarounds used by train drivers can help identify locations where many transitions fail in order to resolve them. Furthermore, the lack of standardization of on-board ETCS units is a potential source of confusion for train drivers that can lead to more mistakes. Finally, failed ATP system transitions can be resolved more quickly if more information is available to the train driver and he or she is able to understand and interpret this information well.

Conclusion and recommendations

Single operational transitions have little influence on the reliability of train operations. The frequency and severity of delays is not significantly higher when single operational transitions in comparison with track sections without any transitions. When transitions are combined, the frequency and severity of delays and disruptions are increased significantly. The extent to which transitions cause delays is greatly dependent on the configuration and combination of different operational transition types. Some transition types, such as power supply system transitions, catenary-free bridges and upward slopes can let trains strand when trains come to a stop on or in them. Other transition types, such as transitions between dispatching centres and ATP system transitions have to ability to slow down or even halt a train. Combining both groups of transitions significantly increases the frequency and severity of delays.

Based on the conclusions of this study, several recommendations are made.

- It is recommended not to combine power supply system transitions, catenary-free bridges and steep inclines with other operational transitions, as these three operational transition types are the most vulnerable to disruptions.
- Transitions must be standardized as much as possible, both the infrastructure and the train equipment. At the moment there are still many differences in the local layout of infrastructure and in the operation of the different types of trains. This can lead to unnecessary confusion for train drivers and thus increase the chance of errors.
- It is recommended to improve the interaction between train and infrastructure and to make the reliability of transitions a criterion when purchasing new trains.
- Following on from earlier advice given by ProRail and NS, when ERTMS and 3kV are being gradually implemented on the railway network, it is recommended not to combine the transitions between the old and new systems, as this combination of transitions can lead to frequent and long delays.
- It is recommended to make more use of full train paths at vulnerable points, as is the case with deep tunnels where an X/G regime is used.
- During failed transitions, drivers should be better informed about the causes for the failure of a transition. They must also be able to interpret that information and act on the basis of that information.

As this research has been explorative in nature, it is advised to conduct more case studies in order to gain a more comprehensive understanding of the relation between operational transition(s) (combinations) and the reliability of train operations. It is also advised to investigate whether more features in the railway infrastructure could be identified as operational transitions. The used methodology was unsuitable for CBG/NCBG transitions and suboptimal for TSRs and dispatcher mandates. Investigating these transition types will require other approaches.

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Glossary

A2-corridor	Railway line Amsterdam – Utrecht – Eindhoven
A15-corridor	Betuweroute
ARI	Automatische RijwegInstelling
ATP	Automatic Train Protection
ATB-EG	Automatische TreinBeïnvloeding – Eerste Generatie
ATB-NG	Automatische TreinBeïnvloeding – Nieuwe Generatie
ATB-VV	Automatische TreinBeïnvloeding – Vernieuwde Versie
BR	Betuweroute (freight railway line Kijfhoek – Zevenaar oost)
BRmet	Betuweroute Meteren
CBG/NCBG	Centraal Bediend Gebied/ Niet-centraal Bediend Gebied
DMI	Driver-Machine Interface
ED-brake	Electrodynamic brake
EM-brake	Electromagnetic brake
EMU	Electric Multiple Unit
EoA	End of Authority
EP-brake	Electro-pneumatic brake
ERTMS	European Rail Traffic Management System
ETCS	European Train Control System
Gdm	Geldermalsen
GSM-R	GSM-Railway
Hn	Hoorn
HSL-Zuid	High Speed Line Zuid (railway line Amsterdam – Rotterdam – Belgium border)
Hsp	Havenspoorlijn (railway line Maasvlakte – Kijfhoek)
Kfh	Kijfhoek shunting yard
MA	Movement Authority
Mbtwan	Meteren Betuweroute aansluiting Noord
Mbtwaz	Meteren Betuweroute aansluiting Zuid
NTC	National Train Control
OBE	Overzicht Baan en Emplacement
OBU	On-board (ETCS) Unit
PPLG	Primair ProcesLeidingsGebied
PZB	Punktförmige Zugbeeinflussung
VIRM	Verlengd InterRegio Materieel
RBC	Radio Block Center
SNG	Sprinter Nieuwe Generatie
SMB	Stop Marker Bord
TIM	Train Integrity Module
TROTS	Train Observation and Tracking System
TSR	Temporary Speed Restriction
Utg	Uitgeest
VL-centre	VerkeersLeiding
Zbm	Zaltbommel
Zvo	Zevenaar Oost

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Chapter 1. Introduction

In this chapter, the research problem is introduced. Section 1.1 starts with some context on the historic development of the railway system and the coordination problems that the growth of the railways caused. In section 1.2, the concept of operational transitions is introduced. The research gap is described in section 1.3 and in 1.4, the research goal is formulated. The research questions are formulated in section 1.5. In section 1.6, the scientific and societal research relevance are described. Section 1.7 gives an overview of the research scope. Finally, in section 1.8, the structure of the report is given and the main research methods are described.

1.1 Context

2020 marks the 181th birthday of the railways in the Netherlands. In 1839, the first railway line was opened between Haarlem and Sloten, near Amsterdam (Faber, 1989). Railway development in the Netherlands was relatively slow to start. In the 1820s and early 1830s, the first steam-operated railways had been opened in England, Belgium, Germany and France (Mayntz & Hughes, 1988; Dunham, 1941). The purpose of these early railways was either to connect commercial trading hubs along already existing trading routes or to transport raw materials, such as coal and iron ore to harbours or steel mills (Mayntz & Hughes, 1988). The industrial revolution, which had already begun in the 1830s, required vast amounts of raw materials like coal and iron ore. The railways were the ideal transport mode to transport large amounts of bulk material.

In the coming decades, the local and regional railway networks of continental Europe kept expanding up to the point where they would cover entire countries and create an interconnected network. It was at this point that coordination issues between different railway companies became apparent. Connecting the networks of different railway companies was especially important for the transport of goods, as a lot of time and energy was required to transfer goods from one train to another (Mayntz & Hughes, 1988). However, most railway companies used different standards, leading to differences in loading gauge, track width, signalling system, rail profile and operating rules.

In the Netherlands, this problem became especially evident when the Dutch Rhenish Railway company (Nederlandse Rijn-Spoorweg or NRS) intended to connect their Amsterdam – Utrecht – Arnhem railway line to the Prussian railway network in the 1850s. Up until that point, all lines built by the NRS had been built with a track gauge of 1950 mm. The German network, however, was constructed with a track gauge of 1435 mm, following the standards set by the English railway industry. Subsequently, the entire NRS network was converted to 1435 mm track gauge. Other railway companies soon followed and by 1866 the entire main line network of the Netherlands had been converted to 1435 mm track gauge (Faber, 1989).

This Dutch example indicates that the first railways were not intended to operate in an international context, but rather in a regional or national context. National governments soon stepped in to resolve coordination issues between private railway companies (Faber, 1989). On an international level, coordination issues were often resolved on a case-to-case basis. In order to improve international coordination between railway companies, the Union Internationale des Chemins de fer (UIC) was founded (UIC, n.d. a). However, the founding of this organisation in 1922 did not prevent that a large variety of power supply systems, automatic train protection (ATP) systems and other systems and standards emerged, based on national conditions and interests. As a consequence, international trains required their locomotives to be changed at border stations, which meant time losses.

As these historical reflections indicate, problems with transitions between multiple systems have existed since the emergence of the first railways. These transitions were often time-consuming.

Therefore, in the 1950s and 1960s, locomotives and Electric Multiple Units (EMUs) were developed to operate under multiple power supply systems, which eliminated the need for locomotive changes at border stations (Kurz, 1999; Stiemel, 2012). The appearance of these locomotives and EMUs not only increased the complexity of the train itself, but it also increased the complexity of train operations, since the driver would now manually have to switch between different power supply systems (Branton, 1993). Moreover, as ATP systems differed per country, drivers also have to switch between different train protection systems. This increased the technical and operational complexity of train operations even more, as locomotives had to be fitted with multiple ATP systems and drivers had to be able to work with different ATP systems with widely differing operating requirements. (Siemens, n.d.; Vitins, Januari 2008).

In order to increase the competitiveness of the European rail network in comparison to road traffic, the European Commission (EC) started investigating ways to increase interoperability of the European rail network and to decrease its complexity, which lead to the specification of the European Rail Traffic Management System in the early 2000s (European Commission, n.d.), a cab signalling system with radio communication. The ECs aim is to create a trans-European network of railways, roads and waterways, known as the TEN-T policy (European Commission, 2013). ERTMS shall in future years be applied to all rail corridors in the TEN-T network. Apart from increasing interoperability, ERTMS has the potential to increase safety, capacity, speed and reliability of the railway network (Ministry of Infrastructure and Water Management, 2014a).

1.2 Operational transitions in railway operations

Roughly two methods can be used to increase the interoperability of trains on the rail network. On the one hand, trains are equipped with multiple ATP systems and are designed to run under multiple power supply systems, if required. New trains are equipped with multiple ATP systems (CAF, n.d.), or they are designed to allow easy retrofitting of new systems. The most recent generation of sprinter rolling stock for NS is equipped with ERTMS and ATB-EG (Via a STM-module). Dutch Railways (NS) is currently also tendering for ERTMS baseline 3 to be retrofitted into their existing VIRM double decker fleet (NS, 2020). Furthermore, a large majority of electric locomotives owned by freight railway companies operating in the Netherlands (most notably, the Bombardier TRAXX F140 MS, Siemens ES64F4 and Siemens Vectron) are equipped with multiple ATP systems and power supply systems to allow international operation of freight trains (Bombardier, 2017; Hoppe, Matschek & Müller, 2006; Siemens, n.d.). Operators with locomotives that lack ERTMS equipment can apply to

Figure 1 ERTMS transition strategy until 2030 (Ministry of Infrastructure and Water Management, 2018b)

the Dutch government for a subsidy to install the necessary equipment in their locomotives (ERTMS-NL, 10-12-2019).

On the other hand, the railway infrastructure is standardised in order to reduce the overall complexity of the railway network. Currently, all main lines and some secondary lines in the Dutch railway network are equipped with the ATP system ATB-EG. All other secondary lines are equipped with ATB-NG (ProRail, 2019d). Between now and 2050, the currently used ATP systems are gradually being replaced by ERTMS in order to create an interoperable European railway network with one ATP system (Although multiple variants remain) (Ministry of Infrastructure and Water Management, 2018b).

This gradual transition strategy to a new ATP system in the Netherlands creates many points in the railway infrastructure where operational transitions are required to transition between the old and new ATP system. The first phase of ERTMS implementation on the Dutch main line network consists of six highly utilised railway lines in and around the Randstad area and multiple freight corridors (see Figure 1) (Ministry of Infrastructure and Water Management, 2018b; ProRail & NS, 2018a). As a consequence, most trains operating in the Netherlands will have to switch between ATB-EG and ERTMS/ETCS in daily operations. The number of operational transitions between two different ATP systems will increase even further due to the fact that complex station layouts, such as at Amsterdam, Utrecht and Rotterdam will not be equipped with ERTMS in the near future, as the infrastructure manager ProRail wishes to gain more experience in ERTMS implementation before converting such complex track layouts (Ministry of Infrastructure and Water Management, 2018b). Trains entering these stations will therefore have to transfer to the old ATP system, ATB-EG. An example of the consequences of this strategy on train operations is described in box 1.2

Box 1.2 consequences of ERTMS migration strategy on train operations

The ERTMS migration strategy in which only a few main lines will initially be equipped with ETCS level 2, will lead to an increase in operational transitions. For example: six intercity trains connect Schiphol/ Amsterdam, Utrecht and Eindhoven each hour. These six intercity trains can be subdivided in three series with a frequency of two trains per hour. The intercity series 800 starts in Alkmaar and ends in Maastricht. The 3500 series Starts in Enkhuizen and terminates in Heerlen. Finally, the 3900 series starts in Enkhuizen and ends in Venlo. Between Amsterdam and Eindhoven, the 800 and 3500 series require four operational transitions in train protection system: one when leaving Amsterdam central station (ATB-EG to ERTMS level 2, baseline 3), two when entering and leaving Utrecht central station (ERTMS level 2, baseline 3 to ATB-EG and back) and one when leaving Eindhoven in the direction of Maastricht and Heerlen (ERTMS level 2, baseline 3 to ATB-EG). The 3900 series requires only three operational transitions as the track section Eindhoven – Venlo will be equipped with ERTMS level 2, baseline 3, in contrast to the track sections south of Eindhoven.

The increasing number of power supply systems used in the Netherlands also leads to more operational transitions. Whereas the Dutch mainline network has been electrified with a 1,5kV DC power supply system, two relatively new railway lines (HSL-Zuid and the Betuweroute) have been equipped with a 25kV AC power supply system. At the entrances of these railway lines, trains have to switch between power supply systems. As these lines are also equipped with ERTMS instead of ATB, a transition in ATP system is also required.

Moreover, ProRail and NS are currently advocating the main line power supply system to be converted to 3kV DC in order to decrease energy usage and to increase train acceleration and speed (NS & ProRail, 2016a). A phased transition, in which clusters of substations are converted at once from 1,5kV DC to 3kV DC, is expected to take 10 years for the entire rail network to complete and would increase the number of operational transitions significantly during this period. As these operational transitions are temporary and will be present in the Dutch railway network for different lengths of time, combining these operational transitions with ERTMS – ATB transitions is not recommended (NS & ProRail, 2016a). Whereas the time frame for the conversion of the entire power supply system from 1,5kV to 3kV is approximately 10 years, the conversion of the entire network form ATB to ERTMS will take over 30 years, which makes combining both transitions impractical.

Earlier experiences with operational transitions between conventional mainline tracks and special tracks such as the HSL-Zuid and Betuweroute have shown that operational transitions between tracks with different systems can be a major cause for disruptions. Connection problems between on-board equipment of the train and the Radio Block Centre (RBC) have plagued train operations under the ERTMS system for quite some time. Both the HSL-Zuid and Betuweroute have faced with, and still face connection problems between train and (trackside) equipment (Israël et al., 2016; Ministry of Infrastructure & Water Management, 2016). These problems most often occur at the location where the train transitions between ATB and ERTMS. Other causes for the generally poor performance of train services on the HSL-Zuid are the combined, simultaneous transition of power supply system and ATP system (ProRail & NS, 2018a). When the transition between ATB and ERTMS fails, the train brake is automatically applied and trains potentially come to a stop in the neutral (i.e. powerless) section of the power supply system transition. Software problems of some sort play an important role in failed ATP system transitions (Bremmer, 26-02-2019; NOS, 26-03-2019; Treinreiziger.nl, 30-01-2019).

Failing technology is not responsible for all disturbances during operational transitions. Disturbances and delays may also be caused by faults made by the humans in the system. Train operations is a complicated business as multiple actors have to work together in close harmony in order to provide smooth services. Most tasks involved in real-time train operations are therefore highly institutionalised, in instructions, regulations and guidelines in order to ensure that every tasks is performed in the right way. In practice however, humans can deviate from these instructions. Bieder & Bourrier (2013) identify four different types of instruction violations by operators, based on Reason (1990):

1. Routine behaviours, due to overly restrictive rules
2. Situational violations, when rules do not apply to a situation
3. Exceptional violations, in new situations where consequences are unknown
4. Optimizing violations, done to solve trade-offs of safety and other objectives

Human errors do not solely arise from violations by train drivers or other railway staff. The design of railway equipment influences the probability of human error to a large extent. Firstly, workload of train drivers has a large impact on their work performance. Both under- and overload of human capacities can cause a decrease in work performance (Young et al., 2015). Hely et al. (2015) found that transitioning from trackside signals to in-cab signalling, where signal aspects are indicated in the driver-machine interface (DMI) increased workload of train drivers. Although they retained reasonable levels of work performance, drivers did shift their (visual) attention more toward the in-cab signalling at the expense of observing the track ahead. This example demonstrates that operational transitions do not only have technical implications, but they also influence driver behaviour and can suddenly change the driving regime during an operational transition.

In short, the number of operational transitions that the train driver is faced with in the Netherlands during operations has increased considerably in the past years and is expected to increase even further due to the gradual and prolonged replacement of old systems by new systems. There are multiple causes for the vulnerability of operational transitions in train operations, both from a technical view as well as a human factors view.

For the purpose of this research, operational transitions are defined as physical locations in the railway infrastructure where a train driver should execute certain tasks while switching between two systems, or require the train driver to considerably change his/her behaviour.

1.3 Knowledge gap

Certain operational transitions, like ATB-ERTMS transitions and transitions in power supply system have received considerable attention in the Netherlands in the last few years (see chapter 3). However, other types of operational transitions, such as changes in vertical track alignment, transitions between dispatching centres and other changes in driving regimes have received much less attention. The scientific literature on human factors in combination with operational transitions in railway infrastructure is very limited in size and scope (see chapter 2). As a consequence, little is known about train behaviour and driver behaviour during operational transitions, nor is there an overview of operational transition types. It is unclear to what extent these operational transitions have a negative relation with the reliability of train operations, nor how train drivers cope with operational transitions in general.

1.4 Research goal

The aim of this thesis is to investigate the relation between operational transitions in railway infrastructure and disruptions in train operations. A three-step approach will be used. The first aim of this thesis is to identify operational transition types and locate them on the Dutch railway network. The second goal is to find out if a heightened frequency and severity of delays can be observed near operational transitions and to find the underlying causes for these disruptions. The third goal is to investigate the role of train drivers in operational transition failures.

1.5 Research question

Based on the problem analysis and the research goals, a main research question (RQ) has been formulated:

What is the relation between operational transitions and disruptions in train operations?

Furthermore, four sub questions (SQ) will be used to structure the research:

1. *What types of operational transitions can be identified?*
2. *To what extent do delays emerge from operational transitions?*
3. *What are the underlying causes for failed operational transitions?*
4. *What is the role of human factors in failed operational transitions?*

1.6 Research relevance

There are multiple reasons why this research is deemed relevant. Firstly, knowledge on operational transitions is largely lacking as little research has been done on this topic before. Research has been conducted on track sections where conditions with operational transitions are especially poor, such as the entrances of the HSL-Zuid (ProRail & NS, 2018; Van Es, 2020) and the Betuweroute (Appendix B; Appendix E; Appendix G), but the geographical scope of these studies and the diversity of operational transition types is limited. Furthermore, this research would add to that knowledge by investigating (combinations of) operational transitions that have thus far not been researched. Moreover, the driver perspective is not often investigated in the field of railway reliability research (chapter 4).

From a societal point of view, increased knowledge on the reliability of operational transitions can help infrastructure managers and railway operators to decrease the number of failures during operational transitions, whether they are caused by human factors or caused by technical failures. Infrastructure managers can use this new knowledge to create better designs for operational transitions and rail operators can improve the education of drivers and dispatchers on how to deal with operational transitions in order to reduce failures in train operations.

1.7 Scope

This research will focus on the Dutch railway network only. Border sections between the Netherlands and Germany and between the Netherlands and Belgium will also be excluded from further analysis. Acquiring data from three countries would take a lot of time, which is not available. Research will therefore be limited to operational transitions that take place within the Dutch rail network.

Another demarcation is the focus of this research on physical operational transitions, which means that all operational transitions that will be studied have a fixed location. Train drivers (are able to) know the location of operational transitions and are able to anticipate on their passage. This does not mean that all operational transitions are permanently located at the same location. The focus on physical operational transitions does not mean that operational transitions are purely defined by physical infrastructure, as human factors may also influence train operations at operation transition points.

This study aims to investigate the relation between operational transitions and the reliability train operations. The concept of train operations can however be understood in many ways, so a clear demarcation is required. This study will focus on the relation between operational transitions in railway infrastructure and delays and disruptions that may emerge from these operational transitions.

When studying operational transitions, the train driver perspective will be used. Train driver behaviour and the interaction between technology and humans operating in the technical system are important factors in order to understand why some operational transitions are potentially vulnerable in train operations.

1.8 Methodology

In this section, the research methodology is described. In subsection 1.8.1, the overall structure of the research is explained (Figure 2). The main research methodologies, grounded theory approach and the mixed methods approach, are described in subsection 1.8.2 and 1.8.3

1.8.1 Research structure & methods

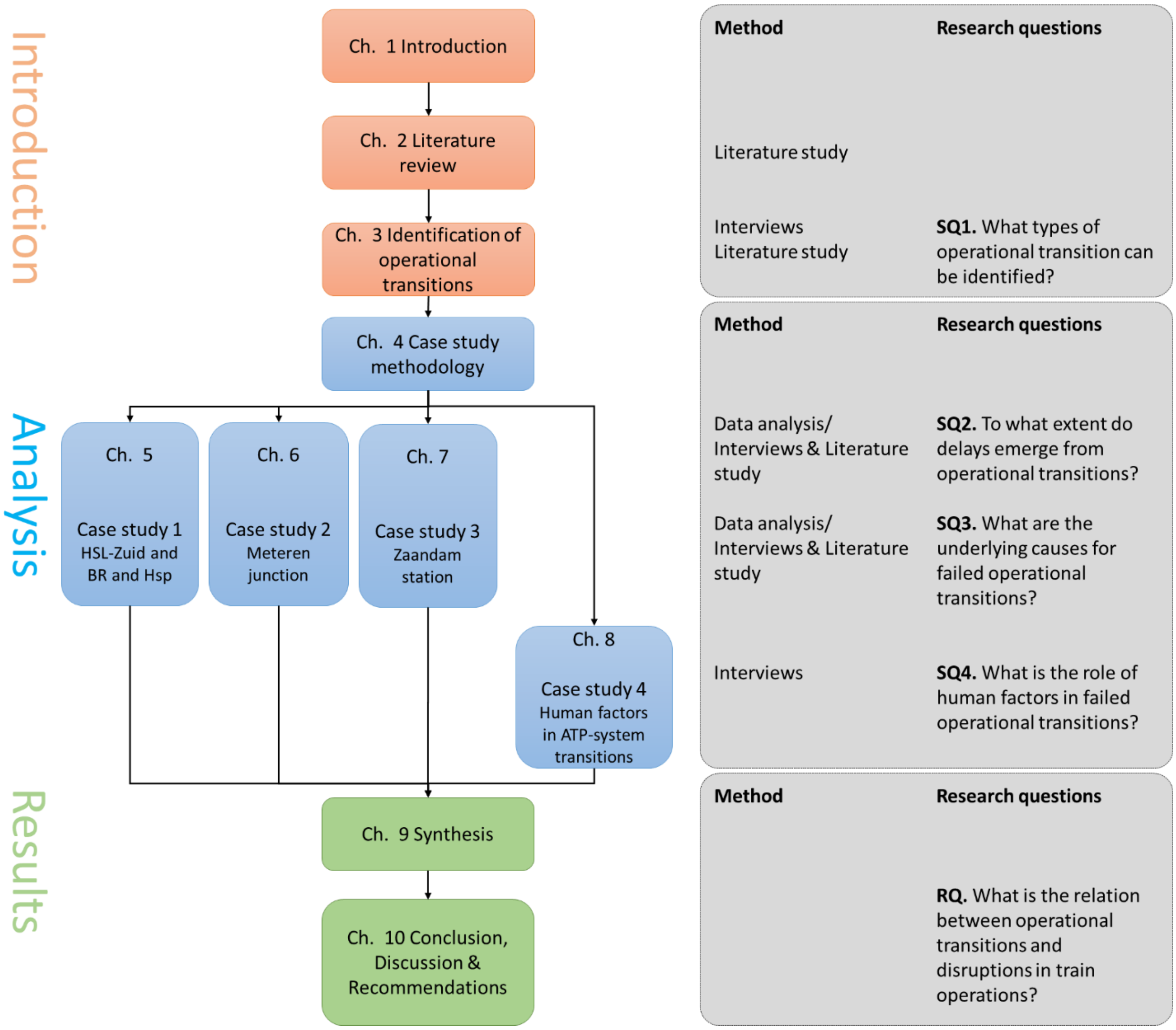
In section 1.2, the concept of operational transitions has been introduced. The historical emergence of multiple, often incompatible systems in railway infrastructure has been described as well as methods to increase the interoperability of railway networks on an international level. Based on this analysis, knowledge gaps, research goals and research questions have been formulated. The research problem is demarcated as well in order to make it manageable within the given time frame.

The 2th chapter consists of a literature review containing three main components: literature on the reliability of train operations, human factors in the railway sector and human factors and operational transitions in other sectors. The literature on reliable train operations will be used for determining indicators that can be used for measuring the reliability of train operations. The literature on human factors in the railway sector and in other sectors will be used to identify relevant concepts for the study of human factors in operational transitions

Based on the definition of operational transitions and on the scope presented in section 1.2, types of operational transitions will be identified in the 3rd chapter. The first sub question will be answered in this chapter. An initial overview of operational transitions has been made by the Architecture Platform (APP) within ProRail (ProRail, 2019a), which can be used as a basis. Not all operational transition types defined by APP fulfil the definition of operational transitions or fit within the scope of this research. Insights into operational transition types will also be acquired through interviews with train drivers. Based on these data sources, a complete image of operational transitions on the Dutch railway network can be created. With this data, maps can be constructed of all operational transition types on the Dutch railway network.

Four case studies will be conducted in this research. In chapter 4, the four cases will be selected and the methods that will be used in each case study will be explained. The case studies of chapter 5,6 and 7 are used to answer sub question 2 and 3, while the case study in chapter 8 is used to answer sub question 4.

Chapter 5 contains the first case study on operational transitions at the HSL-Zuid, Betuweroute and Havenspoorlijn. Literature study and interviews will be used as input for this case study. Chapter 6 and 7 contain case studies on Meteren junction and Zaandam respectively. At both locations, the effects of the present operational transitions on the reliability of railway operations will be examined.



Method	**Research questions**
Literature study	
Interviews Literature study	**SQ1.** What types of operational transition can be identified?

Method	**Research questions**
Data analysis/ Interviews & Literature study	**SQ2.** To what extent do delays emerge from operational transitions?
Data analysis/ Interviews & Literature study	**SQ3.** What are the underlying causes for failed operational transitions?
Interviews	**SQ4.** What is the role of human factors in failed operational transitions?

Method	**Research questions**
	RQ. What is the relation between operational transitions and disruptions in train operations?

Figure 2, research plan operational transitions

Quantitative methods will be used in these two case studies. Chapter 8, finally, will cover the role of human factors in operational transitions. This chapter will focus specifically on ATP system transitions.

Chapter 9 contains a synthesis of the four conducted case studies. Using the input from these four case studies, the role of each operational transition type in train operations is examined. Finally, in chapter 10, conclusions are drawn, the results and conclusions are discussed and recommendations for further research are given.

1.8.2 Grounded theory approach

As little information on operational transitions is available, an explorative research approach will be used as main research method. Exploratory approaches are used in cases where little theoretical background is available to base research upon, which is the case in this research (see also chapter 2). Glaser & Strauss (1967) developed an approach, grounded theory approach (GTA), in which data gathering, data analysis and theory formulation are a continuous process. GTA is therefore considered to be a mostly inductive approach (Backman, 1999).

The aim of GTA is conceptualisation of the research problem and initial theorizing (Khan, 2014). In contrast to traditional qualitative research methods, where research is mapped out prior to the actual investigation, the end stage of the research cannot fully be determined at the start of the research process. Based on initial data, new targets are set for further research. This means that the grounded theory approach is very flexible in its application (Backman, 1999; Bryant & Charmaz, 2007). Data is typically acquired through interviews, field observations and focus group discussions. Based on collected data, initial theories are constructed. More data is gathered when the theoretical framework is unsatisfactory and incomplete. Data gathering is halted when no new concepts and relations can be identified from newly gathered information.

Although Glaser & Strauss (1967) developed GTA together, their visions on its application soon started to diverge. Glaser has remained closest to the original intents of GTA (Beckman, 1999). His approach to grounded theory research was to acquire all possible data sources, irrespective whether qualitative or quantitative data sources (Kelle, 2007). As a consequence, Glaser's approach allows more freedom in using data for analysis. Strauss set out his approach together with Corbin in 1990 (Strauss & Corbin, 1990). They emphasised the importance of systematic data gathering and the application of coding schemes. Although the application of a coding scheme helps to analyse quantitative data in a consequent manner, the risk of 'forcing' the data into a theoretical framework exists (Kelle, 2007).

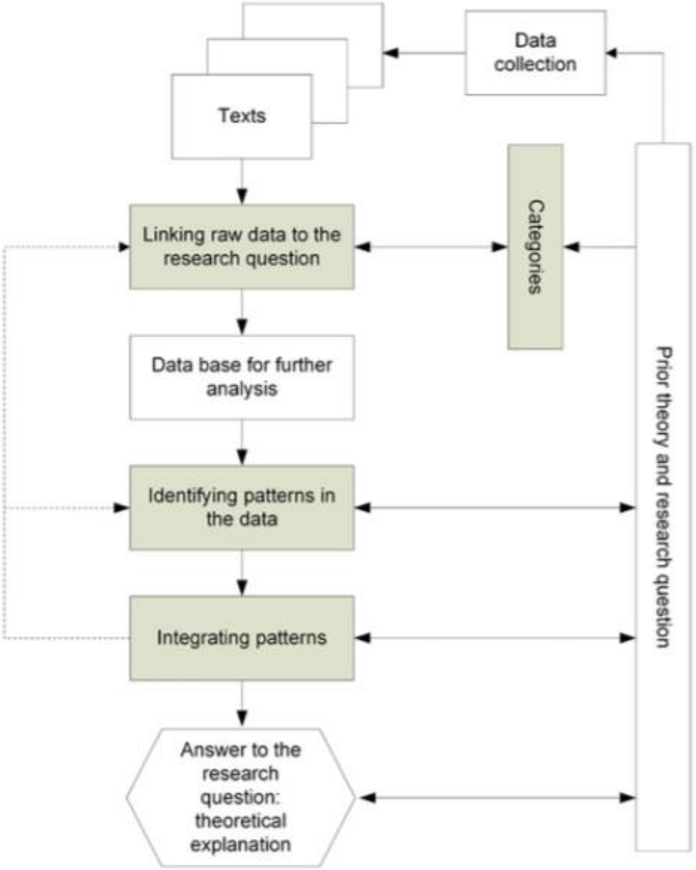


Figure 3 Glaser & Laudel (2013), steps in coding qualitative data

This research will follow Glaser's maxim: "All is data". Which means that both quantitative and qualitative methods will be used to gain more insight into the vulnerability of operational transitions in general.

Glaser & Laudel (2013) provide a framework that helps to convert raw data into theory (Figure 3). First, raw data is extracted from the verbatim interview transcripts. This data is than categorised in order to structure the data. Based on the categories, patterns can be distinguished in the data. Next, multiple patterns can be integrated into higher level patterns. Based on these patterns, a conceptual model of operational transitions is made which can help to answer the research question. Glaser & Laudel (2013) stress that, although a systematic approach is used to analyse and categorise data, researchers should be careful not to draw conclusions based on only a part of the data and then subconsciously interpreting the rest of the data based on these conclusions. A regular revision of conclusions during the process is therefore necessary.

In this research, GTA will be used mainly in selecting cases for analysis. Based on the results of the first case study, new case studies will be chosen that are able to complement findings of the earlier case study. Also, follow-up case studies can be chosen in order to investigate topics that have not been covered in earlier case studies. In the synthesis (Ch. 9), these findings will be combined.

1.8.3 Mixed methods approach

As stated in section 1.8.2, both qualitative and quantitative data will be used in order to find patterns. The mixed methods approach (MMA) emerged in the 20th century as an alternative research paradigm along the traditional positivist paradigm, mostly found in quantitative research, and the traditional constructivist paradigm, used in qualitative research. For positivist researchers, the objective recording of data, whether it be quantitative or qualitative data, is important. Positivist researchers should not engage with their object of study and let their judgements be biased in any way. The interpretive or constructivist paradigm rejects the notion that objective and context-free research is a viable way to gather data. In contrast to the positivist paradigm, multiple realities and interpretations can coexist in the interpretive paradigm (Johnson & Onwuegbuzie, 2006; Doyle, Brady & Byrne, 2009).

The mixed methods approach uses neither of these paradigms, as both paradigms would be incompatible with the mixed methods methodology. The pragmatic research paradigm is mostly, though not exclusively, linked to MMA. The pragmatic paradigm is aimed to solve the research problem in any possible way. Solving the research problem is thereby leading over methodological considerations. 'What works' is considered to be the right research methods, as long as it helps to answer the research question (Hall, 2013, Johnson & Onwuegbuzie, 2006; Denscombe, 2008). Another used research paradigm for MMA studies is critical realism, which typically makes a distinction between the 'real' world on the one hand, which exists independent of human observation and on the other hand the 'observable' world, which is constructed based on our own perspectives and experiences (Creswell & Clark, 2017). Therefore, multiple research methods combined can provide the best understanding of that 'real world'

The MMA has several benefits over purely quantitative or purely qualitative research. Firstly, the combination of both data sources can provide a more complete picture of the research problem. Secondly, the validity of research can be increased by using multiple data sources and by comparing patterns in heterogeneous data sources. Thirdly, MMA has a high explanatory power as questions that arise from the usage of one research method can be answered by using a different research method (Doyle, Brady & Byrne, 2009; Halcomb & Hickman, 2015).

Some reservations should however be made on the usage of MMA. First of all, the fact that quantitative and qualitative data sources can be combined in MMA research does not necessarily make the research better (Halcomb & Hickman, 2015). There should always be a good reason why MMA is the most suitable method for research. Furthermore, the notion of mixed methods research may suggest that there is no heterogeneity in methods within qualitative and quantitative research (Giddings, 2006).

In this research, various case studies will be conducted, using both quantitative and qualitative methods. Qualitative research methods will be used to gain a general understanding of the study object. Literature, interviews and panel group discussions are the main sources for quantitative research. When a deeper understanding of the study object is required or desired, quantitative methods will be used in order to achieve a deeper level of understanding of the research problem. Multiple quantitative data sources will be combined for this purpose.

Two case studies, Ch. 5 on operational transitions at the HSL and the Betuweroute and Ch. 8 on human factors in ATP system transitions, will use quantitative methods for data gathering, such as literature study and interviews. The case studies in Ch. 6 on Meteren junction and Ch. 7 on Zaandam mainly use quantitative methods, such as quantitative data analysis. Ch. 5, 6 and 7 cover the same sub questions, allowing a comprehensive picture to be created of the impact of operational transitions on train operation reliability and on the underlying causes for transition failures (Doyle, Brady & Byrne, 2009).

Chapter 2. Literature review

Ensuring reliable train services is one of the main concerns for railway operators, which is why the causes for train service unreliability have been studied extensively. Many factors influence the reliability of train operations, which are discussed in section 2.1. Human factors play an important role in train service reliability. The role of train drivers (and dispatchers) in train operations is described in section 2.2. Operational transitions are not limited to the railway sector, but also appear in other sectors of industry, such as in aviation and in autonomous vehicles research. Human factors in operational transitions in these fields are discussed in section 2.3.

2.1 Train service reliability

Train schedules are usually designed to be free of any conflicting train paths, that is, when all trains run according to their schedule. In practice, trains can deviate from their predefined paths. Small delays can usually be accounted for by using running time supplements and buffer times in timetable construction. Running time supplements are added to the minimum running time of a train between two timetable points in order to account for the variability in actual running time (Scheepmaker & Goverde, 2015). Buffer times on the other hand prevent that slight delays immediately influence following trains (Goverde, 2010). Using running time supplements between timetable points and buffer times between train paths both reduces the probability that primary delays result in follow-up secondary delays (Goverde & Hansen, 2001). When primary delays are larger than the margins incorporated in timetable designs, secondary delays start to arise. The primary delay propagates throughout the following trains. Especially in rail networks with high interdependencies between trains, due to transfer guarantees at stations, high track occupancy rates and many intersecting train paths, primary delays can propagate all over the network and have far-reaching effects on train operations (Meester & Muns, 2007).

The reliability of train operations is influenced by multiple factors. Barron et al. (2013) identify five main factors that influence reliability of metro operations: rolling-stock failures, signalling failures, staff behaviour, passenger-caused delays and the failure of other equipment. Although the relative importance of each factor differs between metro operations and train operations, they're all relevant to train service reliability. In contrast to metro operations, rail traffic heterogeneity also plays an important role in train service reliability. Rail traffic heterogeneity refers to the different types of trains and train services that use the same track section. In metro operations, all metros have similar technical characteristics (speed, acceleration, etc.) and stop at each station. In train operations, tracks are often shared with different train types and different train services, hence the higher heterogeneity. Generally, increases in heterogeneity lead to decreases in service reliability (Vromans, Dekker & Kroon, 2006) and in infrastructure capacity (Dinger, Lay and Barkan, 2009; Boysen, 2013). Jong et al. (2010) find similar causes for train service disturbances on Taiwan's high speed line as Barron et al. (2013). On this line, railway infrastructure failure, mainly signalling and interlocking failure, is the most common cause for disturbances.

Landex (2012) takes a passenger-oriented approach to service reliability. For high-frequency train services, departure delays are not very problematic to travellers. In contrast, the headway between consecutive trains is the main concern of passengers. Not only do variations in headways lead to longer on average waiting times at platforms, but they also lead to an uneven distribution of passengers over the available vehicles, leading to on-board crowding and underutilisation of rolling stock at the same time (Van Oort, 2011). This passenger-oriented approach is, however, less useful when investigating the reliability of operational transitions. First of all, the freight services have a low frequency and often lack a clear frequency at all. Second of all, passenger arrival delays are not the primary focus of this research.

Disruptions occur when the planned timetable can no longer be executed, due to long-term track blockages (Veelenturf et al., 2016). Disruptions therefore require the rescheduling of trains in order to divert traffic away from the disrupted area. Contingency plans are used to restructure train services according to a predefined plan. Golithly & Dadashi (2017) make a further distinction between incidents and disruptions. Incidents such as infrastructure or rolling stock failure do not always lead to disruptions to normal operations. The severity of the disruption depends on local circumstances and railway infrastructure occupation rate.

Concluding remarks on the reliability of railway operations

The concept of disruptions as described by Veelenturf et al. (2016) will be used in this research project to investigate the effect of operational transitions on railway operations. By definition, disruptions lead to the rescheduling of trains. Due to data limitations, it may not be always possible to measure the impact of a delayed train on other trains. Disruptions therefore take the meaning of long-term delays, irrespective of the hindrance caused to other trains. These long-term delays (in practice, delays lasting more than 30 minutes) will be analysed in more detail in case studies.

The length of a delay event is not the only criterion by which the reliability of operational transitions is measured. The frequency of delays, relative to the number of trains using each track section, will also be used as an indicator for operational transition reliability. This indicator will be named: delay probability. Using the data on the number and total length of delay events, relative to the total number of trains using each track section, the average delay time per train can be calculated. These two indicators, delay probability and average delay time per train, are the main indicators that will be used to measure the reliability of operational transitions in railway operations.

The delay categories as listed by Barron et al. (2013) and Jong et al. (2010) form a good starting point for determining delay type categories for two quantitative case studies that will be conducted in chapter 6 and 7. Following the grounded theory approach (Subsection 1.8.2), the delay categories will be constructed, based on patterns emerging from the datasets.

2.2 Human factors in railway operations

In this section, human factors in the railway sector are discussed. The study of human factors, also referred to as ergonomics, investigates the relation between humans and the systems they operate in. In the railway sector, research and developments have focussed on improving cab design, driver machine interfaces (DMI) and the effects of automation on actors (Drivers, signallers, dispatchers, etc.) in the railway sector (Wilson et al., 2007). One of the domains in railway human factors is the study of driver workload. Both higher and lower levels of workload can influence the behaviour of the train driver. Similarly, sudden changes in workload, for instance when the driver passes a number of operational transitions in a short time period, can significantly alter driver behaviour. Studying this literature may therefore provide useful concepts for the role of human factors in operational transitions.

Research on actor workload in the railway sector has led to multiple definitions of the concept. One of the earlier works of Jahns (1973) identifies four aspects that influence the workload by railway staff:

- Intensity and complexity of tasks
- Perceived load of operators
- Variety of functions and tasks
- Compatibility of working arrangements with expected tasks

Furthermore, Jahns (1973) developed a framework in which driver (or signaller) workload was linked to work result. The input load influences the amount of effort the operator has to put into his work. High effort tasks in turn influence the performance and wellbeing of the train driver. These two factors, performance and wellbeing influence the quality of the work result (Figure 4, top figure). Pickup et al. (2005), building on the work of Jahns (1973), developed a more elaborate framework linking workload and work performance (Figure 4, bottom figure).

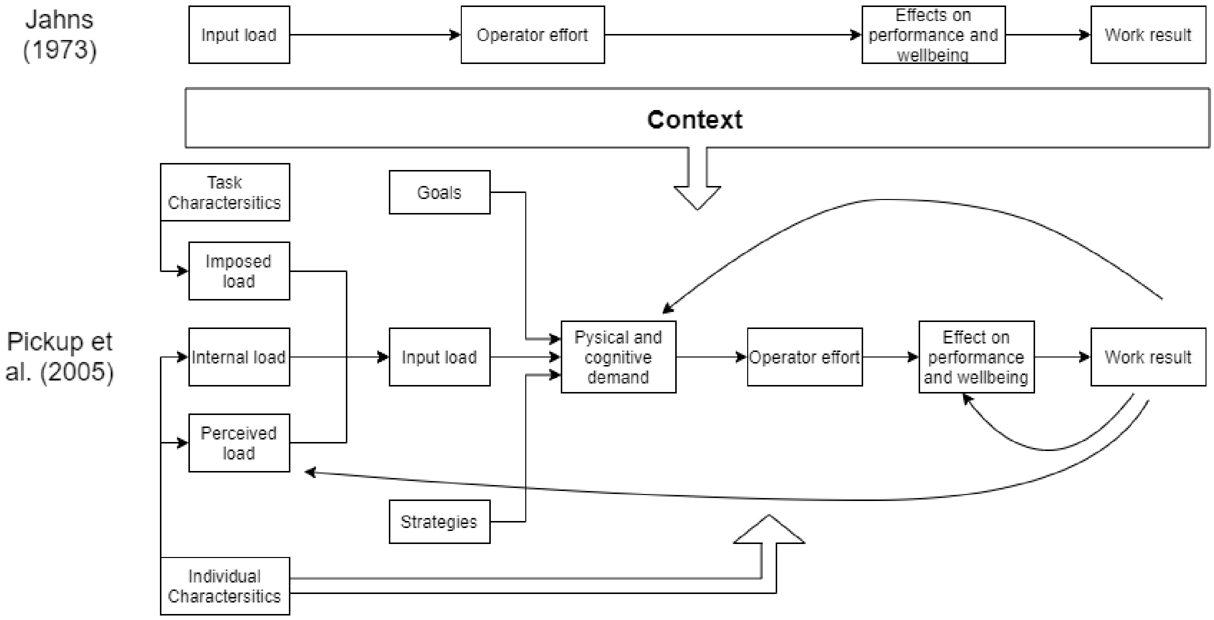


Figure 4 Conceptual framework of mental workload of Jahns (1973) on top and Pickup (2005) bottom

Pickup et al. (2005) greatly expanded Jahns' original framework, but the four main concepts: workload, effort, performance and wellbeing and work result remain the main concepts in their model. Apart from these four concepts, driver context and individual (driver) characteristics are added. The driver context is the environment in which the driver operates. Individual driver characteristics refer to the personal characteristics of individual drivers and the effects of these characteristics on (dealing with) workload. The structure of Pickup et al.'s (2005) model will be used to structure recent research on driver workload. In subsection 2.2.1, literature on driver context is described. In subsection 2.2.2, individual driver characteristics are covered. In subsection 2.2.3, The input load is discussed. In subsection 2.2.4, driver effort is discussed. Subsection 2.2.5 covers the effects of driver effort on performance and wellbeing and the work result. As these two factors are indistinguishable in literature (Pickup et al., 2005), they are investigated together. In subsection 2.2.6, concluding remarks on human factors in the railway industry are given.

2.2.1 Driver context

Driver context refers to "the context in which mental workload is to be understood", as this context "usually directs the interpretation of its meaning and the choice of assessment methods" (Pickup et al., 2005).

Branton (1993), observing the general trend of automation in military and industrial complexes, foreshadows on the role of humans in the operations of the future railway system. In some industries, the role of operators had shifted from controller and active operator to the role of observer and passive operator. Branton is concerned that increasing level of automation the railway sector will reduce the efficiency of the system, as humans do not respond well to infrequent events, due to distractions. Branton points out that driver alertness can be enhanced by decreasing the monotony of the job. This can be done by careful and gradual changes in driver stimulation. Brandenburger and Naumann (2019), investigating the effect of automation on driver behaviour, find that the attention level of driver is impacted by increased levels of automation (see also subsection 3.2.3 and 3.2.5).

Due to the influx of new technologies (Branton, 1993), the railways have developed in the direction of distributed systems, where decision making processes are distributed over multiple actors and computers. As a consequence, drivers make less decisions in isolation and more in conjunction with other actors in railway operators, such as signallers and controllers (Wilson et al., 2007). Young, Stanton & Walker (2006) find similar problems of increased complexity in ERTMS implementation. ERTMS will only deliver on its expected benefits if human factors are incorporated in the design of the user interface. Young, Stanton & Walker also specifically raise the issue of ERTMS migration and transitions. The migration of drivers to the new system mainly takes time and practice. They further state that transitions between ERTMS and non-ERTMS line sections should be designed with human factors in mind, although no specific criteria are given.

The trends of increased automation and interconnectedness between actors and systems change the context in which the driver operates in a fundamental way. If driver attention slips due to increases in automation, this may have serious consequences for dealing with operational transitions, where a high level of attention is required and where time windows in which the driver has to act are small.

2.2.2 Individual driver characteristics

Although the imposed workload might be similar for all drivers, the way in which drivers process information and react to workload differs per individual. Furthermore, each driver has individual goals and strategies while driving (Pickup et al., 2005).

One of the driver characteristics that influence behaviour is the level of experience of each individual train driver. Driver behaviour evolves during the career of the train driver. Rajabalinejad, Maartinetti & Van Dongen (2016) identify three phases in the working live of a driver: inexperience phase, operating phase and routine phase. During the inexperience phase, the driver has to become accustomed to his or her operating environment, which leads to a heightened probability of human error. In the operating phase, the driver is aware of the dangers of his job and acts to avoid these dangers. The probability of human error is low. The final phase, routine phase, starts when drivers are very confident in their job and their attention to detail slips. The probability of human error therefore can therefore increase in the case of very experienced, but complacent drivers (Kumar & Sinha, 2008).

Apart from experience, the skill set of individual drivers greatly influences their performance. There are multiple skills that train drivers consider necessary for a good execution of their job (Branton, 1993). Based on interviews with train drivers, Branton (1993) found that, among other factors, driver anticipation on future events, a good internal representation of the system the driver operates in and constant testing of internal representations with reality are essential skills required in train driving. Furthermore, performance of train driver could be improved by aiding their orientation in the railway system, by enhancing their anticipation by informing the driver better, by improving driver motivation and by enriching the environment the driver works in. Balfe & Smith (2017) did a follow-up research of Branton’s work (1993). Their aim was to operationalize aspects of driver quality. Balfe & Smith (2017) propose the use of On-train-data-recorders (OTDR) for monitoring driver behaviour. They found that OTDRs are useful tools for recording acceleration, braking rate, speed, lateral acceleration and other metrics that influence passenger comfort and thus the driving quality of train drivers.

Driver characteristics also play an important role in safety-related incidents and accidents in the railway sector. Baysari, McIntosh & Wilson (2008) found that human errors are the primary cause for safety-related railway incidents and accidents. Almost half of all accidents in Australia were caused by inadequate monitoring and inspection of equipment. An adverse mental state by operators and organisational factors are important underlying factors for these incidents.

Kyriakidis et al. (2012) made a more elaborate subdivision in human factors contribution to railway incidents and accidents. They found similar results in their study as Baysari, McIntosh & Wilson (2008). After examining 179 reports of incidents and accidents of Swiss railway operator SBB, they found that a considerable part of all incidents could be contributed to distraction of the driver or a general lack of concentration. Similar results were found by Madigan, Golightly & Madders (2016) , who studied minor incidents on UK's rail network. Work-related distractions caused nearly 50% of these incidents, which means that drivers were thinking about something work-related. Safety risk also increase if railway staff is not properly introduced to new railway technologies. Staff needs to be made familiar with each new technology introduced to the railway system. Each new system results in new safety challenges that need to be addressed (Kumar & Sinha, 2008).

The literature on driver characteristics contains several connecting points to driver behaviour during operational transitions. To start with the last point of Kumar & Sinha (2008), unfamiliarity with (new) technologies inhibit the driving from using these technologies to their fullest extent and increase the probability of an operating error. Similar patterns may be visible when drivers are not accustomed to operational transitions. Apart from that, Branton (1993) reports skills that a driver ideally possesses, such as the ability to anticipate, a good internal representation of the operating environment an situational awareness. These three abilities are all necessary when passing combined operational transitions. A lack of attention, on the other hand, can have a negative impact on the number of human faults during transitions (Kyriakidis et al., 2012; Baysari, McIntosh & Wilson, 2008).

2.2.3 Driver workload

Pickup et al. (2005) discerns three components of input load. The imposed load is the amount of tasks, time and energy required by the task. The imposed load is therefore dependent on the characteristics of the task. A timetable may be considered an imposed load. When trains run without delays, this load is manageable, but when delays start to occur, the perceived load of operators may increase, even though they are not expected to perform additional tasks by definition. The perceived load therefore is the second component of input load. Internal load refers to the goals and expectations of individual operators, which may deviate from company norms. Both perceived and internal load are influenced by individual characteristics of operators/drivers.

All loading factors combined result in a certain level of physical and cognitive demand on operators. Demand on operators, according to Pickup et al. (2005) "is created by the need to maintain awareness of the situation, to process relevant information, to make decisions and to act". If demand on operators is high, processing all relevant information becomes increasingly difficult. Goals refer to the expected end-state of the system. Individual goals of the operator may deviate from company goals, leading to differences in effort. Strategies refer to the path through which these goals can be attained. Operators may follow the rules and procedures along the official guidelines, but they can in practice also apply 'shortcuts' in their work.

The effects of automation on driver workload is discussed by Brandenburger et al. (2018) and Brandenburger & Naumann (2019), who argue that increasing levels of automation leads to underload of drivers and signallers. Deviations from an optimal workload, both overload and underload, lead to missed information, either of in-cab signals or trackside signals. In an experiment, train drivers and signallers indicated a lower work pressure under automation than in manual mode. Hely et al. (2015) on the other hand, found that driver workload increased when driving under a highly automated ETCS regime, although only small increases in workload were measured when driving in normal, non-degraded conditions. As expected by Hely et al. (2015), eye tracking data showed that driver attention was focussed considerably more to in-cab equipment than the outside world. The differences in findings with respect to automation and workload might be explained by the fact that ETCS and DAS do not take away tasks from the driver. Under ETCS, the driver remains responsible for observing signals and speed limits, although this information is now communicated via in-cab instruments rather than by trackside signals. Similarly, DAS do not take away any driving tasks. Driving tasks, such as speed supervision, were taken away in the studies of Brandenburger et al. (2018) and Brandenburger & Naumann (2019), leading to a reduction in the number of tasks the driver had to perform.

Other methods of testing driver workload are available as well. Crowley & Bafle (2018) investigated if a correlation could be found between train driver workload and certain physiological aspects, such as heart rate and the amount of moisture on skin surfaces. No correlation could be found between the number of tasks that a driver performed per minute and the driver heart rate or the amount of moisture on the fingertips of the driver. The data did show increases in heart rate and moisture during unexpected events, in which the driver had to act fast.

Similar to Hely et al. (2015), Large, Golightly & Taylor (2014) found that Driver Advisory Systems (DAS), driver aides that advise the train driver on the optimal driving strategy with regards to speed, acceleration and braking points generally increased workload of train drivers. In experiments, situation often appeared in which DASs gave advise that was conflicting with the driver’s intentions. In addition to the workload of normal train operations, drivers now also had to consider if they would follow the advice given by DASs.

On the other hand, a lack of driver information can lead to problems as well. Kecklund et al. (2001) found that a high (temporary) work load in combination with limited information and low driver motivation is a major safety and efficiency risk for railway operations. Information is especially limited when ATP systems are operating in degraded mode, partially through reduced functionality of a degraded mode system and partially because of a limited understanding of ATP in degraded modes by drivers. Kecklund et al. (2001) therefore stress the importance of keeping the driver active and informed in an automated working environment.

Luke et al. (2006) investigate driver strategies for signal monitoring. The difficulty of monitoring the right signal is increased significantly when signals are located in curves, when signals are eluded from sight because of foliage and infrastructure obstructing a clear line of sight and in case of multi-signal gantries. Due to the route knowledge of the driver, he or she is aware of these oncoming situations and reacts by increasing his level of concentration, by being more careful than under normal circumstances and by actively looking for obscured or poorly sited signals. Philips & Sagberg (2010) found that drivers often lack an adequate plan when approaching a signal, for instance when a signal indicates an unusual aspect. Drivers record absent or forgotten knowledge as the cause for inadequate planning of a signal passage.

Concluding, both under- and overload can lead to undesirable mental states of a train driver. In both circumstances, the driver is not able to concentrate fully on the tasks at hand. With regards to operational transitions, the risk of temporary overload is present. Under normal circumstances, the workload during transitions may be within an acceptable range, but during deviations such as driving in degraded mode, as stated by Kecklund et al. (2001), workload is too high, which may lead to driver errors. The literature on driver signal monitoring strategies indicate the importance of driver anticipation and situational awareness, as stated in subsection 2.2.2

2.2.4 Driver effort

Effort is the required amount of time, strength and energy required to fulfil the demand placed on the operator. The operator's goals and strategies influence the required amount of effort. It can be seen as the maximum capacity of human information processing. The maximum processing capacity is not fixed, but it may drop during low demand periods. During sudden changes in demand, effort takes some time to recover. For train drivers, this is especially relevant in the case of operational transitions happening nearly simultaneously after a period of relatively low demand on the driver. Effort, according to Pickup et al. (2005) can be seen as the subjective workload of the driver.

Zoer, Sluiter & Frings-Dresen (2014) conducted a study on multiple aspects of driver workload, including the cognitive requirements of train drivers. Although they did not find the workload on train drivers to be very high on average, they found that there are large variations in work effort. Routes that require a lot of multitasking by the driver are considered more mentally demanding than routes where relatively few tasks need to be fulfilled. Therefore, these route require train drivers to have more vigilance (sustained effort). High levels of effort are required when entering and leaving train stations, and by encountering restrictive (yellow or red) signals.

Train automation also impact the driver effort. Brandenburger & Naumann (2019) find that drivers' performance in emergency situations is considerably worse under Grade of Automation (GoA) 2 in comparison to GoA 1. A lack of situational awareness when driving under GoA 2 and reduced driver concentration are the main causes, according to Brandenburger & Naumann (2019). Therefore, they prefer the implementation of GoA 3, in which the driver no longer performs the primary tasks of train driving: speed adjustment, track integrity checks and safety checks. The train hands over control when the ATO-system does not function properly anymore. After handing control back, the train can be controlled by an on-board attendant or by a remote train driver in a control center, where he has access to more information. Contradicting results on driver effort were found by Spring et al. (2009), who found a significant reduction in train driver vigilance with high levels of automation. Although low and medium levels of automation resulted in slight improvements in driver reaction time, a high level of automation, where drivers where supported by in-cab signalling and an auto-pilot. Caution should be paid to the findings of Spring et al. (2009), as the different levels of automation that were used in the experiment do not fully coincide with the GoA classification as used by Brandenburger & Naumann.

Rhaman et al. (2013) found that driving effort is dependent on weather conditions, using a simulation study. In comparison to daytime driving with sunny conditions, the vigilance of train drivers dropped considerably when driving a night-time shift in rainy weather conditions. This drop in vigilance is most likely caused by fatigue, according to Rhaman et al. (2013).

Large fluctuations in the required driver effort require a lot of vigilance of the train driver as well. Combined with suboptimal driving conditions as described by Rhaman et al. (2013), drivers may 'wear out' faster when confronted with large fluctuations in driver effort. This may not directly affect their performance during operational transitions, but it does impact their vigilance and overall concentration during the entire shift. Indirectly, a large number of operational transitions may therefore negatively influence overall driver performance.

2.2.5 Driver performance, wellbeing and work result

Pickup. et al. (2005) note that the relationship between driver effort on the one hand and driver performance and wellbeing on the other hand is generally not very well understood. Operators may lower their working standards when required effort is too high. Similarly, operators can increase their effort to meet the demand. In both cases, the effect on work performance is not clear and certainly not straightforward.

Filtness & Naweed (2017) investigated the causes, consequences and countermeasure to driver fatigue by performing focus group discussions with train drivers. A mismanagement of shift swapping was the main cause for driver fatigue. As a consequence, drivers were more distracted during their shift and their performance was influenced by cognitive impairments. Drivers were found to be reluctant to report fatigue, as it would result in a mandatory medical assessment. In some cases, drivers may even have slept during a shift. Drivers suggested countermeasures such as providing coffee and having the ability to talk to people.

Philips & Sagberg (2010) also found that driver inattention is a major cause for missed information, such as signal aspects. Some drivers reported that their concentration decreased after passing many green signals. Drivers also suffered from bad signal visibility, similar to the results found by Filtness & Naweed (2017). Zoer, Sluiter & Frings-Dresen (2014) found that driver vigilance dropped considerably during a shift. On average, the level of vigilance dropped by 20 points on a 0-100 point scale. Rhaman et al. (2013) found similar drops in train driver vigilance over the course of an entire shift.

The alertness of drivers is usually controlled by asking a driver to press a button at regular intervals. Scaccabarozzi et al. (2017) developed equipment to measure the level of drowsiness of train drivers, using input from pressure force and strain meters and contactless temperature meters. With this dynamic driver awareness testing system, the number of feedback moments required by the driver can potentially be reduced with 30% to 66%.

Work result is determined by the performance of the operators (Pickup et al., 2005). Again, the relation between these two factors is not necessarily straightforward or linear. The work result influences performance and wellbeing. Bad results may lead to a decrease in wellbeing and performance through demotivation. Similarly, the perceived load can be reduced or increased when work results are respectively good or bad.

To conclude on driver performance and work results, there are several factors that negatively influence driver performance. Fatigue, drowsiness, distraction and a lack of situational awareness all decrease driver performance. Due to increasing levels of automation, drivers are more easily distracted as they’re no longer part of the primary process of driving a train. When transitioning from systems with a high level of automation to systems with lower automation levels, this may lead to unexpected situations for the driver. As a consequence, the driver may not react to signals in time.

2.2.6 Concluding remarks on human factors in the railway industry

In section 2.2, multiple connections have been made between the literature and the concept of operational transitions. Connections to operational transitions can be made at multiple levels in human factors research. Operational transitions can be considered as being higher-workload situations. The high workload does not necessarily have to be caused by the large number of tasks to be performed. It may also be the result of having to distribute attention over multiple aspects of driving. As a result of the high workload, the driver may not be able to put enough effort into driving and thereby miss information or signals. This in turn will increase the probability of a failure by the driver during an operational transition.

Anticipation may help to prepare the driver for the upcoming operational transition(s) in focussing on the right instruments and tasks. Similarly, experienced drivers know what tasks and functions are vital during operational transitions and are better able to handle unexpected events as a result. Irrespective of the experience level of the train driver, providing the driver with sufficient, but not too much information at all times can help the driver to make better decisions and to be better prepared for upcoming transitions. Finally, when designing operational transitions, human factors should be taken into account, in order to prevent unnecessary faults during transitions, due to a too high workload.

2.3 Operational transitions in autonomous driving and aviation

In section 2.2, human factors in the railway sector have been investigated. Multiple connections between driver workload and the concept of operational transitions have been found. In this section, the search for academic literature with connections to transitions is expanded outside the scope of railway systems. In subsection 2.3.1, transitions between different levels of autonomous car control are investigated. In 2.3.2, transitions in automation in the airline sector are investigated. In subsection 2.3.3, a synthesis of the findings of both subsections is given.

2.3.1 Transitions in car autonomy

In the field of autonomous vehicles, transitions are defined as the change from one static state to another static state (Lu & De Winter, 2015). Lu et al. (2016) make a further classification of transitions in automated driving transitions. Transitions can both be initiated by the driver or by the system. Both can decide to engage or disengage the auto-pilot function. When the driver or the system engages the auto-pilot, this does not seem to have large safety consequences. When the driver disengages the auto-pilot, she/he is prepared to regain control of the car. But when the auto-pilot system decides to disengage itself, or hand over control, there is no guarantee that the driver is capable of safely driving the car at that point in time.

Merat et al. (2014) investigated driver behaviour in autonomous cars in case the driver has to regain control of an autonomous car and continue driving manually, after the auto-pilot was disengaged by the system. Drivers were tested in a simulation environment. At some point in time during the experiment, the auto-pilot was switched of and the driver had to regain control of the car. This was either after a fixed period of 6 minutes, or when driver attention for other traffic was too low. As expected, drivers initial reaction was worse in the second experiment than in the first experiment. In case of a transition to manual control due to distraction, it could take up to 40 seconds after the transfer of control until the driver had regained full control of the car, physically and mentally. In both experiments, driver behaviour stabilised after a period of 40 seconds.

Apparent parallels exist between reductions of automation in the autonomous car sector and the human factors with regards to operational transitions in the railway sector. Similar to car drivers, train drivers can be surprised by a sudden change in automation or system functionality when driving through an operational transition. As stated by Pickup et al. (2005), it takes some time before driver effort is increased sufficiently to deal with a high-workload situation. In principle, the location of each operational transition is known to the train driver, but surprises can remain when the transition does not go as planned. These unanticipated events can cause confusion to the train driver and therefore to a loss of situational awareness and focus.

2.3.2 Transitions in the airline sector

Many tasks in aviation that were originally conducted by (co-)pilots in aviation are nowadays performed by automated systems. Under most circumstances, these systems are able to operate, steer and land an airplane. In some situations however, the systems malfunction or are not capable of handling the situation at hand. The cockpit crew therefore have to take over some tasks. Stoop & Van Kleef (2015) investigate system failures and the reaction of cockpit crew to sudden reductions in system automation levels. Many tasks in aircraft operations are automated under normal circumstances. These automated controls are directed by the Flight Management System (FMS). The FMS provides a flight envelope, dimensioned in space and time, in which the crew can operate safely. Three flight modes can be distinguished in aviation: normal mode, degraded mode and manual mode.

Within a flight (or mission), transitions between these three system states can occur. The same applies to the operators. They can switch between mental modes befitting the operating mode. While system transitions can be instant, it takes time to switch between different mental modes. Therefore, in some cases, mental mode and system state are not compatible. This situation is referred to as cognitive dissonance. Cognitive dissonance is the situation in which two beliefs or cognitions of a person are contradictory to each other (Harmon-Jones & Mills, 2019). In case of aviation, the information that a pilot receives from his instruments may contradict his own perception of the situation. Similarly, a train driver may not always be aware of the mental state he or she is supposed to be in, for instance, the driver may look out for trackside signals while operating under ETCS level 2, where signal aspects are shown on the driver DMI.

Another concept that is connected to operational transitions is automation surprises. Automation surprises are situations in which systems act differently than expected by the operator and in some cases, the operators is not even aware of these unanticipated actions (Sarter, Wood & Billings, 1997). De Boer & Dekker (2017) investigate the effect of automation surprises in the aviation sector. They found that trust of airline personnel in automated systems remained high, even after experiencing automation surprises. Most respondents to the survey reported system malfunctions as one of the main reasons for automation surprises, but as aviation systems are in general very reliable, misinterpretation of the system is a more likely explanation (De Boer & Dekker, 2017).

Automation surprises are closely related to sudden reductions in automation (section 2.3.1) and are also closely connected to operational transitions. The driver can be surprised by unexpected system state transitions. The driver may not always be able to intervene accordingly and make mistakes. The concept of automation surprises can also be applied to other transition types that are out of scope of this research, such as transitioning to degraded mode running and driving at sight.

2.3.3 Synthesis on operational transitions in aviation and autonomous driving

Both drivers and pilots are occasionally surprised by sudden changes in levels of automation. For a short period of time, they are unable to fully oversee the situation and only after that time period are they able to refocus their attention and take full control of the situation. Similar situations can occur to train drivers. System changes can occur at operational transitions, where the driver might expect them and anticipate on the possibility of an unexpected event during an operational transition, but they may also occur away from any operational transitions. Pickup et al. (2005) noted that driver effort does not directly respond when workload increases. Only after a short time period did driver effort match workload.

Chapter 3. Identification of operational transitions

As stated in section 1.2, operational transitions are defined by two characteristics. Firstly, they are physical locations in the rail infrastructure. Secondly, operational transitions require the driver to switch between two systems, or to change behaviour significantly. The task of train drivers during operational transitions differs per transition type. Some transitions require the driver to perform certain tasks, while other operational transition types are characterised by a change in (local) regulations, processes or safety protocols. Other transition types again require the driver to change his or her mindset, i.e. shift the focus of attention, increase overall attentiveness or to interpret information in a different manner (ProRail, 2019a).

The temporal scope of operational transitions is a third distinctive feature, which differs significantly per operational transition type. While most transitions have a near permanent location, other transitions types have a short time span and a variable location. This chapter will give an overview of all relevant systems in the context of operational transitions. First, in section 3.1, a short overview of all system transitions is given. In section 3.2, all relevant operational transition types are described in more detail.

3.1 Operational transition types

Based on the definition of operational transitions and using brainstorming techniques and interview data (Appendix B, C, D and E), eight types of operational transitions have been identified. In Table 3, six operational transition types have been listed that fulfil the two conditions that have been listed in

Table 3 Permanent systems requiring operational transitions

TRANSITION TYPES	DESCRIPTION
POWER SUPPLY SYSTEM	Power supply system transitions are necessary when two different power supply systems are used. Trains require equipment to use both power supply systems. The driver is responsible for conducting the transition between both systems. Phase separations occur on 25kV track sections to separate currents which are not in phase. Here, the train driver should lower the pantograph.
AUTOMATIC TRAIN PROTECTION SYSTEM (ATP)	Multiple train protection systems are used in the Netherlands: ATB-EG, ATB-NG and ETCS. Transitions between these systems are performed automatically by the on-board ATP system. The driver must acknowledge these transitions.
MOVEABLE BRIDGES	Different types of bridges require different actions to be undertaken by the driver. Some bridges, like catenary-free bridges, can only be passed when no traction is applied. Other moveable bridges do not have this restriction.
VERTICAL TRACK ALIGNMENT	Vertical track alignment can change at bridges, tunnels, fly-overs, dive-unders and the (natural) terrain on which the track is built. Steep gradients cause changes in train speed. The train driver should be aware of this and anticipate the presence of gradients in the line.
TRAIN TRAFFIC CONTROL DISPATCHING (DISPATCHING CENTRE)	The Dutch railway network is controlled by dispatching centres that solve real-time problems and conflicts. When conflicts are not handled by dispatchers in time, trains will encounter yellow and red signals, causing trains to slow down. The handover between dispatchers and between dispatching centres can cause delays.
NON-CENTRALLY CONTROLLED AREA'S (CBG/NCBG)	On some sidings and emplacements, switches are not controlled by dispatchers, but by shunters or train drivers. The dispatcher directs the actions of driving personnel, but he/she cannot intervene. Transitions from non-centrally to centrally controlled areas are indicated by signs or signals.

the introduction of chapter 3 and that can be characterised as permanent structures. In Table 4, two temporary operational transitions have been described. Temporary transitions are variable in time and location. In section 3.2, the argumentation for defining these systems as operational transitions is given for each system and the occurrence of these transition types on the Dutch railway network is examined.

Table 4 Temporary systems requiring operational transitions

TRANSITION TYPES	DESCRIPTION
TEMPORARY SPEED RESTRICTIONS	TSRs are imposed when full-speed driving is deemed unsafe, either because of degraded or malfunctioning infrastructure, or because of maintenance works in order to protect the maintenance crew
DISPATCHER MANDATE	Mandates are imposed by the dispatcher on certain line sections when a dangerous situation exists along the line, like people or large animals along the line, or a fire close to the line.

Though all eight identified operational transition types fulfil the definition of operational transitions, it should be noted that other features that are not discussed in this research might be classified as operational transitions as well. Further research is therefore required in order to investigate whether more features in the railway infrastructure can be defined as operational transitions. Furthermore, if the definition of operational transitions is altered, this may increase or decrease the number of identified operational transitions as well.

3.2 Operational transition classification

In this section, each of the eight aforementioned transition types will be briefly discussed. For each system, the grounds for their inclusion in this research, the main operating principles and distinctive features within each system are given. Furthermore, their locations on the Dutch railway network are determined.

3.2.1 Power supply systems

Transitions in power supply systems are currently limited to the entrances of the Betuweroute freight railway line and the HSL-Zuid and to border crossings. Power supply system transitions fulfil both criteria of operational transitions that were stated in the introduction of chapter 3. Changing between two power supply systems can require multiple actions to be performed by the train driver, depending on the train type (Appendix F). Furthermore, power supply transitions can be physically identified. Therefore, power supply system transitions are deemed as operational transitions. Four power supply systems are present on the Dutch railway network:

- 1,5kV DC
- 3kV DC
- 15kV AC
- 25kV AC

Below, these four systems are described in more detail. In Figure 5, an overview is given of al operational transition points between these power supply systems.

1.5kV DC

The Dutch main line railway network is equipped with a 1.5kV DC power supply system. In substations, located along the railway line, high voltage is transformed to 1.5kV DC. Power is transmitted to the train via catenary wires. In comparison to other European countries, this is a relatively low voltage. As a consequence, the amperage in the catenary is high. Most 1.5kV DC power supply systems are dimensioned for a maximum amperage of 4000 ampere. The maximum useable power for trains on the Dutch railway network therefore is 6000MW or 6GW (ProRail, 2018a). Due to the relatively high amperage, the power losses in the catenary are high and a dense network of substations is required to supply the network. The average distance between 1.5kV DC substations is 7km (ProRail, 2013b).

25kV AC

The limited maximum power output of trains in combination with the large amount of required substations in a 1.5kV DC system have led to the usage of 25kV AC on the HSL-Zuid and the Betuweroute. Trains on both lines require more power than the 1.5kV DC power supply systems can provide, either due to high speed or due to large train weight. The maximum amperage with a 25kV power supply system is 800 ampere (ProRail, 2013a), which results in a maximum power output of 20MW. The maximum current that a train can 'consume' is 800 ampere, but the infrastructure is able to provide higher amperage if required (Infrasite, 2010). Due to the lower amperages in a 25kV-system, the power losses are substantially lower than in a 1.5kV-system. Therefore, the distance between two 25kV substations is considerably larger than the mean distance between two 1.5kV substations. A distance of 50 km between two 25kV substations is possible (Infrasite, 2010).

25kV Phase separations

The 25kV AC power supply system uses a frequency of 50Hz (Infrasite, 2010). Two substations that feed different parts of a 25kV railway section may, however, not be in sinc with each other. Phase separations therefore exist in order to prevent that a train is 'fed' by two substations simultaneously. Each phase separation has a neutral section separating both sections. The neutral sections of the phase separations on the HSL-Zuid are approximately 600 meter in length, while phases separations on the Betuweroute freight railway line are 30 meter in length (Appendix O.1). The train driver has to switch of traction well ahead of the neutral section of the phase separation. In order to prevent that trains have to stop in or close to the phase separation, an uninterrupted train path should always be provided to a train before passing the neutral section of the phase separation (ProRail, 2013a).

3kV DC

3kV DC is the Belgian main line power supply system. It is, however, also used on some Dutch railway lines near the Belgian border. On the line Roosendaal – Essen (B) – Antwerp, the 3kV DC section continues from the Belgian border right up to the station of Roosendaal, which is approximately 5 km from the Belgian-Dutch border. Similarly, the Belgian 3kV DC system is used on the line Liège – Visé (B) – Maastricht. Again, the 3kV section continues for approximately 5 km into the Netherlands. The transition between 1.5kV and 3kV is located between Maastricht Randwyck and Eijsden. This means that Eijsden is the only station in the Netherlands that is inaccessible by trains equipped with 1.5kV only (ProRail, 2019d; Appendix O.1).

ProRail is currently studying the replacement of the 1.5kV DC system with 3kV DC. A 3kV power supply system has several advantages of 1.5kV. Firstly, the maximum power usage of trains is increased. Providing the maximum amperages remains at 4000 ampere, the maximum power output would be doubled from 6 MW under 1.5kV to 12 MW under 3kV. This means that trains can accelerate faster, higher maximum speeds can be achieved and less energy is wasted due to power losses in the catenary. It is estimated that an energy usage reduction of 19,5% can be attained when the entire network is switched to 3kV (ProRail & NS, 2018b).

Converting the entire power supply system to 3kV requires all substations to be converted and each train to be suitable for 3kV running. Converting the entire network would take approximately 7 years, which means that both the old and the new power supply system will be in operation simultaneously for some time. A number of transition points between 1.5kV and 3kV will therefore exist on the network for several years, which are potentially vulnerable to disruptions (ProRail & NS, 2018b).

15 kV AC

Germany, among other countries, uses 15kV AC as power supply system for electrified main lines. This system is used at the station and the shunting yard of Venlo and the railway line Venlo – Kaldenkirchen. The 'German' side of the shunting yard is equipped with 15kV, while the 'Dutch' side is equipped with 1.5kV. For trains with locomotives that can only operate under one of this systems, this means that they enter the shunting yard with their pantograph down. Using their kinetic energy, they coast to the end of the track, where a (diesel) shunting engine brings the locomotive back to the 'right' side of the

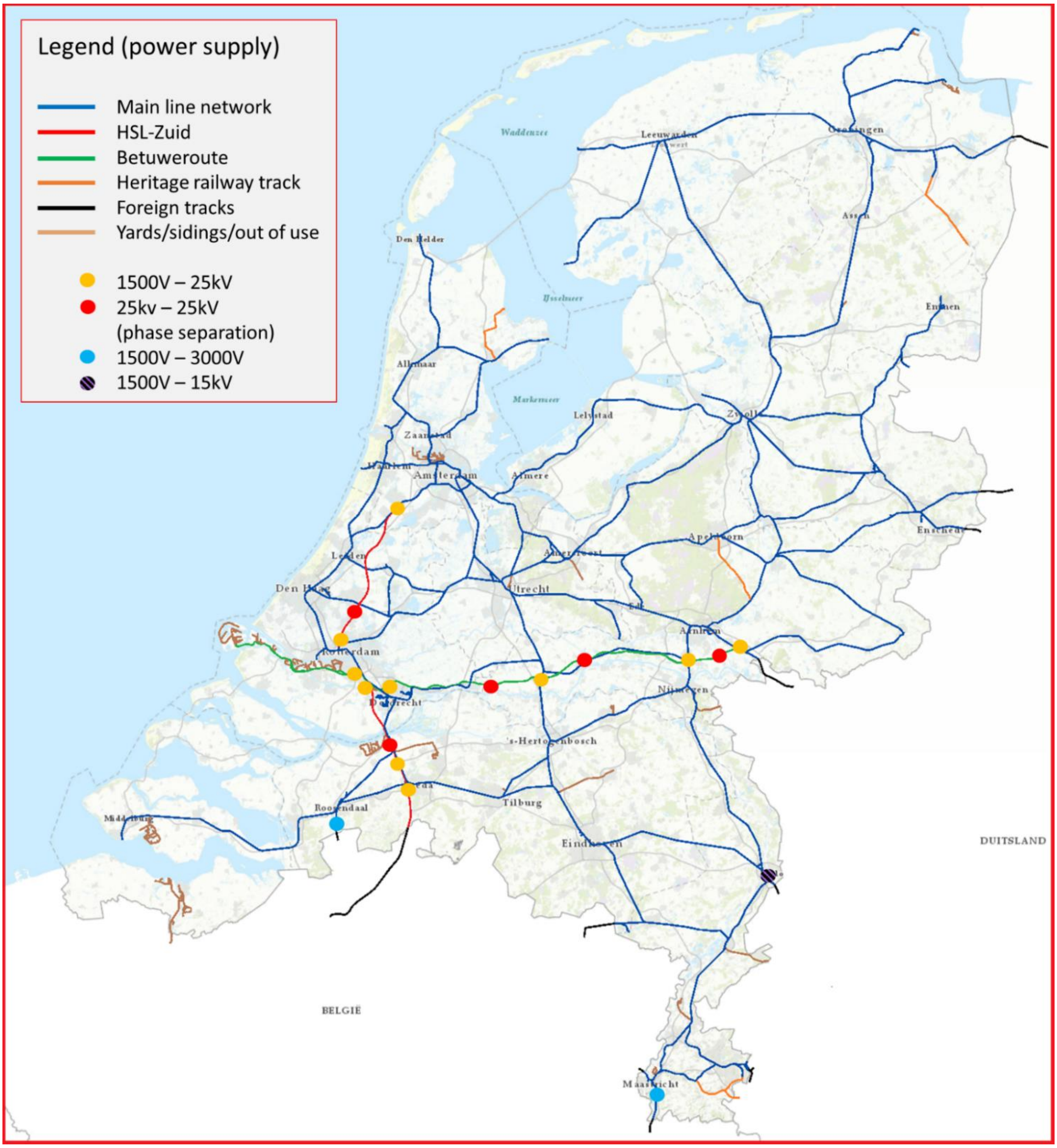


Figure 5 operational transitions in power supply system shunting yard. Some platform tracks at Venlo stations are equipped with switchable catenary, which can be used to provide either 1.5kV or 25kV (Movares, 2017).

3.2.2 Automatic train protection (ATP) systems

Multiple ATP systems are used in the Netherlands. Most main lines are equipped with Automatische TreinBeïnvloeding Eerste Generatie (ATB-EG). Most secondary lines are equipped with ATB Nieuwe Generatie (ATB-NG). Some recently-built lines are equipped with a new European train protection system: ERTMS/ETCS. The basic principles of these systems will first be described in this subsection. Figure 9 indicates the locations on the Dutch railway network where operational transitions are required between two ATP systems (ProRail, 2019d; Appendix O.2). Switching between different ATP systems requires the train driver to perform certain actions. Furthermore, due to different operating principles of the ATP systems, drivers also need to drive with a different mindset. First of all, drivers may have to start focussing on in-cab signalling, rather than trackside signals, as is the case with ATB to ETCS transitions. Although ETCS uses in-cab signalling, the driver should keep observing the outside world for unexpected obstacles, track defects, etc. The attention of the driver is therefore divided between the DMI and the outside world, which increases workload slightly (Hely et al., 2015).

ATB-EG and ATB-VV

ATB-EG is the earliest form of ATP system used in the Netherlands. One of the functions of ATB-EG is overspeed protection (ProRail, 2017a). When a train travels at a higher speed than permitted, the ATB-EG system automatically intervenes. First, ATB-EG warns the driver that the train is overspeeding. When the train driver does not react within 3 seconds, an emergency brake is applied by the system. The communication of the maximum speed to the on-board ATB-EG equipment occurs through electronic pulses running through the rail or a cable running close to the rail (also known as coded track circuits). The frequency of the pulses corresponds to a certain maximum speed (See box 3.2.2). Trains are equipped with an ATB-coil that receive the signal and transmit it to the on-board ATB unit. The DMI communicates the permissible speed to the driver via a set of lights in the cabin (ProRail, 2017a).

Box 3.2.2 ATB-EG pulses

ATB transmits information to the train through coded track circuits. A 75Hz AC-current is sent through this rail or cable. By interrupting the current at regular intervals, the supervised train speed is communicated to the train driver. six ATB-EG codes are currently used in ATB-EG:

code 220 – 60 km/h
code 180 – 80 km/h
code 120 – 130 km/h
code 96 – 140 km/h
code 75 – ATB-EG switched of
no code – 40 km/h

When approaching a signal at danger or driving on a track section without ATB-EG, no code is transmitted, which means that the maximum speed of the train is limited to 40 km/h (ProRail, 2019h).

When a train passes a yellow signal, the trainborne ATB equipment receives a code for 40 km/h. The driver acknowledges this signal by applying the brakes. The driver has to apply a certain minimum braking power. When the driver applies too little braking power or releases the brake before reaching the new speed limit, the ATB-EG equipment warns the driver to apply the brakes further and automatically applies the emergency brake when the driver does not react. This is known as the braking criterion or 'remcriterium' (ProRail, 2017a).

ATB-EG has some notable limitations. Firstly, ATB-EG only enforces five speed limits: 140, 130, 80, 60 and 40 km/h. When the line speed is 100 km/h, ATB-EG supervises a speed limit of 130 km/h, which gives a lot of freedom to the train driver to deviate from the speed limit (Tweede kamer, 2012). Secondly, ATB-EG provides no dedicated Signal Passed At Danger (SPAD) protection. When a signal is red, no electronic pulses are transmitted through the rail. This corresponds to the lowest enforceable speed, which is 40 km/h is transmitted via the rail to the train. Train drivers can therefore pass a signal at danger when driving at maximum speed of 40 km/h without any intervention by the ATB-EG equipment (ProRail, 2017a). Thirdly, the highest enforceable speed of ATB-EG is 140 km/h, which means that it is unsuitable for usage on high speed lines. ATBL-NL has been developed to allow trains to run at speeds up to 160km/h. This system is applied between The Hague Mariahoeve and Leiden. ATBL-NL uses ATB-NG beacons to transmit this information to passing trains. Only Thalys trains have been equipped with the necessary trainborne equipment of ATBL-NL. They used ATBL-NL, until the Thalys started using the HSL-Zuid (ProRail, 2007). Today, this system is no longer used in regular service.

Measures have been taken to provide additional train protection functionalities at speeds lower than 40 km/h in the form of ATB Verbeterde versie (ATB-VV). ATB-VV consist of three beacons located at 120, 30 and 3 meter in advance of a signal. When a train approaches a signal showing red, it passes the first beacon at 120 meter. This beacon transmits a signal to the train via the ATB-coil under the train. Based on the characteristics of the train (Braking capacity, weight, etc.) the trainborne ATB-VV equipment calculates a braking curve to the red signal. When the driver exceeds the speed of the braking curve, the driver is warned and subsequently the emergency brake is applied. The release speed of ATB-VV is 10 km/h. Under this speed, no protection is given by the ATB-VV system (ProRail, 2011a).

ATB-NG

ATB-NG was originally developed to replace ATB-EG. The development of ATB-NG was abandoned after the choice was made to use ERTMS as a replacement for ATB-EG (Robertson associates, 2003). ATB-NG is therefore only applied on secondary railway lines that did not have any form of automatic train protection at all.

There are some notable differences between ATB-EG and ATB-NG. While ATB-EG sends a continuous signal to the train via electronic pulses in the rail, ATB-NG sends information to the train at intermittent points in the infrastructure via beacons (ProRail, 2019c). Two types of beacons are used to send messages to the train. The first type of beacon, block beacons or 'blokbakens' inform the train of the currently applicable speed limit. The second type of beacon, intermediate beacons or 'tussenbaken', informs the train of upcoming speed changes at the next block beacon. With the information transmitted by the block beacon to the train, the trainborne ATB-NG equipment is able to calculate a braking curve to the next signal (ProRail, 2019c). When the train driver exceeds the braking curve speed, the driver will be warned by the system and subsequently, the emergency brake will be applied. This is a major improvement over ATB-EG, which has no braking curve supervision at all. The braking curve is communicated to the driver via the DMI (ProRail, 2017b).

ATB-NG has a dedicated functionality to intervene when a train passes a red signal unauthorized. Directly after passing the beacon in front of the red signal, the emergency brake will be applied irrespective of the train speed. Passing a red signal without intervention under ATB-NG regime is only possible after holding the STS-button for 5 seconds, after which the red signal may be passed at low speed (ProRail, 2017b).

ATB-NG has a more elaborate overspeed protection in comparison to ATB-EG. Whereas ATB-EG can enforce five speed limits, ATB-NG can enforce every speed every speed limit below 200 km/h in steps of 10 km/h. Above 200km/h, ATB-NG enforces in steps of 20 km/h (220 km/h, 240 km/h, etc.), until 300 km/h. This means that the train driver has much less freedom to drive over the maximum speed limit under ATB-NG than under ATB-EG (ProRail, 2019c).

The trainborne ATB-NG equipment is fully compatible with trackside ATB-EG equipment. Trains equipped with ATB-NG driving on an ATB-EG rail section have the same train protection functionalities as trains equipped with ATB-EG. This means that while driving under ATB-EG, there is no braking curve provided, that there is no dedicated red signal passage intervention and only five speed limits can be enforced (ProRail, 2019c).

ERTMS/ETCS

ERTMS is a signalling system that has been in development since the 1990s within the EU (ERA, 2016). ERTMS is a set of specifications for an ATP system and for data communication (Ministry of Infrastructure and Water Management, 2014a) that encompasses two elements (UIC, n.d. b):

- European Train Control System (ETCS). ETCS is a cab signalling system. In the Netherlands, ETCS has been applied on several railway lines.
- GSM-Railway (GSM-R). GSM-R is used for voice and data communication between drivers, dispatchers and lineside workers. Furthermore, data is transmitted between the on-board ETCS equipment and the Radio Block Centre (RBC)

ETCS has three main levels of train protection. With each increasing ETCS level, train detection, train integrity monitoring and signalling, shift from trackside equipment to on-board equipment (Furness et all., 2017). All levels of ETCS use speed supervision, braking curve supervision and use cab signalling (ERA, 2016). The main function of speed supervision is to prevent overspeed. The main function of braking curve supervision is to prevent a train from passing its End of Authority (EoA), the point after which the train has no Movement Authority (MA). If the train driver does not start slowing down in time for the EoA, the braking curve is exceeded and the on-board ETCS unit will apply the train brake. There are multiple braking curves incorporated into ETCS. The main distinction is between service brake curves and emergency brake curves. If the train does not slow down sufficiently with a service brake and also exceeds the emergency braking curve, the emergency brake will be applied (Nachtigall, & Ouředníček, 2018). Braking curves are calculated by the on-board ETCS computer based on multiple input parameters (ERA, 2012):

- Fixed values such as driver reaction time
- National values for ETCS
- ETCS trackside data on signalling and track alignment
- On-board parameters such as train characteristics

The basic principles of each ETCS level will be discussed in more detail.

ETCS level 1

Under ETCS level 1, eurobalises or beacons are used for transmitting data from the Lineside Electronic Unit (LEU) to the on-board ETCS unit (Figure 6). A LEU is used to translate the lineside signal aspects or information from the interlocking system into movement authorities (ERA, 2016; Rhein & Ziering, 2002). When a train passes a eurobalise, the eurobalise transmits data on its location and on the train direction to the on-board ETCS unit, which is used to calibrate the on-board odometer of the train. Furthermore, the Eurobalise transmits a movement authority (MA) to the passing train. Under ETCS level 1, train detection and train integrity monitoring are carried out by track-clear detection systems, such as axle counters and track circuits. The lineside

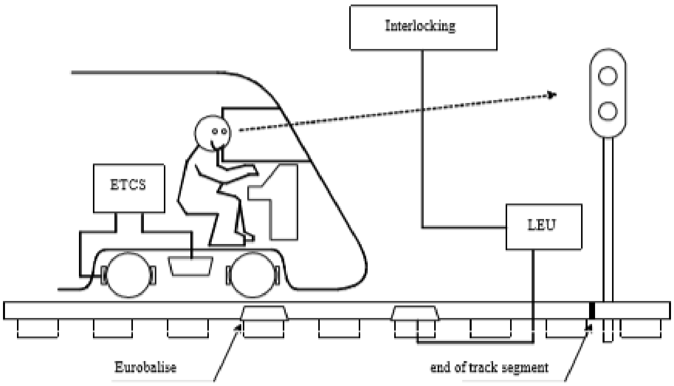


Figure 6 ETCS level 1 principles (ERA, 2016)

signals, which are still present, inform the driver if a new MA is available. Instead of a three-aspect signal, a single aspect that communicates the presence of a new MA is therefore sufficient. As data is transmitted at discrete locations, the principles of ETCS level 1 are comparable to ATB-NG. ETCS L1 is applied on parts of the shunting yard Kijfhoek and on the Rotterdam harbour freight railway line (Havenspoorlijn) running from Kijfhoek to the Maasvlakte. Although ETCS L1 uses cab signalling, there are still physical, three-aspect signals along the Havenspoorlijn (Ministry of Infrastructure and Water Management, 2014a). ETCS L1 has been constructed as an overlay on ATB-EG, which is why the trackside signals were left in place.

ETCS level 2

In ETCS level 2, MAs are transmitted to the on-board ETCS equipment via GSM-R. MAs are provided by a Radio Block Centre (RBC). MAs are calculated by the interlocking and transmitted through the RBC via GSM-R to the on-board ETCS unit (Figure 7). Trains transmit data on their real-time location to the RBC via GSM-R. Train detection and train integrity monitoring are conducted by track-clear detection. Lineside signals are no longer required, as MAs are transmitted via GSM-R, rather than through the combination of signals, LEUs and balises (ERA, 2016; Ministry of Infrastructure and Water Management, 2014a). ETCS level 2 has been applied on the Betuweroute between Kijfhoek and the German border and on the HSL-Zuid. Amsterdam-Utrecht and on Zwolle – Lelystad have been equipped with an overlay of ETCS L2 over ATB-EG. Only trains with an on-board ETCS unit are able to use ETCS on these track sections. However, the lineside signal are still leading for train drivers. All other trains use ATB-EG. On the HSL, a ETCS level 1 fall-back option is available in case the RBC cannot provide MAs (Ministry of Infrastructure and Water Management, 2014a).

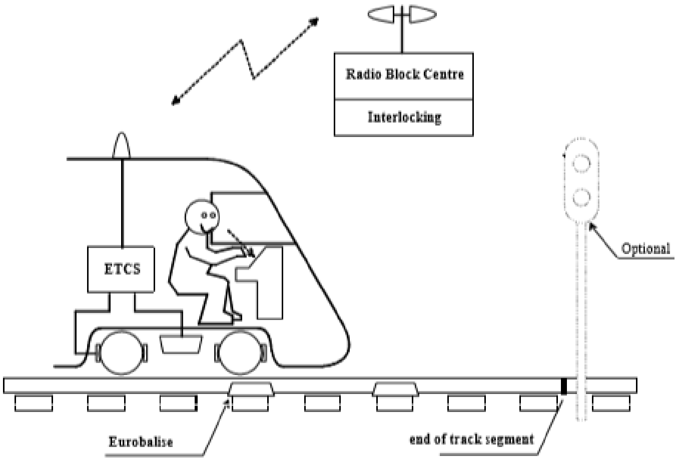


Figure 7 ETCS level 2 principles (ERA, 2016)

ETCS level 3

The main distinctive feature of ETCS level 3 in comparison to level 1 and 2 is the possibility to use full moving block sections as well as virtual fixed block sections. Railway lines are no longer divided into long, physically fixed blocks that are protected by a signal (Figure 8). Via GSM-R, the RBC has real-time information on the location of every train (Ministry of Infrastructure and Water Management, 2014a). Train detection and train integrity monitoring are no longer performed by axle-counters or track circuits. Under ETCS level 3, these tasks are performed by the RBC, using data retrieved from the train (Furness et all., 2017). Similar to ETCS level 2, only cab signalling is used. Reliable train detection depends on a continuous connection between the RBC and the on-board unit. Guaranteeing a connection between ETCS unit and RBC at all times is challenging, as has become apparent in chapter 1. Furthermore, Train Integrity

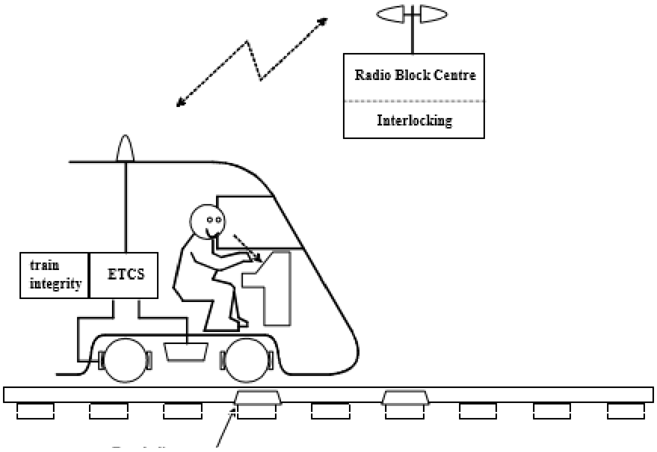


Figure 8 ETCS level 3 principles (ERA, 2016)

Monitoring (TIM) equipment will have to be fitted to rolling stock. This also applies to trains of varying composition, such as freight trains. A reliable and cost-effective TIM unit that can cope with trains of varying compositions currently is not available (Furness et all, 2017). For this reason, ETCS level 3 has only been tested in experimental settings. As a solution to the aforementioned problems, attempts are made to enrich ETCS level 2 with some elements of ETCS level 3, such as a hybrid systems where trains with and without TIM can coexist on the same track. ETCS level 3 hybrid would use a combination of physical and virtual fixed blocks (Furness et al., 2017). This allows the train location to be known by the RBC, although less accurately then when using physical blocks only.

ETCS level NTC

Special modules can be attached to the on-board ETCS unit to translate the signals of national train control (NTC) systems in ETCS signals. For each NTC a specific transmission module (STM) is required to translate the NTC signals into ETCS signals. While driving under a NTC like ATB-EG, the DMI displays a standard ATB-EG DMI to the driver (ERA, 2016).

ETCS Versions, SRS, baselines and the concept of downward compatibility

The ERTMS software is updated on a regular basis in order to remove bugs in the system or to increase the functionality of the system. Updates to ERTMS are described in System Requirement Specifications (SRS) which can then be implemented. A finalised, fully developed SRS is known as a baseline. On the Betuweroute freight railway, ETCS version 2.2.2 was implemented at the start of the operation in 2007. Later, ETCS was upgraded to version 2.3.0d, in which 2 refers to the baseline, and 'd' denotes debugged. ETCS 2.3.0d is used on all ETCS-equipped railway lines except for the HSL-Zuid. Even though the ERTMS version of each line except the HSL is similar, this does not mean that there are no differences. Suppliers of trackside and on-board ETCS units still have some freedom to design their own system, providing the systems meet all requirements as specified in the SRS. There can be small differences between ERTMS versions of different suppliers (ERA, 2016).

The HSL-Zuid uses a non-standard ETCS version, 2.3.0c, in which c denotes corridor. When new baselines are specified, trains equipped with ETCS units constructed according to these baselines should be able to operate on infrastructure (balises, RBCs) built according to older baselines. This principle is known as downward (ERA, 2016). Downward compatibility does not only apply to baselines, but also to ETCS levels. Trains equipped with on-board ETCS equipment for level 2 should be able to operate under ETCS level 2 and ETCS level 1. ETCS L2-equipped trains must be able to receive MAs through GSM-R under ETCS L2 as well as by passing balises under ETCS L1.

Krokodile and PZB

Krokodile is a Belgian train warning system that checks drivers attention in the advent of a speed restriction. It does not provide overspeed prevention, nor does it intervene when passing a red signal (Infrabel, 2011). Krokodile is used on two railway sections near the Belgium border where 3kV is also applied as power supply system (ProRail, 2019d). PZB is one of the German train protection systems. PZB uses switchable magnets along the track that can transmit at a frequency of 500Hz, 1000Hz and 2000Hz. When passing a restrictive signal, the driver has to acknowledge this signal and reduce his speed within a certain time frame with a braking curve (DB Netze, 2014). PZB also intervenes when a red signal is passed. PZB is used on the shunting yard of Venlo, on the rail section between Venlo and the German border and between Enschede and the German border (ProRail, 2019d).

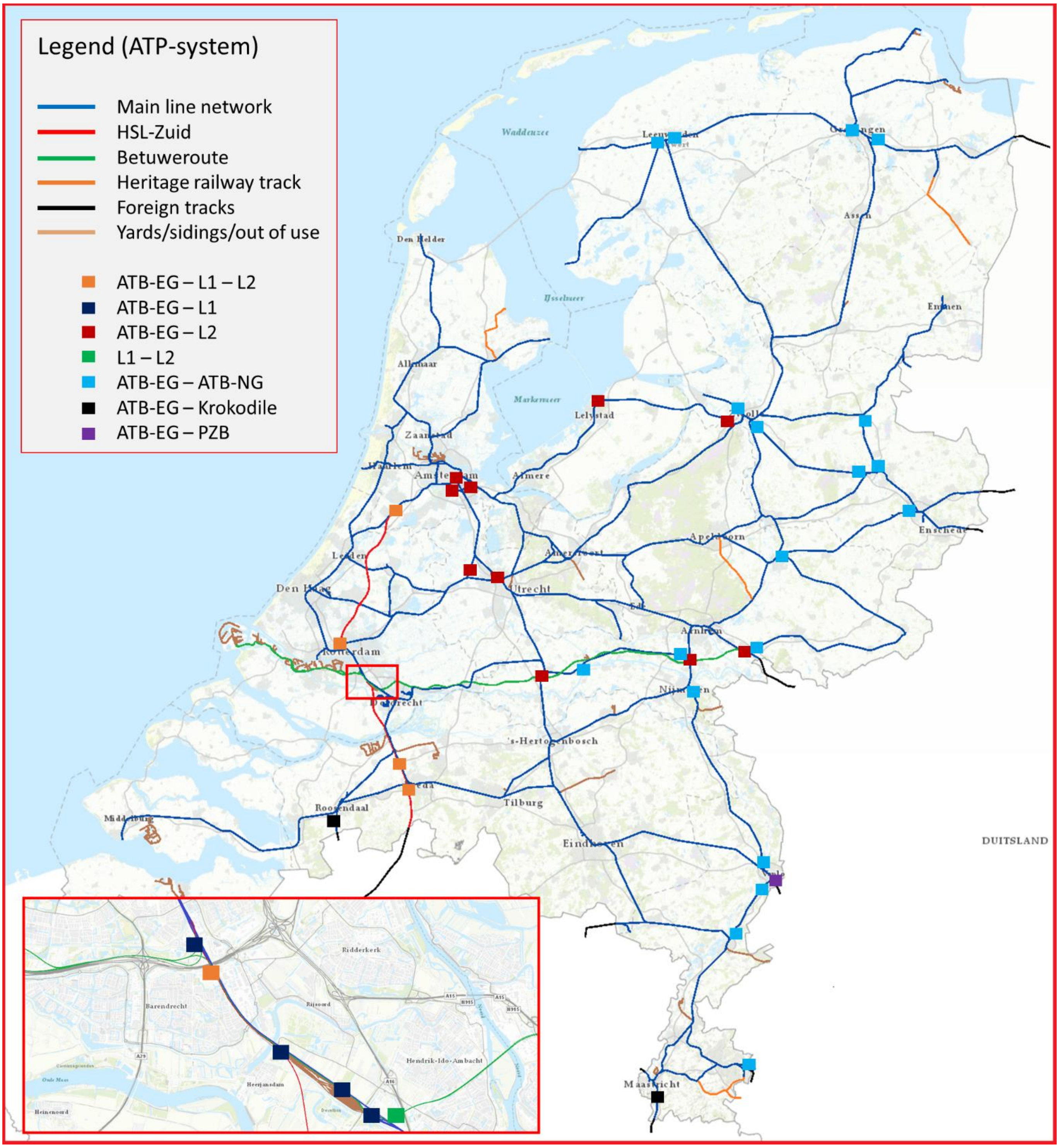


Figure 9, operational transitions in ATP system

3.2.3 Moveable bridges

There is a large number of bridges over rivers and canals that periodically open to let oversize vessels pass. Moveable bridges not only influence train operations when they're opened to let vessels pas, but they also influence train operations in closed state. There are multiple manners in which power is supplied to trains via the catenary on bridges that have an impact on train operations. Some of these bridge types require the train driver to perform special actions, which is why they can be seen as operational transitions. A complete overview of all moveable bridges on electrified railway lines is shown in Figure 11, which is based on the ProRail network statement (ProRail, 2019d) and Appendix O.3. Four types of moveable bridges can be distinguished:

- Bridges with catenary and without any operating restrictions. In closed state, these bridges do not pose any operational restrictions on the train driver. The driver can cross the bridge with raised pantographs and while applying traction.
- Bridges with independent catenary and without any operating restrictions. A limited number of bridges in the Netherlands have catenary that is unconnected to the moveable part of the bridge. If the bridge moves, the catenary does not move with it. The maximum height of vessels passing the bridge is in this case limited by the height of the catenary itself. When the bridge is closed, trains can pass the bridge without any operating limitations as the catenary is uninterrupted.
- Bridges with catenary and with operating restrictions. The bridge of the Harinxma channel near Leeuwarden is equipped with catenary, but train drivers must shut of traction while passing the bridge. The instruction to shut of traction is communicated to the driver by trackside signs in front of the bridge (Figure 10). The driver may apply traction after passing a sign on the other side of the bridge (Regeling spoorverkeer, 2019).
- Bridges without catenary. A large number of bridges without catenary are present on the Dutch railway network. Bridges without catenary on non-electrified lines have been left out of this overview as they pose no operational restrictions. Bridges without catenary are announced by signs along the line well in front of the bridge. Drivers have to shut of traction, but they do not have to lower the pantograph (Figure 10). All Dutch rolling stock is equipped with a pantograph overshoot function. When the pantograph passes the bridge section without catenary, the contact strip is maintained at the same height. The train driver raises the pantograph when the entire train has passes the bridge (Regeling spoorverkeer, 2019). When a train does not have this functionality, the driver has to lower the pantograph at these bridges. Low (catenary) line amperages in power supply happen frequently in the vicinity of catenary-free bridges, which greatly reduces the ability of a train to accelerate (Box 3.2.3).

Figure 10 Signs indicating 'power off' left and 'power on' right'

Figure 11 Operational transitions at moveable bridges

Box 3.2.3 catenary-free bridges and minimum line currents.

While electric trains normally operate under 1.5kV, leaving aside the HSL-Zuid and Betuweroute, the actual catenary voltage can vary significantly locally. Electricity is supplied to the catenary via substations. Near these substations, the voltage usually exceeds 1.5kV. At catenary-free bridges, line currents can be considerably lower. Real-time data on line current, collected in November 2019 by 80 VIRM double decker trains, indicate that line currents were especially low in the vicinity of catenary-free bridges (Figure 12).

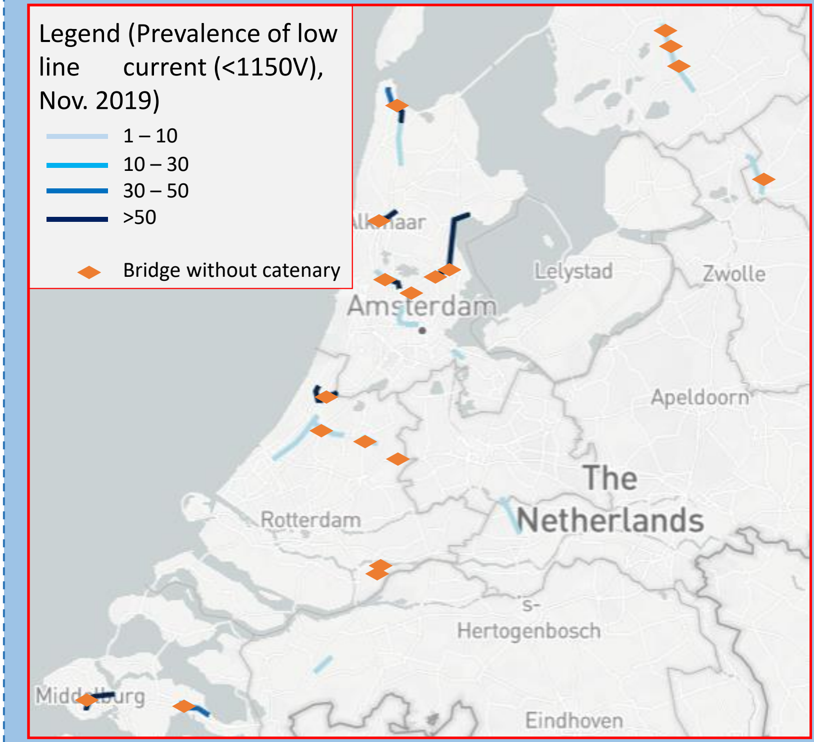


Figure 12 Prevalence of low line currents (<1150V) (ProRail, n.d.)

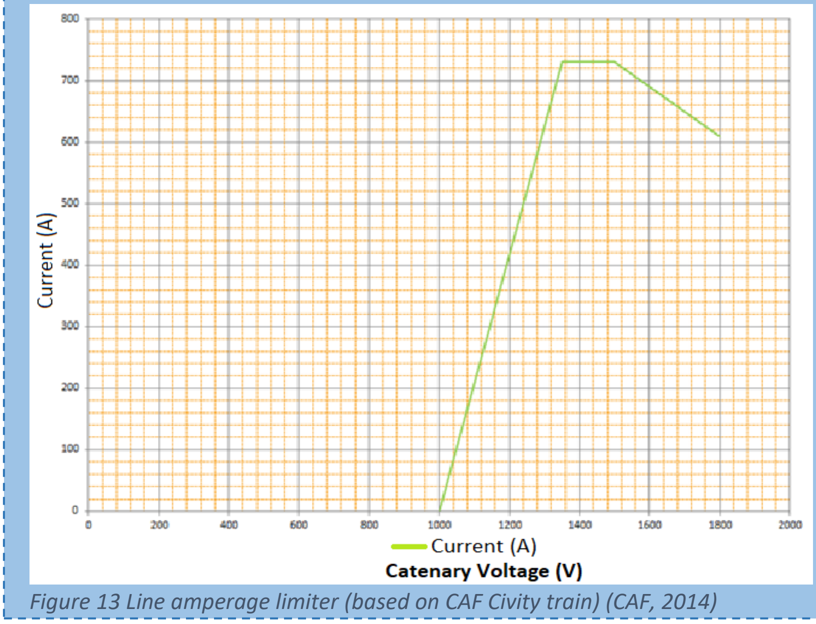


Figure 13 Line amperage limiter (based on CAF Civity train) (CAF, 2014)

Between Hoorn and Purmerend, for instance, 56 events were recorded where the line current was lower than 1150V. On average, the line current was 1040V, while some instances of line currents of 1010V have also been recorded (ProRail, n.d.). When line currents are low, the train traction engines have to use more amperage, in order to get the same power. When trains use power, the catenary is also 'drained', leading to even lower line currents.

In order to prevent that trains 'drain' the catenary of energy, modern trains are equipped with line amperage limiters. When the line current drops, the maximum line amperage that a train can use is limited as well (Figure 13). With a line current of 1040V, trains would only be able to use a small fraction of the available amperage, greatly reducing the train acceleration (CAF, 2014).

When trains have to wait for a signal in front of a catenary-free bridge, the acceleration of these trains is limited when they can continue their journey, increasing the total travel time between stations considerably. In extreme circumstances, trains may not be able to gain enough speed to clear the catenary-free section of the bridge or may not be able to accelerate at all.

3.2.4 Vertical track alignment

Vertical track alignment refers to the presence of gradients in the track alignment. In the Netherlands, most gradients are caused by civil structures in the infrastructure. Train drivers need to anticipate on gradients in the track alignment, especially when driving with heavy trains. This shift in driver mindset is the reason why changes in vertical track alignment can be considered operational transitions. Upward and downward slopes increase driver effort as the driver has to concentrate more on maintaining the right train speed and anticipate more on upcoming speed changes and restrictive signals (Pickup et al., 2005).

A comprehensive overview of gradients in the Dutch railway system is currently lacking. Four types of structures are therefore investigated in order to acquire an extensive, although most likely not complete, list of significant gradients in the Dutch railway network: tunnels, bridges, fly-overs and dive-unders.

- Tunnels. A complete list of all tunnels in the Dutch railway network is present in the ProRail network statement (ProRail, 2019d). The gradients and operational restrictions of all tunnels in this list have been investigated.
- Bridges. The search for significant gradients at bridges has been limited to bridges crossing major waterways in the Netherlands, as these bridges have to be sufficiently high to allow the passage of larger vessels. All bridges crossing waterways classified as CEMT Va or higher (Ministry of Infrastructure and Water Management, 2017) have therefore been investigated.
- Fly-overs and dive-unders. In order to reduce the number of crossing movements at railway junctions, fly-overs and dive-unders are sometimes used in order to create a conflict-free crossing. All fly-overs and dive-unders at or close to junctions have been investigated.

The complete list of tunnels, bridges, fly-overs and dive-unders investigated can be found in Appendix O.4. Near significant slopes, multiple measures can be taken to ensure that heavy trains, mainly freight trains, are able to pass these slopes. These operational restrictions will be described in more detail below. For some tunnels, entry speed restrictions also apply, in order to prevent overspeed at the bottom of the tunnel.

L, H and X/G signals.

In front of some (steep) gradients, L-signals and H-signals are used to halt trains well in front of the gradient. These signals only apply for freight trains and other designated trains (Regeling Spoorverkeer, 2019). An L-signal indicates that these trains should slow down and prepare to stop for a H-signal. Only when a free passages over the entire gradient has been guaranteed will the H-signal dim and is the train allowed to continue. L- and H-signals are usually applied in front of tunnels, bridges and fly-overs.

X/G-signals are applied in front of some tunnel entrances. Heavy trains have to stop when the signal indicates X and may proceed when the signal indicates G. When the signal indicates G, a continuous train path is guaranteed through the entire tunnel without interruptions. In a X/G-regime, ATB restricts the entry speed of the train at the tunnel entrance in order to prevent overspeed at the bottom of the tunnel. The final operating anomaly is that an extra block separation is kept between the freight train moving through the tunnel and the following train. When the freight train stalls on the upward slope of the tunnel and rolls back, there is an extra safety margin between the freight train and any following train (Infrasite, 2008; ProRail, 2011b). Only some of the deeper tunnels were found to have speed restrictions for freight trains entering the tunnel. These tunnels are also equipped with either X/G signals or L and H signals.

Based on this analysis, three categories of structures with gradients can be distinguished, gradient without any extra operational restrictions, gradients with operational restrictions (either L and H signals or X/G signals) and gradients with operational restrictions and speed restrictions. In Figure 14 all gradients at tunnels and bridges are shown. Figure 15 shows all gradients at fly-overs and dive-unders. Gradients are indicated with various colours, depending on how steep they are. For some gradients, data on the exact gradient angle is lacking. These gradients are indicated in grey.

Figure 14, Gradients at tunnels and bridges

Figure 15, Gradients at fly-over and dive-unders

3.2.5 Dispatching centres

Dispatching centres (Verkeersleidingspost or VL-post in Dutch) control all train traffic on a part of the railway network. The Dutch railway network is currently controlled by 12 regional dispatching centres throughout the Netherlands (ProRail, 2017c). The degree to which transitions of trains between two dispatching posts are successful primarily depend on the skill and cooperation of dispatchers. Although this research focusses on operational transitions from the train driver point of view, train operations and thus train drivers are possibly influenced by these transitions. Therefore, this transition will be investigated in this research.

Figure 16 borders of dispatching post control area's

The controlled area of each dispatching centre is further subdivided into multiple control areas, called Primaire ProcesLeidingsGebieden or PPLGs (ProRail, 2019e). Dispatchers within a dispatching centres are responsible for one or multiple PPLGs. Dispatchers provide train paths to trains. Under most circumstances, this process is automated. Train paths are provided by the automatic route setting tool (Automatische RijwegInstelling or ARI). A train path is automatically provided when a train passes the ARI-trigger point (ProRail, 2019e). ARI is only active in case a train is running on schedule to a certain degree. If a train is either too late or too early, ARI will deactivate and the dispatcher will have to set a route manually. The exact boundaries of ARI can be adjusted by the dispatchers themselves for each PPLG under their responsibility (ProRail, 2019e). Generally, the ARI time boundaries are smaller on highly utilized railway lines, as there is a smaller headway between trains. When a route is not set for the approaching train in time, the train driver will encounter yellow or red signals or the end of its movement authority, forcing the train to slow down and stop.

When ARI is inactive, due to a train running too late, the dispatcher may not immediately be aware that he/she should act. The dispatcher may not expect a delayed train to enter one of his/her PPLGs or the dispatcher may be busy with other tasks and notice the delayed train too late. When a route is set too late, the delayed train will encounter restrictive signals (yellow or red signal aspects) or near the EoA point. Delayed route setting may also occur when a dispatcher is distracted as a result of underload. This general lack of attention in automation work environments has been hypothesised by Branton (1993) and investigated by Brandenburger et al. (2018) who found a decrease in train driver and signaller attention during automated operations/driving due to underload. Parallels could also be drawn between unexpected manual route setting by the dispatcher and the concept of automation surprises as described by Merat et al. (2014) and Sarter, Wood & Billings (1997). When a dispatcher is not expecting a delayed train that requires manual route setting, he or she is surprised when such a train suddenly approaches. While setting a route for this train manually, the dispatcher may lose overview over all PPLGs that he or she is responsible for, which may lead to other missed trains.

Handovers of trains between two dispatching centres is also automated. ARI can provide paths over the borders of the dispatching centres. Manual handovers between dispatching centres requires the coordination of two train dispatchers of two different dispatching centres. Although the train driver is not involved in this process, (s)he is impacted by the actions and decisions of dispatchers. As the location of handovers between dispatching centres is defined, and as these handovers require human actions, these handovers can be considered to be operational transitions. All 12 dispatching centres and the handover points between dispatching centres are shown in Figure 16.

3.2.6 Non-centrally controlled areas

Non-centrally controlled areas (Niet Centraal Bediende Gebeiden, NCBGs) are parts of the railway network on which signals and switches are not or only partially controlled by train dispatchers. NCBGs are often located on yards, on terminal areas and on sparsely used branch lines. These NCBGs often lack any form of train protection and signalling. In total, there are 96 NCBGs in the Netherlands (ILT, 2018). Traffic on NCBGs is coordinated by special dispatchers that control multiple NCBGs (ILT, 2018).

NCBGs lack train detection, which is why the speed in these areas is restricted to 40 km/h. Due to the lack of train detection, train drivers entering a NCBG are granted a time/space-slot (TijdRuimte-Slot or TRS) by NCBG-dispatchers, which is a movement authority for a specific area and time frame (ILT, 2018; ProRail, 2019f). The entrance to an NCBG is controlled by a stop-sign or a provisional stop-sign. In the latter case, drivers can directly enter the NCBG if they already had received permission of the dispatcher to enter the NCBG-area. The exit of NCBGs is guarded by a signal, which is part of the centrally controlled area (CBG) of ProRail dispatching (Regeling spoorverkeer, 2019). A complete list of all active NCBGs is provided by ProRail (2020a).

The transition from CBG to NCBG is paired with a handover of responsibility from the dispatcher and the interlocking system to the train driver. The train driver is responsible for every movement of the train and is unassisted by any other actor or technical device. This transition of responsibility and of safety management is the reason why CBG-NCBG transitions are included in this research. The transitions of responsibilities to the train driver poses the risk of cognitive dissonance, as described by Harmon-Jones & Mills (2019). While driving in an NCBG the driver may not be aware of the transition of responsibilities from the dispatcher to the driver. In NCBGs, drivers are virtually unassisted and unprotected by any safety systems. If the train driver is not aware of these responsibilities, he or she might consider the situation safer than it actually is. The transition from CBG to NCBG therefore mainly has to do with a change in driver mindset. The driver should be aware of his newly acquired responsibilities when entering the NCBG in order to continue safe train operations.

3.2.7 Temporary speed restrictions

Temporary speed restrictions (Tijdelijke SnelheidsBeperkingen or TSRs) are imposed when it is deemed unsafe for trains to drive at normal line speed at a certain location. TSRs are mostly imposed during (re)construction works on part of the line or when the conditions of the infrastructure has deteriorated too much (ProRail, 2020c). Either railway contractors or inspectors are responsible for requesting TSRs to be implemented. Each TSR-request is received and processed by ProRail department of infra availability planning (InfraBeschikbaarheidsPlanning or IBP). Within this department, the Manager Maintenance and Operarations (Manager Onderhoud en Operatie of MOO) is responsible for all approved TSRs (ProRail, 2020c).

TSRs are considered to be operational transitions as they fulfil the definition of operational transitions. TSRs are physical locations in the infrastructure, although they're temporary. Furthermore, they require a more attentive attitude by the train driver as there is an increased level of hazard. During (re)construction works for instance, the driver can expect maintenance workers close to the track, towards which he or she should pay special attention.

TSRs are communicated to the train driver in two ways. First, TSRs are announced in weekly and daily publications with additional driver information (weekpublicatie en dagpublicatie). These documents contain all locations of active TSRs. The daily publication may contain additional information to the weekly publication. Second, TSRs are communicated to the driver via three trackside signals. The L-sign is the first sign that a driver encounters and it orders the driver to slow down to 40 km/h. The start of the TSR-area is indicated with an A-sign and the end of the TSR-area, after which the driver can accelerate again, is indicated with an E-sign (ProRail, 2019d; ProRail, 2020b).

TSRs are enforced in most cases by the ATP system. On track sections with ATB-EG, the maximum train speed is communicated to the train via electronic pulses via the rail (see section 3.2.2). When a speed of 40km/h is enforced by ATB-EG, this corresponds to a pulse frequency of 0 pulses per minute, i.e. no pulses at all. Paradoxically, 'switching off' ATB-EG on the TSR section is sufficient to enforce the speed limit of 40km/h (ProRail, 2010). TSRs on track sections with ATB-NG require the ATB-NG beacons in front of the TSR to be reprogrammed. These reprogrammed beacons are not only able to enforce the maximum speed at the TSR, but the presence of TSRs can explicitly be communicated to the driver via the DMI (ProRail, 2019g). Similar to ATB-NG, TSRs can be applied in ERTMS level 1 regimes by reprogramming the balises. In both cases, a contractor has to reprogram the beacons/balises on-site (ProRail, 2015).

Special rules apply for TSRs in transition points between HSL-track and HRN-track. Due to the transition from ATB-EG to ERTMS, providing adequate train protection in the TSR requires some extra effort. The TSR has to be programmed both in ATB-EG and in ERTMS. In the ATB-EG-area, this is done by simply changing the electronic pulse frequency in the rail. In the level 2 ERTMS-area of the HSL, TSRs are enforced through the interlocking system of the HSL. VICOS-MMI is a control terminal that allows TSRs to be included in the interlocking. Extra signs are placed at the ATB-EG – ERTMS transition point to communicate to the train driver that the TSR is not finished after the transition point (ProRail, 2012).

3.2.8 Dispatcher mandate

When unexpected events happen on or along the railway line, dispatchers can inform train drivers of these events and order them to adjust their driving behaviour. These dispatcher mandates (Dutch: lastgevingen) can be applied in a wide range of situations. Mandates are applied when objects, animals or humans are detected too close to the railway line or when the infrastructure is damaged or malfunctioning. Dispatcher mandates are (very) temporary in nature. Although dispatcher mandates are imposed for a limited time, they are imposed for a specific place. The driver is aware at which point he should change his or her driving behaviour.

Dispatcher mandates require more attentive driving behaviour by the train driver. The driver should be aware of unexpected events and of potentially hazardous situations. As human errors are the primary cause for safety-related incidents and accidents (Baysari, McIntosh & Wilson, 2008), the driver should pay extra attention when driving under influence of a dispatcher mandate in order to identify potential hazards well in advance and act accordingly. For this reason, dispatcher mandates are considered as operational transitions in this research, as a shift in driver mindset is required.

Dispatchers can use seven different types of mandates (Regeling Spoorverkeer, 2019).

1. Passing a signal at danger (STS). The train driver is allowed to pass a signal at danger and continue driving with a maximum speed of 40 km/h until the next signal.
2. Passing a signal at danger at normal speed (STS-A). The train driver has permission to pass a signal at danger and continue with normal line speed. The maximum speed at switches is 10 km/h.
3. Drive with attention (VR). The driver must slow down to 40 km/h or less in order to be able to react to unforeseen and unsafe situations.
4. Railway crossings (OVW). Malfunctioning railway crossings should be approached with a limited speed while repeatedly whistling to warn road traffic. While passing the railway crossing, the maximum speed is 10 km/h.
5. Reduce speed (SB). The dispatcher mandates the train driver to reduce his speed to a specified limit.
6. Drive in opposite direction (VS). The dispatcher grants permission to the train driver to drive in the other ‘wrong’ direction.
7. Permission to depart via telephone (TTV). The train driver has to ask permission to depart via telephone.

While the detection of some unexpected events rely on human detection, some events are detected automatically. For instance, when a railway crossing is closed for road traffic for more than 5 minutes, a message is automatically sent to the dispatcher that is responsible for the track section. Simultaneously, the signal in front of the railway crossing is automatically set to display danger. The driver may only pass the signal at danger after receiving a dispatcher mandate (ProRail, 2005).

Chapter 4. Introduction to case studies

In order to investigate the relation between operational transitions and the reliability of railway operations, four case studies are conducted. In this chapter, the methodology that will be followed for these case studies is described. In section 4.1, a short overview of literature on case studies is given. The purpose of case studies as well as the generalizability of case study results are topics for debate. Cases selection is covered in section 4.2. In 4.3, a method for quantitative data analysis is explained, which is used for answering the second sub question. In 4.4, a methodology is explained which is used for determining causes for delays, which is used for answering the third sub question.

4.1 Case study method

Case studies have been used extensively in both qualitative and quantitative research (Stake, Danzin & Lincoln (1998). A Case study can consist of the study of one single case (N=1) or of studying a small group of interrelated cases (N>1) (Swanborn, 2010). Case studies are conducted to gain a deeper understanding of the case by studying all aspects of a case in terms of its processes, relationships and so forth. A wide range of methods can be used for this purpose.

The extent to which the case study methodology is able to produce scientific knowledge that is generalizable across a wider population of cases is very much under debate. Flyvbjerg (2006) believes that a single case study can be the very core of scientific research. Providing the case is chosen carefully, its insights can be used in theory building without much difficulty. While Flyvbjerg is optimistic about the generalizability of case study results, Yin (2012) is more reserved on the ability of case studies to generate new information. Although Yin refutes the notion that case study results (meaning in this context: facts and figures) can be generalized to the 'population', he approves of the generalisation of concepts, frameworks and theories based on case studies. Swanborn (2010) is even more frugal in his remarks on the generalizability of case study findings. He states on case studies: "Whether its results can be generalised in other contexts remains an open question, to be answered by complementary case studies and/or an extensive approach." Swanborn's concerns are backed up by Beverland and Lindgreen (2010), who reviewed a large set of case studies. Less than 25% of the investigated papers addressed the validity or generalizability of the outcomes of their study explicitly.

Three main types of case studies are identified in Stake, Danzin & Lincoln (1998). Intrinsic case studies are conducted to provide a better understanding of a specific case, without the explicit desire to generalize the findings of the case study. In contrast, the instrumental case study is conducted specifically to acquire generalizable results. In this context, the chosen case resembles a larger population of roughly similar cases. The third case study strategy is named 'collective case study' by Stake. A collective case study is best described as a combination of multiple instrumental case studies. Multiple cases, that are all examples of a wider population of similar cases, are studies, further reducing the importance of each individual case.

When selecting specific cases, multiple case selection mechanisms can be used. When sample sizes are sufficiently large (N = 1,000), random sampling is a viable strategy (Flyvbjerg, 2006; Seawright & Gerring, 2008), but when the sample size is small, which is most often the case in qualitative research, random selection of cases is not an option and purposive case selection is required (Seawright & Gerring, 2008). Seawright & Gerring (2008) provide an overview of methods that can be used to select cases for further analysis:

- Typical cases, resembling a larger amount of cases
- Diverse cases, covering the diversity a group of cases

- Extreme cases, not representative of the average
- Deviant cases, deviating from a certain relationship
- Influential cases, significantly influencing the entire population
- Most similar cases, which are similar on key characteristics
- Most different cases, differing on key characteristics

Although this overview provides a clear starting point for selecting cases within a wider population, it should be noted that there are no distinct boundaries between these categories and that categories are partially overlapping. Selecting a suitable selection strategy is an important tasks for qualitative research. As the number of cases is typically limited, choosing one case over another can have a large impact on the outcomes of the study. Curtis et al. (2000) therefore provide six general sampling guidelines in qualitative research:

1. "The sampling strategy should be relevant to the conceptual framework and the research questions addressed by the research"
2. "The sample should be likely to generate rich information on the type of phenomena which need to be studied."
3. "The sample should enhance the 'generalizability' of the findings"
4. "The sample should produce believable descriptions/explanations"
5. "Is the sample strategy ethical?"
6. "Is the sampling plan feasible?"

Yin's position on the usability of case studies for creating new scientific knowledge appears to be most applicable in the case of operational transitions. Every transition or combination of transitions is able to provide new information about what factors influence the reliability of railway operations. Caution should, however, be paid to generalizing case study information outside of the context in which operational transitions are studied. A collective case study approach will be used in this research. The aim of these case studies is to gain a general understanding of operational transitions by studying a selected sample of transitions. The cases will be selected in order to investigate as much operational transition types as possible.

4.2 Case selection

Four cases are selected that will be used for further analysis. In this section, the rationale for each case choice is explained. Furthermore, the methodology that will be used for each case study will be explained. Finally, not all case studies are used to answer the same sub questions. An answer has been provided to sub question 1 in chapter 3, by identifying and locating operational transitions on the Dutch railway network. Sub question 2 and 3 will be answered using three case studies (Chapter 5, 6 and 7). The fourth sub question will be answered with the case study in chapter 8.

Sub question 2, 3 and 4

2. To what extent do delays emerge from operational transitions?
3. What are the underlying causes for failed operational transitions?
4. What is the role of human factors in failed operational transitions?

Selected cases

This study aims to investigate a large number of operational transitions. A large diversity of transition types covered in the case studies reflects this. Nonetheless, the case studies should also provide sufficient depth to the research. Figure 17 gives an overview of the position with relation to depth and width of the four case studies within this research. 'Blue' case studies are location specific and 'yellow' case studies are not location-specific. Research starts with a case study on operational transitions on the HSL-Zuid, Betuweroute (BR) and Havenspoorlijn (Hsp) in chapter 5. Four transition types are studied in this chapter. These four transitions are investigated on a general level In chapter 6, the same transition types are investigated, but they investigated specifically at Meteren junction. This allows these transitions to be studied at a deeper level, providing more details into the role of transitions in train service disruptions. In chapter 7, a case study of Zaandam is conducted in order to investigate two transition types that have not been studied in chapter 6 yet, NCBGs and moveable bridges. Finally, chapter 8 adds to this collection of case studies by studying the role of human factors for one specific type of transition: ATP transitions. Via this case study, the most detailed information can be acquired on operational transitions and specifically on the role of human factors (HF) in these transitions.

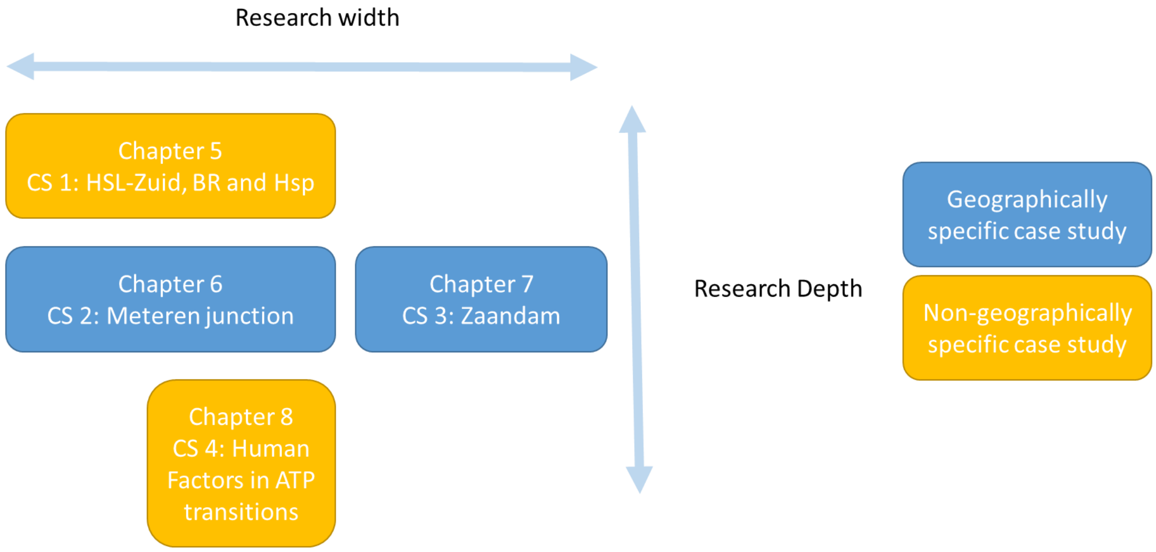


Figure 17 Case study cohesion

- **Ch.5 HSL-Zuid, Betuweroute and Havenspoorlijn**

  In chapter 5, a study will be conducted on operational transitions occurring on the HSL-Zuid and on the Betuweroute and Havenspoorlijn. A large number of operational transitions can be found on these recently built railway lines, including transitions in power supply system (1.5kV to 25kV), ATP system (ATB-EG to ETCS), vertical track alignment and handovers of trains between dispatching centres. The unique characteristic of these railway lines is that these four transition types are often combined. Qualitative research methods, such as literature study and interviews will be used in this case study. An overview of the interviews conducted for this case study is given in Appendix A.

- **Ch.6 Meteren junction**

  At Meteren junction the Betuweroute connects to the railway line Utrecht – Den Bosch (A2-corridor). The same four transition types that are covered in chapter 5 are present at Meteren junction. The case study of Meteren junction will be used to complement the case study of chapter 5. Whereas chapter 5 uses qualitative research methods, quantitative research methods will be used in this case study. The methods used in the Meteren junction case study might be able to provide more detailed information on the effect of operational transitions on train operation reliability and on the underlying causes of transition failures. Similar to chapter 5, the case study of Meteren junction will be used to answer sub question 2 and 3. The methods used to answer sub question 2 are explained in section 4.3 and the methods used to answer sub question 3 are explained in section 4.4.

- **Ch.7 Zaandam station**

  The case study of Zaandam station will be used to study operational transitions types that have not been covered in chapter 5 and 6. Three transition types are present close to Zaandam station: a transition in vertical track alignment (Hem tunnel), a catenary-free bridge and a transition from CBG to NCBG. Similar to chapter 5 and 6, the case study of Zaandam station will be used to answer sub question 2 and 3. The methods used to answer sub question 2 are explained in section 4.3 and the methods used to answer sub question 3 are explained in section 4.4.

- **Ch.8 Human factors in ATP system transitions**

  The final case study does not study a specific track section, but a specific transition type. In chapter 8, a case study is conducted on the role of human factors in the failure of ATP system transitions. This transition type is chosen for further analysis as the number of ATP system transitions will increase significantly in the upcoming years. Studying train driver behaviour during such transitions can help to identify design flaws and operational difficulties experienced by the drivers. Interviews with ERTMS experts and managers closely connected to train operations on the HSL-Zuid and panel group discussions with train drivers are used to acquire data on the contribution of train drivers to failed ATP system transitions. An interview guide, with a short introduction to semi-structured interviews, is provided in appendix A. With this case study, the fourth sub question will be answered.

4.3 TROTS section and subsection analysis methodology

In this section, the methodology for analysing delays at track sections is explained. In order to obtain data on delays, data on train locations is of vital importance. The TRain Observation & Tracking System (TROTS) is used to monitor the location of each individual train on the Dutch railway network. This data, among other data sources, is accessible through the software package 'Sherlock'. TROTS-data is used by dispatchers in order to know the real-time location of a train within a block section. A block section, the track section between two signals, is divided in one or more TROTS sections. TROTS registers the entry and exit time of each TROTS-section. Based on the actual passage time and the planned passage time of TROTS sections, delays can be detected. Moreover, increases and decreases in delay time can be detected. The increase in delays (also known as delay jump or 'vertragingssprong' in Dutch) will be used to identify delays on TROTS sections.

Each TROTS section is subdivided into multiple TROTS subsections with a length ranging from approximately 100 to 500 meter. TROTS subsection data can therefore be used to relate delays on a track section to certain features in the railway infrastructure, such as operational transitions, signals and stations with a good accuracy. Delays are automatically registered for each train. A train passage of a TROTS (sub)section is registered as a delay if the average train speed in the section is less than 25 km/h. An extra minute buffer time is added to this calculation in order to account for measurement errors. If a train satisfies these constraints, Sherlock assumes that the train has come to a complete stop. Scheduled stops are not marked as delays. For both case studies, data on train delays has been gathered for the period 01-01-2019 and 31-12-2019 for the case studies of Meteren junction and Zaandam.

Data on delays on TROTS sections is used to find track sections on which a relatively high number of delays or a relatively high total delay time (the sum of all delay events) is observed. By dividing the number of delays and the total delay time by the number of trains using the TROTS section in the same time period, comparable scores can be constructed to compare the performance of trains on each TROTS section. These two metrics are named ‘delay probability’ and ‘average delay time’ respectively. TROTS sections with the highest delay probability and/or average delay time will be analysed on TROTS subsection level. Subsections with a sufficiently high delay probability or average delay time will be used for analysing the causes for delays at these subsections (section 4.4).

4.4 TROTS delay cause analysis methodology

In this section, the methodology for determining delay causes at TROTS subsections is explained. For each delay event on the selected TROTS subsection, a delay cause is determined. Multiple data sources are available that record the causes for train delays. Sherlock uses three data sources that provide declarations for delays: Monitoring system, STIPT and Spoorweb/ISVL (Informatie Systeem VerkeersLeiding). Each data source has its own benefits and drawbacks that need to be taken into account. Firstly, all three data sources will be described in more detail. Secondly, a method is described to combine these data sources into one metric to determine a delay cause for each delay. Thirdly, a method quantitative analysis is explained for a selection of high-impact delays.

Data sources for delay causes

- Monitoring system: the Monitoring system is used by dispatchers to declare the cause of each delay with a minimum length of 3 minutes, of cancelled trains, of retimed train paths and of rerouted trains (ProRail, 2019i). The dispatcher can choose one or multiple reasons for delays out of a predefined set of 38 causes for delays (ProRail, 2019j). Furthermore, comments can be made to further clarify the causes for train delays (ProRail, 2019i). Although a large number of causes can be assigned to specific delays, the delay categories provided by the Monitoring system are more focussed on the actions of actors in the railway system than on the actual train itself. This makes it difficult in some circumstances to determine why a train is delayed. The comments made by dispatchers can be of help to get a better understanding of a delay, but the number of comments is generally limited, as comments are only made in unusual situations that are not covered by the standard delay causes.
- STIPT: STIPT is an algorithm that assigns causes to delays based on various data sources that are combined in Sherlock. STIPT has approximately 80 predefined causes for delays that can be assigned to a delay. Even the smallest delays are automatically declared by STIPT, although the validity of such declarations can be questioned (Sherlock, n.d.). In contrast to Monitoring, STIPT declarations for delays are more train-centred than the declarations put forward by dispatcher in the Monitoring system. Specific defects and malfunctions to trains can be used to declare delays. Furthermore, STIPT recognizes the propagation of delay from one train to another, which makes it easier to distinguish between primary and secondary delays.
- ISVL/Spoorweb: ISVL, also known as Spoorweb, is a communication platform which is by multiple relevant actors when (usually large scale) delays occur. 35 different railway-related companies have access to Spoorweb (De Bruin & Hoving, 2017). The communication between actors is logged and usable as data for determining delay cause. Studying this communication provides a good insight into the delay causes, the sequence of events that led to a disruption and the steps that have been undertaken to resolve a disruption. Spoorweb provides the most

complete and accurate picture of individual delays, but the availability of this data is limited. Only large scale delays/disruptions are logged in Spoorweb. Approximately 5% of all delays registered by TROTS are declared by Spoorweb.

Combining data sources

Based on the three data sources that are available, a delay cause for each delay on the connecting arches at Meteren is determined. For most delays, only Monitoring and STIPT data is available to determine the cause for a delay. The following hierarchy in data sources will be used to assign delay causes:

1. When Spoorweb data is available, this data is used to declare delays, as this is considered to be the most reliable and complete source of information.
2. When Spoorweb data is unavailable, comments made by dispatchers in the Monitoring system can provide useful and reliable information. If these comments are available and applicable, they are leading in determining the cause for delays.
3. STIPT data is used to determine the cause of delays when dispatcher comments and Spoorweb data are both unavailable. Although Monitoring data is considered more reliable, the STIPT data provides more useful insights into the causes leading to train delays. For delays smaller than 3 minutes for which no clear cause is apparent, these delays will be registered as 'Minor delays'.
4. If STIPT data is unavailable, Monitoring data is used to assign delay causes.
5. When STIPT data and Monitoring data lead to clearly contradicting causes for delays, 'unknown cause' for delay will be assigned to that specific event. When data from any source is lacking, 'unknown cause' for delay will be assigned as well.

Quantitative analysis of disruptions

After delay causes are determined for each delay event, a more focussed research method is applied to some high-impact delay events. For delay events lasting more than 30 minutes, a more detailed description is given to provide more insight into the sequence of events that lead to these large delays. This analysis can only be conducted if Spoorweb data is available, as only this data source can give insight into the sequence of events leading to delays as well as the sequence of acts that are required to resolve delays.

Chapter 5. Case study 1: operational transitions on the HSL-Zuid, Betuweroute and Havenspoorlijn

In the last years, a multitude of operational transitions has appeared on the Dutch rail network. On three recently built railway lines, the HSL-Zuid high speed line between Amsterdam, Rotterdam and the Belgian border, the Betuweroute freight railway between Kijfhoek and the Zevenaar Oost and the Havenspoorlijn, connecting the Rotterdam harbour and Kijfhoek, a significant number of operational transitions are present. In this case study, the effects of the presence of these operational transitions on train operations are investigated. Furthermore, the underlying causes for transition failures are investigated. The challenges arising from these operational transitions are described as well as the measures that have been taken to increase the reliability of operational transitions by trains or decrease the consequences of failed operational transitions. Multiple interviews have been used to gather data for this case study. Appendix A gives an overview of the interviews that were conducted. In section 5.1, operational transitions at the HSL-Zuid are discussed. Section 5.2 discusses future developments for improving reliability of operational transitions at the HSL-Zuid entrances. Section 5.3 describes operational transitions at the Betuweroute and Havenspoorlijn. In section 5.4, some concluding remarks are made on the gained experience with operational transitions.

5.1 Operational transitions at the HSL-Zuid

The HSL-Zuid is part of a bigger network of high speed lines connecting major cities in western Europe (Figure 18). Amsterdam, Schiphol airport, Rotterdam and Breda are connected to the Belgium high speed network by the HSL-Zuid. The Belgium section of the HSL-Zuid is known as HSL-4, which is completed in 2009, following the completion of HSL-1 (Brussels- French border – Paris), HSL-2 (Leuven – Ans, near Liege) and HSL-3 (Liege – German border – Aachen).

The HSL-Zuid is distinctly different in comparison to the national main line network. Firstly, the power supply system of the HSL differs from normal main lines. Whereas the Dutch main line network is electrified with 1.5kV DC, the HSL is electrified with 25kV AC. Similarly, the HSL-Zuid is equipped with a different train protection system than the Dutch main line network. ATB-EG is installed on the main line network, whereas ERTMS is installed on HSL-Zuid and some other lines such as the Betuweroute. An overview of operational transition points between HSL tracks and conventional tracks is shown in Figure 19.

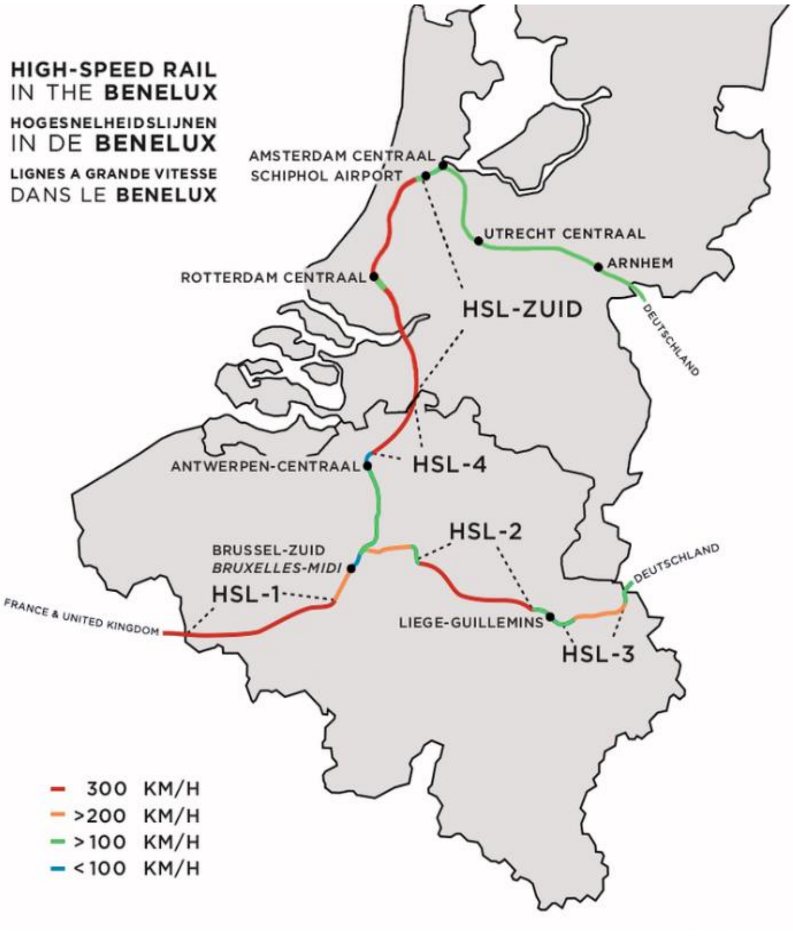


Figure 18, High Speed network of the Benelux (Georgini, 2010)

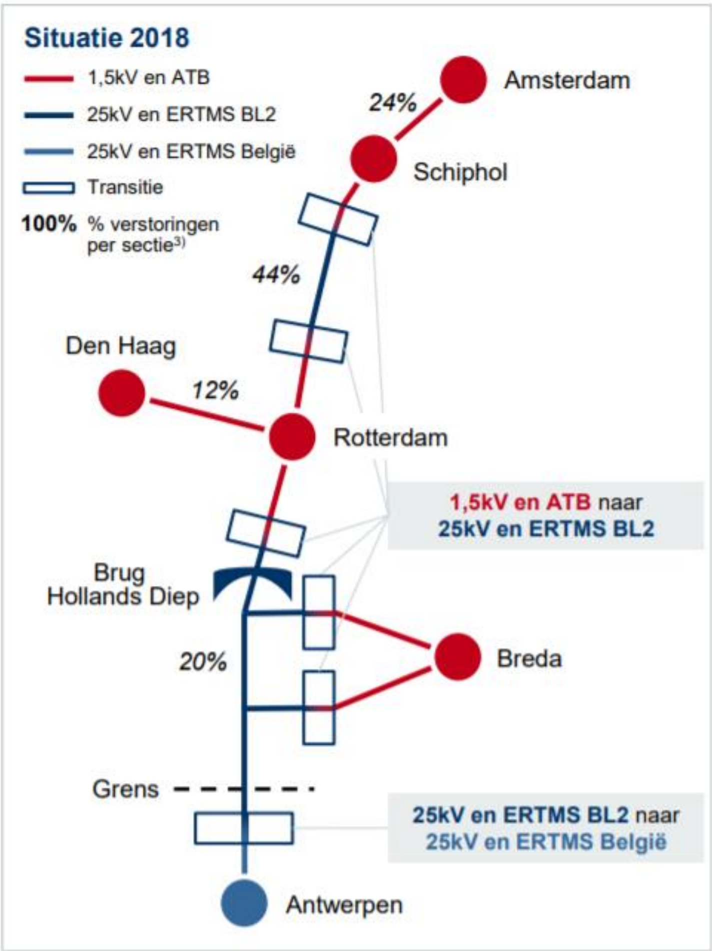


Figure 19, Operational transitions at the HSL-Zuid (ProRail & NS, 2018a). Delay frequency data was gathered between January 2016 and June 2017.

ATP system transitions at the HSL-Zuid

Since as early as 2011, the HSL-Zuid has experienced continuous problems with the ERTMS ATP system (Ministry of Infrastructure and Water management, 2014b). The main cause of these problems was a loss of contact between the on-board ETCS equipment and the Radio Block Centre (RBC). These connection losses had and still have multiple causes. On-board modems often fail and are not able to transmit or receive movement authorities (MAs) from the RBC, unsuccessful handovers between two different GSM-R cells occasionally fail and trains sometimes fail to create a connection between the on-board ETCS equipment and the RBC due to a lack of GSM-R signals (Ministry of Infrastructure and Water management (2014b). In October 2014, two measures were introduced to reduce the impact of these connection losses. Firstly, an update to the on-board ETCS unit was made, so that connection losses would not immediately result in the emergency brake application by the train. Secondly, if the on-board ETCS equipment regained connection with the RBC during an ETCS brake intervention, the brakes would be released. Both measures helped to decrease the magnitude of the impact of connection losses. A year after implementation of these changes, the number of trains that came to a halt as a consequence of connection problems was halved (Ministry of Infrastructure and Water Management, 2015). The result of the second measure, however, was limited. Although braking is terminated when connection with the RBC was regained, in practice, connection was only regained after the disconnected train had come to a complete stop (Ministry of Infrastructure and Water Management, 2016a; Appendix C).

Different causes have been found for connection failures between the on-board ETCS unit and the RBC. In the first half of 2016, almost half of all connection losses were caused by faults in the modems of the train, most of which could be attributed to one individual locomotive. A quarter of all connection losses were caused by a bad quality connection with the RBC. 15% was caused by interfering signals due to a temporarily placed antenna near Barendrecht station. Finally, 6% of all connection failures was caused by a failed connection to the RBC during an operational transition from ATB to ERTMS. While the number of connection failures at operational transitions is limited in comparison to other parts of the HSL, this still means that once or twice a month, a train fails to connect to the RBC via GSM-R during an operational transition (Ministry of Infrastructure and Water Management, 2016b).

Power supply system transitions at the HSL-Zuid

Apart from connection issues between the on-board ETCS equipment and the RBC, operational transitions in power supply system increase the vulnerability of the HSL. Whereas the main line network is electrified with 1.5kV DC, the HSL is electrified with 25kV AC. As these systems are incompatible, transitions have to be created in order to allow multi-system trains to drive under both power supply systems. Two neutral sections, with a total length of approximately 600 meters, separate both systems (ProRail, 2014). When passing a power supply transition, the train driver has to lower the pantograph well in advance of the start of the neutral section. Trackside markers indicate the point where the pantograph has to be lowered. If the driver fails to do this and enters the first neutral section with his pantograph up, the system is short circuited and turned off to prevent damage to the rest of the power supply system. As there is no power for the train, the train coasts to a complete stop (Ministry of Infrastructure and Water Management, 2018a).

Occasionally, the train driver raises the pantographs too soon and creates a short circuit. Short term measures have been taken to reduce the downtime of the system after a short circuit. Power supply transitions are now being monitored with cameras, which decreases the required time to detect a failure. As a result, the downtime of power supply transitions has been reduced from 72 minutes to 13 minutes (Ministry of Infrastructure and Water Management, 2019a).

Transition failures at the HSL-Zuid

As a result of the current configuration of the HSL-entrances, where ATP system transitions and power supply system transitions occur nearly simultaneously, the long neutral sections of the power supply system create the biggest risk for long disruptions in train service. When the neutral sections are passed with a sufficiently high speed and the train brake is not applied just in front of or in the neutral section, the risk of a stranded train in the neutral sections is very limited. Only when a train cannot pass the neutral sections with sufficient speed, does a significant risks of train strandings appear. There are multiple causes why trains are not able to pass the neutral sections with sufficient speed.

One of the causes why a train is not able to pass the neutral sections with sufficient speed is when no connection with the RBC has been established. The on-board ETCS unit will apply the emergency brake as long as no connection has been established with the RBC. As stated earlier in this section, a connection is often only established when the train has come to a complete stop, which often happens to be in one of the neutral sections of the power supply system transition.

Another cause for trains being unable to pass the neutral section with limited speed is the fly-over on top of which the neutral sections at Zevenbergschen Hoek and at Hoofddorp are located. When a train passes the fly-over with traction switched off and pantographs down, the train will lose some of its momentum when climbing the upward slope of the fly-over. Due to the presence of the upward slope, the minimum speed for passing the neutral section is increased to 40 km/h, while the normal minimum design speed for power supply system transitions is 15 km/h (ProRail, 2014).

Apart from connection failures and the location of the neutral section on top of a fly-over, the risk of strandings is also increased when there is no free train path unto the HSL. When the track is blocked by another train, trains entering the HSL at Zevenbergschen Hoek will have to wait until a free train path is available. The waiting point for these trains is at a ETCS Level 1 balise, which is indicated with an SMB with a light. When a new MA is available, the SMB light will light up to inform the train driver of the new MA. The location of this SMB is right in front of the upward slope of the fly-over and just a couple hundreds of meter prior to the start of the neutral section. Trains therefore have a limited amount of space to get the train up to speed in order to coast through the neutral sections. Often, the speed with which trains enter the neutral sections is barely enough to let the train coast to the 25kV area. Train drivers who are aware of this often wait well in advance until a new MA is available, giving them sufficient space to get the train up to speed. This does however mean that the rear end of the train is blocking the Breda – Dordrecht railway line (Appendix F).

Finally, train characteristics influence the risk of a train stranding in the neutral sections. Most trains on the HSL are operated by TRAXX MS2 locomotives. When approaching the power supply transition point, the locomotive passes a balise that informs the train of the upcoming power supply system transition. The train driver can lower the pantograph manually, but when he or she does not do that, the train will lower the pantograph automatically. This happens 17 seconds after the train passed the balise. TRAXX-locomotives are programmed this way. At regular train speed, this means that the pantograph is lowered just in front of the neutral section. But when the train is running at a reduced speed, because another train has been blocking the track, the locations where the pantograph of the locomotive is lowered and where the neutral section begins are far apart, increasing the distance that the train is coasting even more. Furthermore, it means that trains that are accelerating, after being held in front of the aforementioned SMB, are not only limited by the short distance until the neutral section, but also by the amount of time until the pantograph is automatically lowered (Appendix L).

In the current situation with near simultaneous transitions, trains that fail to connect to the RBC at the entrance to the HSL will often come to a complete stop in one of the neutral sections of the power supply system transitions, which means that the train cannot move until power is applied to these sections (ProRail, 2019b). At Zevenbergschen Hoek, the power supply system transition point is located on top of a fly-over, which increases the probability of stranded trains in the power supply transition even further. In the new situation, trains that fail to connect to the RBC will stop well in front of the neutral sections. After a connecting to the RBC has successfully been made, the train can accelerate to the minimum required speed of 40 km/h to pass a power supply transition point (ProRail, 2014).

These four factors all contribute to the risk of trains ending up stranded in the neutral sections of the power supply system transition of the HSL. Not all factors have the same importance at the various entrances to the HSL. The only locations with significant upward slopes are Zevenbergschen Hoek and Hoofddorp. Furthermore, trains can only be blocked by other trains at the HSL-entrances at Zevenbergschen Hoek and at Breda. To conclude this section, neutral sections by themselves do not have to cause vulnerability in train operations, providing trains can pass them with sufficient speed. Similarly, connection failures with the RBC during an ATP system transition by themselves do not lead to large disruptions. The combination of these two transitions with upward slopes and sometimes with conflicting traffic and suboptimal train characteristics, however, make some of the HSL-entrances especially vulnerable to disruptions.

5.2 Improving operational transitions at the HSL-Zuid

Several smaller measures have been taken in recent years to limit the impact of failed transitions on the HSL. As stated in section 5.1, cameras are now used to detect failures earlier. Another measure that has been taken is to relocate the headquarters of the maintenance and repair crew of the HSL-Zuid closer to the HSL-Zuid itself, reducing the time until crew can be at the right site considerably. With these methods, the impact of failures can be reduced considerably (Appendix B).

Some measures have also been taken to reduce the number of failures during transitions and on the HSL-Zuid in general. The connectivity of GSM-R at some locations was quite poor. At these locations, additional antennas have been installed to improve the GSM-R signal and fix 'radioholes' (Appendix F, Appendix I). At the Dutch/Belgian border, trains have to transfer from the Dutch RBC to the Belgian RBC. Due to the fact that these RBCs are constructed slightly differently, the handover of trains between two RBCs regularly failed. This problem has since been solved by equipping both RBCs with a gateway to ‘translate’ incoming signals from the other RBC, thereby preventing communication errors (Appendix D). Improvements have also been made to the rolling stock. Each locomotive is now equipped with two modems, rather than one. If one of the modems fails, the other modem can retain a connection with the RBC (Appendix H). Several software updates have also been performed on the TRAXX locomotives to eliminate bugs and to improve reliability (Appendix H).

Although several improvements have been made to the HSL, the train service performance remains low. The punctuality of trains on the HSL-Zuid remains a lot lower in comparison to trains on the main line network (HRN). In 2018 and 2019, 82,5% and 83,4% respectively of all trains on the HSL ran on time. In comparison, In 2018 and 2019, approximately 92% of all trains on the HRN arrived on time (NS, 05-12-2019). While these measures have been able to reduce the number of transition failures somewhat and reduce the impact of these disruptions, large increases in train service reliability are only expected when large, structural changes are made to the infrastructure layout of the operational transitions themselves (Appendix C, Appendix E, Appendix H, Appendix L).

Measures could be taken in the next five years to reduce the number of failed operational transitions of power supply system (ProRail & NS, 2016) even further. The two most vulnerable transition points, at Hoofddorp and at Zevenbergschen Hoek would in this case be redesigned. The most notable change to the operational transitions is that more physical separation will be created between the operational transition point of power supply system and the transition point of ATP system. Whereas the train driver currently has to perform both transitions nearly simultaneously, these transitions will be performed sequentially in the new situation (ProRail & NS, 2018a). In doing so, trains that are unable to connect with the RBC when transitioning from ATB-EG to ERTMS will not come to a stop in a neutral section, but well in advance of the neutral section, allowing the stopped train to gain sufficient speed again to pass the neutral section.

In the more distant future, ETCS will replace ATB-EG on the entire railway network, potentially eliminating all types of ATP system transitions. In 2050, all railway lines are planned to be equipped with ETCS, both on the main line network and on secondary lines. Between 2026 and 2030, the first six main lines will be equipped with ETCS, which includes all HSL-connections to the rest of the main line network (Ministry of Infrastructure and Water Management, 2018b). ATB-EG to ETCS transitions will therefore be eliminated. The main line network is expected to be equipped with ERTMS level 2, baseline 3.6.0 (Ministry of Infrastructure and Water Management, 2018b). In theory, this means that trains, equipped with ERTMS level 2 baseline 3.6.0 can operate on the HSL, which is equipped with ERTMS level 2 baseline 2.3.0c. One of the basic principles of ERTMS is downward compatibility, which means that trains with higher ERTMS levels or baselines can operate under lower levels and baselines. However, transitioning between two different baselines can be problematic in practice, as the HSL is equipped with a non-standard ETCS version.

The European Union Agency for Railways (ERA) is responsible for creating the specifications for standard ERTMS equipment. These specifications are described in subsets, in which the functionalities of all ERTMS-components are described. The standard and finalised specification for ERTMS baseline 2 is known is 2.3.0d (ERA, 2006). The ERTMS equipment on the HSL-Zuid, however, is non-standard. This version of ERTMS level 2 is referred to as baseline 2.3.0c. As the HSL-Zuid ERTMS baseline is non-standard, no specifications have been made by ERA that specify how transitions between ERTMS baseline 3.6.0 and ERTMS baseline 2.3.0c should be designed.

It is therefore expected that no seamless transition between the RBCs of the two ERTMS baselines (2.3.0c and 3.6.0) can be established without any adaptations to the existing system or the new system.

Both RBCs are equipped with different (generations of) software and the supplier of the RBC on the HSL (Siemens) may not build the RBCs for the main line network.

These two problems have led the ERTMS programme, an overarching organisation entrusted by the ministry of Infrastructure and Water management to coordinate the implementation of ERTMS on the Dutch main line network, among other tasks, to propose solutions for this problem. Five designs for operational transitions between main line network and HSL have been created (Van Es, 2020; Programma ERTMS, 2020; Appendix D). The first three designs will create a seamless transition between the main line network and HSL The last two designs will result in a two-stage transition or double transition at the HSL-entrances. The main principles of all five design solutions will be explained.

Solution 1: RBC – RBC gateway

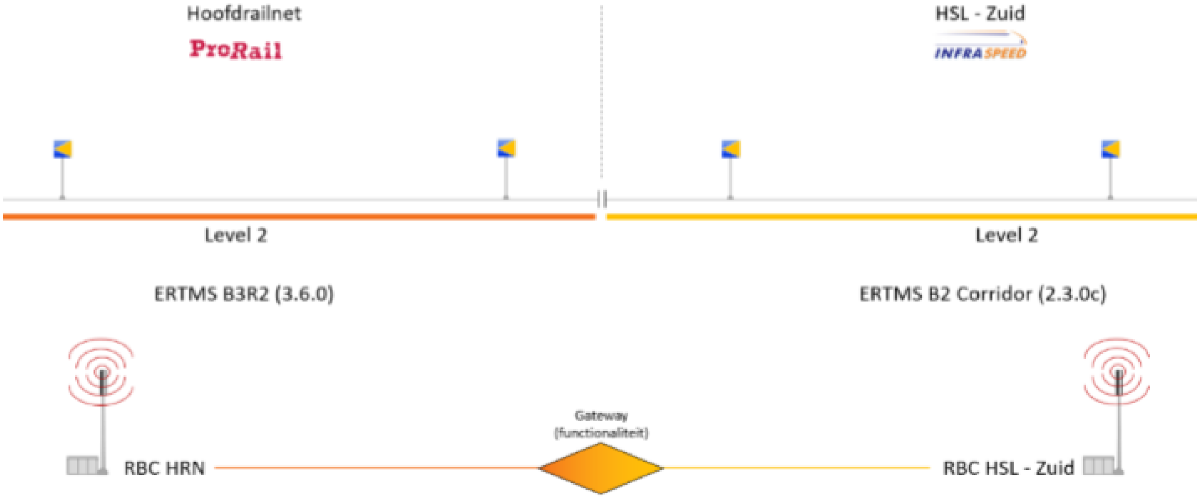


Figure 20 solution 1: RBC-RBC gateway

Both ERTMS versions will be adjacent to each other in this solution (Figure 20). Signals between the two RBCs are translated by a gateway, similar to the gateway used on the Belgian/Dutch border. No design for such a gateway is currently available. If no gateway can be constructed, this design is infeasible.

Solution 2: Renew ERTMS on the HSL

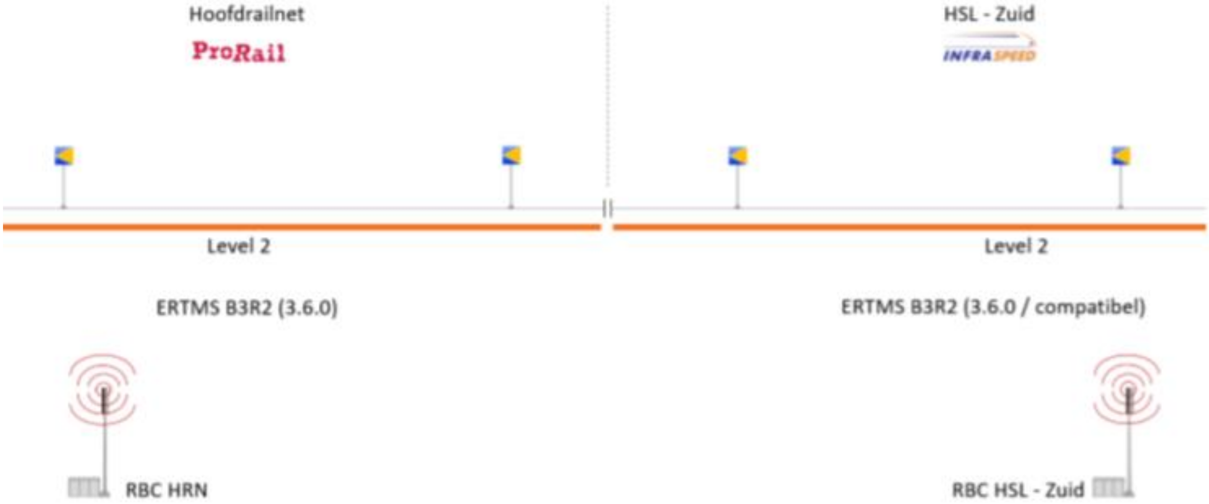


Figure 21, solution 2: ERTMS baseline 3.6.0 retrofit on the HSL

In this solution, ERTMS level 2 version 3.6.0 is retrofitted on the HSL-corridor (Figure 21). As the software versions are similar, the RBC handover between main line network and HSL will function just as any other RBC handover: seamless. This solution requires extensive and expensive retrofitting of ERTMS level 2 version 3.6.0, which will require new balises and a new RBC to be constructed according to SRS 3.6.0 (Appendix D).

Solution 3: HSL and main line network use the same RBC

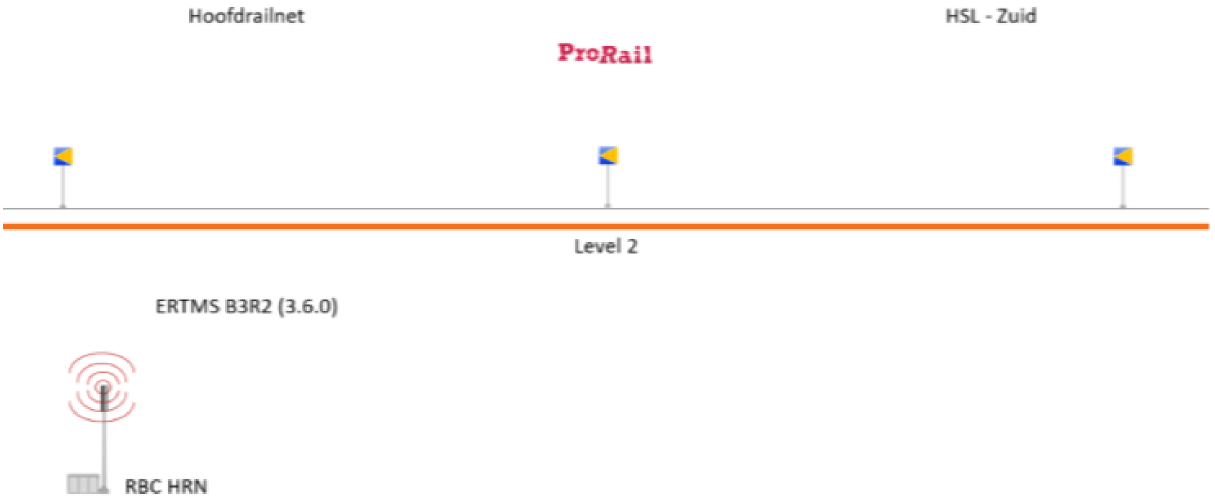


Figure 22, solution 3: RBC integration of HSL

The RBCs used for the main line network could also be used to serve trains on the HSL-corridor (Figure 22). In this case, the number of RBC handovers would significantly be reduced. Similar to solution two, the HSL and the main line network will be equipped with ERTMS level 2 baseline 3.6.0.

Solution 1, 2 and 3 are only viable options in case a suitable solution can be found for a baseline 2.3.0c to baseline 3.6.0 transition, or a large investment is made in retrofitting the entire HSL with a new ERTMS version. In case neither of these conditions will be met, operational transitions in ATP system will remain an intensive process, with a lot of involvement of train drivers.

Solution 4: ATB-island

Figure 23, solution 4: ATB-island

In this solution, the currently existing transitions between the main line network and the HSL will remain unchanged (Figure 23). The operational transition between ATB-EG and ERTMS baseline 2.3.0c, which at this moment is a cause for disruptions due to bad connections with the RBC will remain in place. In addition, an operational transition between ATB-EG and ERTMS baseline 3.6.0 will be constructed. Trains entering the HSL will therefore be faced with two operational transitions of train protection system in a short distance and in a limited time span.

Solution 5: ERTMS level 1-island

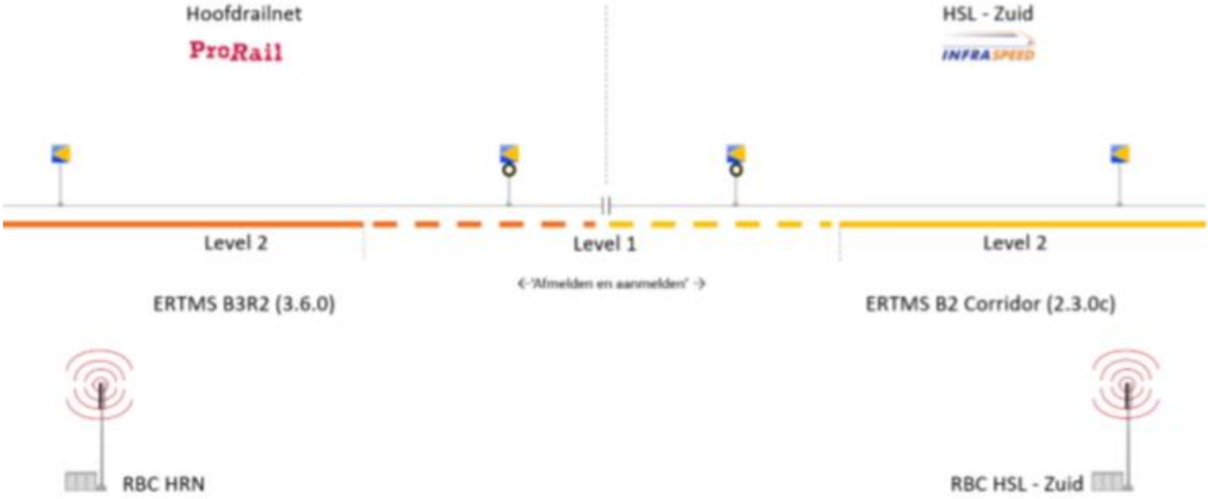


Figure 24, solution 5: ERTMS level 1-island

In the current situation, trains transitioning from ATB-EG to ERTMS level 2 on the HSL first transition to ERTMS level 1 for a short section. In ERTMS level 1, movement authorities are still given by lineside (active) balises, instead of via the RBC. The fifth solution basically mirrors the current situation by creating an ERTMS level 1 island (Figure 24). As level 1 does not use RBCs to provide movement authorities to trains, no direct RBC to RBC transition is necessary. In contrast to the ATB-island, transitions between ERTMS level 2 and level 1 are automatic transitions, which means that no further action is required by the train driver to accomplish this transition.

Which solution will be chosen depends largely on technical feasibility and the availability of financial resources. Solution 1, the RBC gateway is the preferred alternative, as it would eliminate ATP system transitions completely. The technical feasibility of such a gateway remains, however, unproven. Solution 2 and 3 also eliminate ATP system transitions completely. Furthermore, these solutions are technically feasible. Replacing ETCS on the entire HSL-Zuid is, however, a very costly step, which might render these solutions politically infeasible. Solution 4 is technically and financially feasible, but from an operational perspective, this solution is completely undesirable, as it would expand a vulnerable transition (ATB-EG to ERTMS baseline 2.3.0c) with an also vulnerable transition from ATB-EG to ERTMS baseline 3.6.0. Furthermore, it would mean that the aging ATB-EG system would have to remain in operation for a longer period of time. The fifth and final is a good alternative when solution 1 is technically infeasible and solution 2 and 3 are deemed too expensive. The risk of a RBC connection failures remains, but is greatly reduced in comparison to solution 4. Furthermore, no human actions are required in transitions from ETCS level 1 to level 2 and vice versa.

5.3 Operational transitions at the Betuweroute and Havenspoorlijn

The initial plans for a dedicated freight railway between the harbour of Rotterdam and the German hinterland was made by NS in the late 1980s. NS first mentioned the Betuweroute in its ambitious 'Rail 21' modernisation plan. The plan was first mentioned by the ministry of Transport and Water management (V&W) and the ministry of Public Housing, Spatial Planning and Environment (VROM) in 1989/1990 as part of its long-term agenda (Tweede Kamer, 1990). A direct rail link between these areas would increase the competitiveness of the Rotterdam harbour in comparison to its direct rivals, like Antwerp, Zeebrugge and Hamburg. Faster transit times would also increase the competitive position of rail transport in comparison to road and barge transport. Finally, more track capacity could be used for passenger trains on the existing network, as most freight train would use the new link (Eerste Kamer, 1994; Tweede Kamer, 1995).

Construction of the Betuweroute started in 1998. Commercial service was originally planned to start in 2000, but due to multiple delays, the official opening was set back until 2007. In June 2007, the first commercial trains started using the Betuweroute. Initially, only diesel locomotives were used on the line. From November 2007 onwards, electric traction could also be used.

While the Betuweroute connects Kijfhoek shunting yard to the German border (Figure 25), the Havenspoorlijn connects the Maasvlakte and all other areas in the Rotterdam harbour to Kijfhoek as

Figure 25, Betuweroute trajectory (Openstreetmap, 2010a)

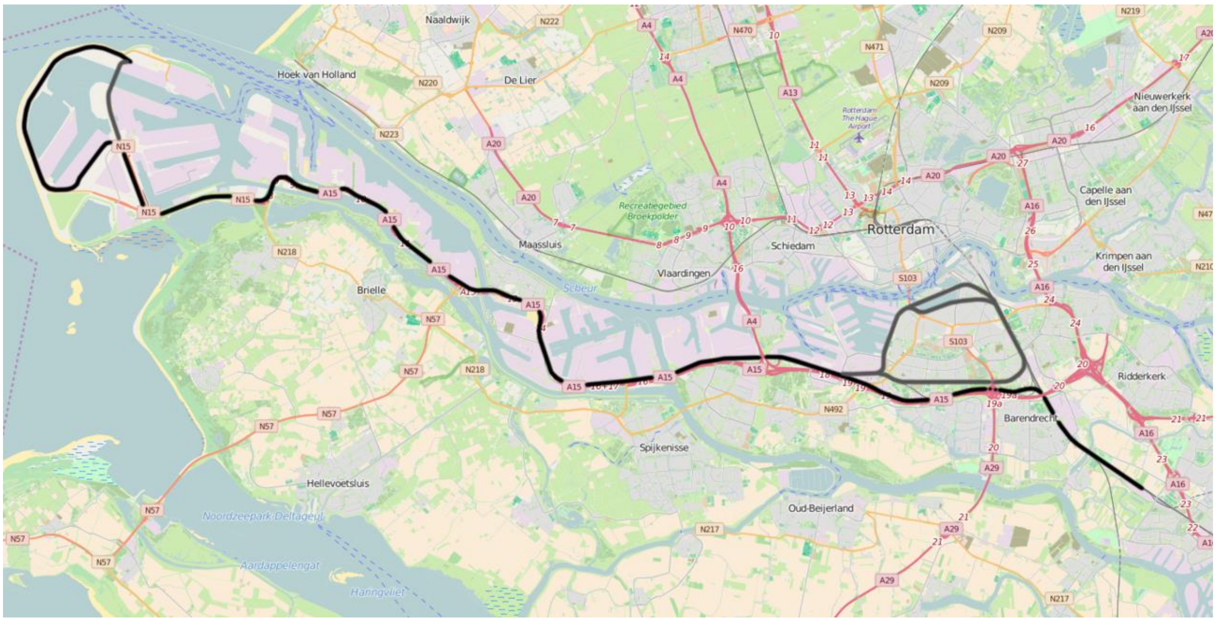


Figure 26 Havenspoorlijn trajectory (Openstreetmap, 2010b)

well. Whereas the Betuweroute is completely new, the Havenspoorlijn used parts of an already existing railway (Figure 26).

Multiple design changes have been made to the Betuweroute and Havenspoorlijn during the design process. Originally, both would be equipped with 1,5kV, similar to the main line network of NS. ATB-NG would be used as ATP system. A high-voltage AC system, however, proved to be more suitable for freight train operations as more power could be provided to a train via the catenary. Furthermore, as ATB-NG had not been fully developed yet and further development of the system was forbidden in favour of the development of ERTMS by the EU, it was decided to electrify the Betuweroute with 25kV AC and to install ERTMS level 2 as train protection system (Robertson Associates, 2003; Appendix E). Originally, ETCS baseline 2.2.2 was used on the Betuweroute (Keyrail, 2012), but as this version was not finalised and contained some flaws (Stoop & Dekker, 2008), the infrastructure has been upgraded to the standards of baseline 2.3.0d (Ministry of Infrastructure and Water management, 2014), the current ERA-standard for ERTMS baseline 2.

Tunnels in the Betuweroute and Havenspoorlijn

After regular train operations started in 2007, three tunnels on the Betuweroute and Havenspoorlijn proved to be a major cause for disruptions in daily operations. (Appendix E & G). The Botlek tunnel on the Havenspoorlijn was the biggest cause for disruptions in train operations (Appendix G). Both tunnel ends have long and steep gradients. Freight trains entering the tunnel gain a lot of speed on the downward slope and loose speed on the upward slope. In order to prevent overspeed at the bottom of the tunnel, signs with advisory speed limits were placed in front of both tunnel ends. In practice, train drivers did not always adhere to these advised maximum speeds. As a consequence, trains would overspeed at the bottom of the tunnel and the on-board ERTMS equipment activated the emergency brake. Once a train was halted in the tunnel, restarting a freight train was very difficult, due to the steep tunnel end inclines. Assistance in the form of other locomotives is often needed to remove the train out of the tunnel. Obviously, this caused a lot of delays to other trains as well (Appendix G).

Apart from the Botlek tunnel, the Sophia tunnel, near Kijfhoek, is prone to the stranding of freight trains. The 1.5kV-25kV transition is located on the bottom of the Sophia tunnel. The announcement of the power supply transition is indicted with a sign approximately 400 meter prior to the actual transition. 150 meter after the neutral section, which is 30 meters long, the train driver may raise the pantograph (Arcadis, 2014). In practice, however, the driver will shut of traction in advance of the pantograph-down sign, which means that the train is travelling unpowered for over 1 kilometre (Appendix E). After the power supply system transition, the train has to climb out of the tunnel. The maximum gradient on this section toward Kijfhoek is 1:45 (or 22.2‰) (Movares, 2013). In some cases, train coast unpowered through the tunnel for even longer distances. One type of locomotive, the Siemens Vectron, is regularly used on the Betuweroute. When a power supply transition is coming up, the pantograph of the locomotive is lowered by the train driver. Before the pantograph for the other power supply system can be raised again, the system performs a set of checks. These checks last more than 2 minutes. As a consequence, freight trains headed by a Vectron locomotive coast unpowered for more than 2 minutes (Appendix M), even though the neutral sections are only 30 meters long.

The exit of the Sophia tunnel directly connects to the Kijfhoek shunting yard. As there are a lot of movement of other trains, the probability of encountering the end of the MA is significant due to conflicting train paths. The ETCS braking curve will force the train driver to slow down in the Sophia tunnel, even though the train may not retain enough speed to make it to the end of the tunnel. As stated in section 3.2.2, braking curves are calculated based on multiple parameter types, including track alignment, train characteristics and national values. The calculated braking curve is relatively flat in comparison to the normal braking curve of a freight train, although braking curves are calculated with a relatively high deceleration rate in the Netherlands in comparison to other countries (Appendix B, Appendix L). Differences in braking curve calculations can be attributed to differences in ETCS national values (section 3.2.2).

As a result of the relatively flat braking curve, the train driver has to start braking earlier than he or she would do when driving under ATB-EG. The restrictive ETCS braking curve in combination with the difficulty of braking a freight train (see Box 5.3.1) lead to situations in which a freight train ends up stranded on the upward gradient of the Sophia tunnel. Most freight locomotives lack the tractive effort or the adhesive weight to restart a train on these steep inclines (Appendix E). When the load of a stranded freight train exceeded 1200 tons, extra locomotives to assist the train up the gradients were almost always required (Appendix G). The ProRail dispatching centre at Kijfhoek has the authority to seize locomotives from any railway undertaking to assist in this operation.

Over the years, dispatchers gained more experience with removing stranded trains form the Sophia tunnel and more standardised solutions were being developed. Based on the exact position of the freight train in the tunnel and the weight of the train, a standardised solution was used, in which one or multiple locomotive would either be attached to the front or the rear end of the train (Appendix G).

At the eastern end of the Betuweroute, the Betuweroute connects to the Arnhem – Emmerich railway line at Zevenaar Oost. This junction is preceded by a tunnel with steep gradients at either end of the tunnel. At Zevenaar Oost, a transition from ERTMS level 2 to ATB-EG takes place just in front of the junction with the Arnhem – Emmerich railway line. Similar to the Sophia tunnel, restrictive braking curves could cause trains to come to a premature stop on the upward slope of the tunnel exit. After the implementation of ERTMS level 2 and 25kV on the rail section between Zevenaar Oost and the German border, the number of failures of this location has decreased considerably (Appendix G).

Box 5.3.1 Braking with pneumatic brakes (Appendix F & Appendix N)

In order to successfully drive a (heavy) freight train through the Sophia tunnel, entering the tunnel at the right entry speed is important. Freight trains are in general equipped with an pneumatic braking system (Railway-Technical, n.d.). One continuous brake pipe connects the master brake cylinder of the locomotive to the brake pads of all individual wagons. When driving at constant speed, the brakes are loose and the pressure in the brake system is 5.0 bar (Appendix F). When the driver applies the brakes, the pressure in the brake pipe starts to drop and the brake pads are applied to the wheels. This is a slow process. It takes some time before the last brake pad at the end is applied. Similarly, releasing the brakes is a lengthy process, as it takes some time before the pressure in the entire brake pipe is stable at 5 bar again. In order to prevent large differences in brake pressure between individual wagons, the train driver cannot release the brake at any moment. The braking process has to be ‘completed’ before the brakes can be released. This can lead to ‘overbraking’ (Appendix F), a situation in which the train loses more speed than the train driver planned. A further elaboration on braking systems is provided in Appendix N.

Route setting delays

The Betuweroute and Havenspoorlijn are controlled by dispatchers from the dispatching centre at Kijfhoek. Trains leaving the Betuweroute or Havenspoorlijn therefore require a train path between the control areas (PPLGs) of two dispatching centres. When a train is running roughly on time (norms can vary per dispatching centre and per PPLG), train paths are automatically provided by ARI (see also section 3.2.5). When trains are running outside the ARI-margins, either too early or too late, a train path has to be set manually by a dispatcher (ProRail, 2019e). Manual route setting leads to extra work for dispatchers. When dispatchers are occupied with other tasks, a train path is not always set in time for an approaching train. As a result trains entering or leaving the Betuweroute are forced to slow down as they encounter yellow and red signals or approach their end of authority (EoA). As dispatching centre handovers are often combined with power supply system transitions at the Betuweroute (section 3.2.1), trains require a minimum speed to pass the neutral section between both power supply systems. Disruptions as a result of underspeed, caused by the absence of a continuous train path into the next dispatching centre-controlled area, regularly lead to disruptions at the entrances of the Betuweroute (Appendix G). Route setting issues not only occur when trains are handed over from one dispatching centre to another. Delayed route setting can also occur when trains are transferred between PPLGs of different dispatchers within the same dispatching centre. In Box 5.3.2, a description is given of delayed route setting at the connection of the Betuweroute and Kijfhoek.

Box 5.3.2 route setting at Kijfhoek (Appendix M)

Interlocking systems prevent that conflicting train paths can be set by dispatchers. Different interlocking systems are applied in the Netherlands. At Kijfhoek shunting yard, VPI or 'Vital Processor Interlocking' by Siemens is used. The Betuweroute is equipped with EBS or 'Elektronische Beveiliging SIMIS' by Alstom. Both systems have different operating rules. With VPI, the next train path can only be set by a dispatcher when the first track section is occupied by the train. With EBS, it is possible to set a train path without the train having to be present on the first track section of the train path. The location where EBS and VPI meet coincides with an ATP system transition from ERTMS L2 to ERTMS L1, which means that a MA can only be granted to a train when passing an active balise. The combination of ATP system transitions and a change in interlocking system means that trains entering Kijfhoek from the Betuweroute will near their EoA and the braking curve will force the train speed down. This all occurs on the upward slope of the Sophia tunnel end. As a result, trains frequently strand on the upward slope of the Sophia tunnel.

Transition failures at the Betuweroute and Havenspoorlijn

On the Betuweroute and Havenspoorlijn, steep inclines (mainly at tunnels) fulfil a similar function that the neutral sections of power supply system transitions fulfil at the HSL-Zuid. In both cases, trains are 'trapped' when tunnels and neutral sections are not passed with the right speed. The neutral sections of power supply systems at the Betuweroute are much shorter than the neutral sections on the HSL-Zuid (approximately 30 meter rather than 600 meter), reducing the risk of trains getting stranded in the neutral sections. However, similar to the HSL-Zuid, neutral sections are often build close to changes in the vertical track alignment. Also similar to the HSL, train characteristics can greatly influence the risk of a train ending up stranded, as exemplified by the Vectron locomotive example.

When a route is not set in time by a dispatcher or the track ahead is blocked by other trains, this has a large impact on the train speed of freight trains. Due to the braking characteristics of freight trains (Box 5.3.1), a freight train will lose a considerable amount of speed even after a short brake application. Near junctions with other railway lines and near dispatching centre handovers, the probability of delayed route setting increases. When these points coincide with either upward slopes, neutral sections or both (as is the case at Kijfhoek, Meteren and Zevenaar), dispatching centre handovers can contribute to trains ending up stranded in tunnels and neutral sections. At Kijfhoek, setting a route on time is made more difficult by the fact that two interlocking systems meet there (Box 5.3.2).

Similar to the HSL-Zuid, a failure to create a connection with the RBC, either through a failing modem, by an unstable connection via GSM-R or other causes, can lead to trains ending up stranded in neutral sections or getting stuck on upward slopes.

5.4 Conclusions on operational transitions at the HSL-Zuid, Betuweroute and Havenspoorlijn

To conclude this chapter, the operational transitions that were studied in this chapter all contribute to some extent to the occurrence of delays. Track sections with (a combination of) operational transitions show a more frequent occurrence of delays and disruptions than track sections without any transitions. Several conclusions can be drawn.

Firstly, ATP system transition failures happen during transitions as well as during 'normal' operations. A failed or unreliable connection between on-board ETCS unit and RBC is the main cause for these transition failures. Most connecting losses occur due to malfunctioning modems inside the train. The number of connection losses during transitions from ATB-EG to ERTMS l2 is limited, compared to other causes for connection losses. However, the consequences of connection failures with the RBC during a transition are, larger due to the presence of other transitions, such as power supply transitions and upward slopes. When disconnected trains come to a stop in a neutral section or on an upward slope, this leads to long delays as the train is unable to move under its own power.

Secondly, delays in route setting can force trains to slow down when encountering yellow and red signals or when nearing the EoA. Delayed route setting can occur when ARI is not active, for instance when trains have deviated too much from their time schedule. Similar to RBC connection failures, delayed route setting can lead to trains being forced to slow down at undesirable locations, such as near neutral sections or on upward slopes.

Thirdly, steep gradients and neutral sections should be passed with sufficient speed by trains. When the train speed is too low, trains are not able to pass steep gradients and neutral sections and end up getting stranded. For freight trains, steep gradients are a larger obstacle than for passenger trains, due to the larger weight of freight trains. When freight trains enter tunnels too slow, they may not make it to the other side of the tunnel. When freight trains enter tunnels too fast, they will overspeed at the bottom of the tunnel. When overspeeding, ETCS will intervene and apply the train brake, making the freight train stop in the tunnel. Failures in ATP system transitions, delayed route setting, trains having to slow down or wait for other trains lead to trains slowing down or even stopping; when these events occur near upward slopes or near neutral sections, the probability of a train stranding on these upward slopes or in neutral sections increase significantly.

Fourthly, train characteristics can contribute to transition failures. Freight trains in general accelerate slowly and are equipped with slow-acting brakes. This creates difficulties when fast acceleration and deceleration are required. But there are also locomotive type-specific characteristics that increase the probability of a transition failure. In these cases, locomotive characteristics and infrastructure features do not match up, leading to problems in daily operations.

Fifthly, reducing the frequency of disruptions seems more difficult than reducing the severity of delays. Most measures that have been taken to reduce the hindrance of operational transitions are focussed on reducing the length of disruptions. This is most likely caused by the fact that major improvements would have to be made to reduce the disruption frequency, as has been described in section 5.2. Reducing the disruption frequency often requires major infrastructural changes that are expensive and time-consuming.

Chapter 6. Case study 2: Meteren junction

In chapter 6, a case study on Meteren junction is conducted. In chapter 3, a wide range of operational transitions has been identified and located. The aim of this chapter is to zoom in on one of these locations and to analyse the role of operational transitions in railway operations reliability. The case study methodology has been described in chapter 4. The Meteren case is described in more detail in section 6.1. In section 6.2, it will be investigated to what extent delays emerge from track sections with operational transitions. TROTS sections will be used in this analysis. In section 6.3, TROTS subsections with a relatively high amount of delays will be studied in more detail. These sections will also be studied on TROTS subsection level. The primary causes for delay will be investigated in section 6.4. Furthermore, the complexity of some larger delays will be studied. Finally, in section 6.5, concluding remarks will be made.

6.1 Description of Meteren junction

In this section, the current configuration of Meteren junction is described in subsection 6.1.1. Traffic flows at Meteren junctions are discussed in subsection 6.1.2. In subsection 6.1.3, future developments at Meteren are discussed, such as a new connecting arch.

6.1.1 Current infrastructure

The Betuweroute and the railway line Utrecht – Den Bosch cross each other just southwest of Meteren (see Figure 27). The Betuweroute passes over the A2-corridor with a bridge. On the western side of this bridge, the Betuweroute is built on a raised embankment, as the Betuweroute crosses the A2 highway 2 kilometres further westward with a bridge. On the eastern side of the bridge over the Utrecht – Den Bosch railway line, the Betuweroute slopes down with a gradient of approximately 10‰. On this sloping track section, multiple connecting arches have been built. The railway junction at Meteren allows the exchange of trains between the A2-corridor and the Betuweroute in eastern direction.

The southern connecting arch is double tracked. Westward trains on the Betuweroute heading in the direction of Den Bosch have to cross oncoming traffic on the Betuweroute and on the A2-corridor. A waiting track is therefore present in advance of the junction that can be used by trains in the direction of both Utrecht and Den Bosch. The connecting arch has a short section with a gradient of 10‰. This short, steep section is necessary as to southern connecting arch crosses the A15 highway with a tunnel. The transition from 1.5kV to 25kV also takes place in this tunnel (Appendix O.2). A short neutral section of 30 meter separates the two power supply systems. The transitions from ATB-EG to ERTMS level 2 and vice versa are located closer to the A2-corridor. In Figure 27, the ATB to ERTMS transition is indicated as a single point, but in reality, the transition between both systems starts well in advance of this point. Multiple eurobalises are built on the Utrecht – Den Bosch railway line that are used to establish contact with the RBC and provide an initial movement authority for trains entering the Betuweroute from either side of the junction (Appendix O.1).

In the northern direction, two separate connecting arches have been built. Trains leaving the Betuweroute in the direction of Utrecht use a conventional connecting arch to drive up to the A2-corridor. This connecting arch is relatively flat, in contrast to all other connecting arches. The 25kV to 1.5kV transition is located approximately 500 meter in advance of the switch that connects the Betuweroute to the A2-corridor (Appendix O.2). A 30 meter long neutral section separates the 25kV area from the 1.5kV area The ERTMS EoA is located approximately 200 meter in advance of the switch leading onto the A2-corridor. At this point, the transition to ATB-EG is made.

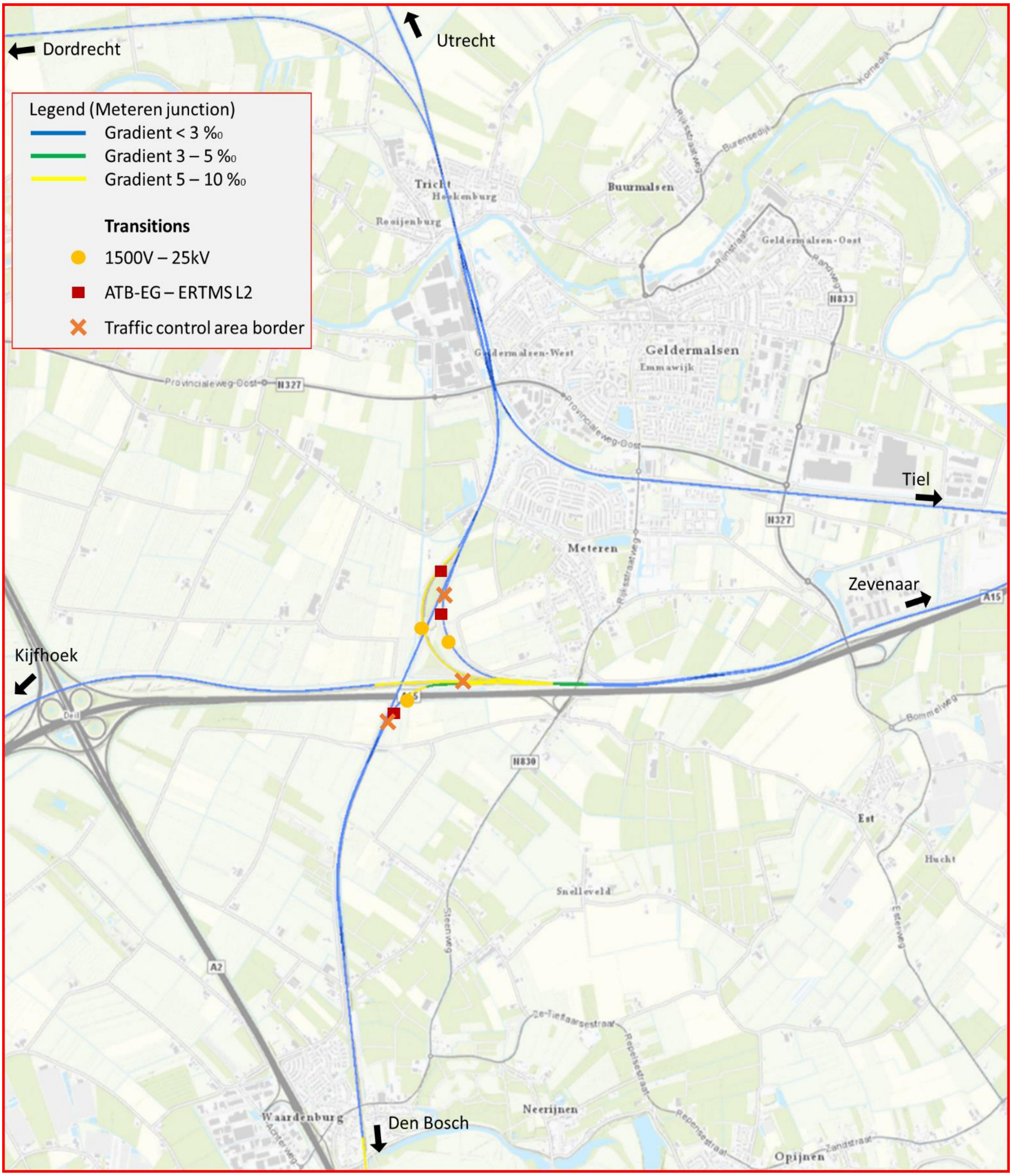


Figure 27 Operational transitions at Meteren junction

In the opposite direction (Utrecht → Zevenaar), trains use a fly-over, built to cross the A2-corridor at a separated level. This fly-over peaks in height at the crossing with the A2-corridor. The slopes at either side of the fly-over have a gradient of 10‰. The power supply system transition is built on a level track section on top of the fly-over. ProRail (2014) advises power supply transitions of any sort to be located on level track, which is why this transition is located at this specific place.

The connecting arches are also the points where trains are handed over between two dispatching centres. While Utrecht – Den Bosch is controlled by the dispatching centre at Utrecht, the Betuweroute is controlled by the dispatching centre at Kijfhoek, which is responsible for the entire Betuweroute, Kijfhoek shunting yard and the Havenspoorlijn.

6.1.2 Traffic flows at Meteren junction

Most freight traffic at Meteren junction (also known as: BetuweRoute Meteren or BRmet) uses the entire length of the Betuweroute. These trains enter the Betuweroute at Zevenaar Oost (Zvo) and drive straight on to Kijfhoek (Kfh) and the Rotterdam Harbour or vice versa. In 2019, close to 20.000 freight trains passed Meteren Junction on this corridor (Figure 28, Appendix P.1). The remaining 2.500 trains used the northern and southern connecting arches. In 2019, a total of 1428 freight trains and redirected ICE-trains used the Northern connecting arches in both directions. The northern connecting on the A2-corridor has been named Meteren Betuweroute aansluiting noord or Mbtwan. Furthermore, 1.108 freight trains used the southern connecting arches in both directions. The southern connecting on the A2-corridor has been named Meteren Betuweroute aansluiting zuid or Mbtwaz.

In 2019, 8 scheduled passenger trains per direction, per hour passed Meteren junction, 6 intercity trains at 10 minute intervals and 2 commuter trains with a frequency of 2 trains per hour on the railway line Utrecht – Den Bosch. At Geldermalsen (Gdm) an additional 2 commuter trains join the flow of passenger trains. On top of that, over 3500 freight trains pass Meteren junction yearly on the A2-corridor, both directions combined.

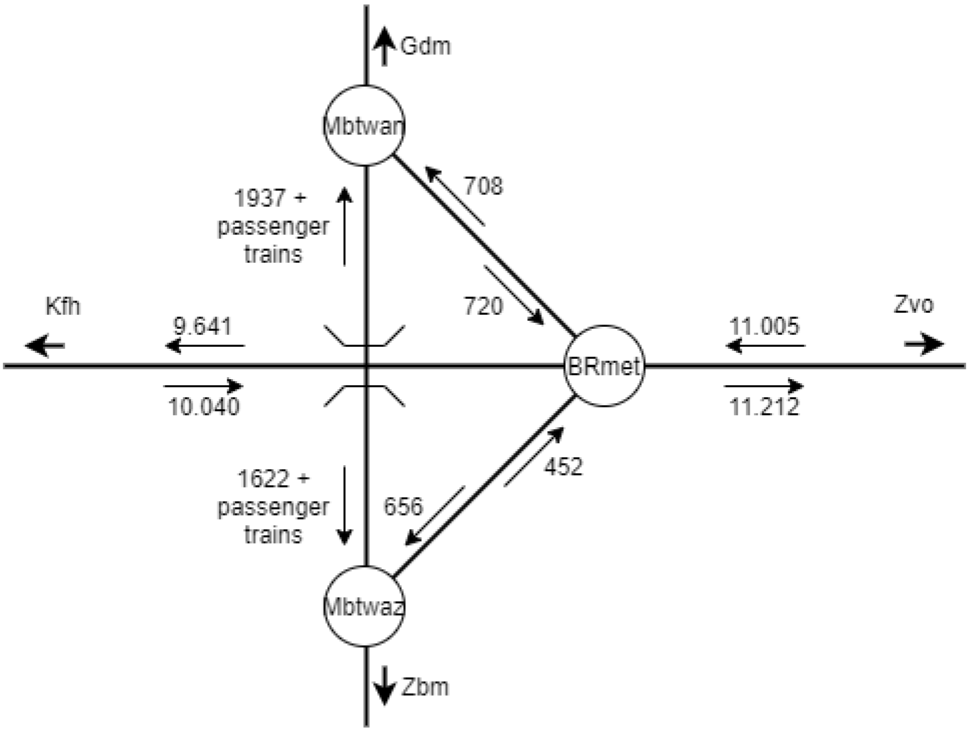


Figure 28 Freight train traffic flows at Meteren junction (ProRail, 2020e)

In Figure 29, the track layout of the Betuweroute-side of Meteren junction is shown. Each individual TROTS section has been named in this figure.

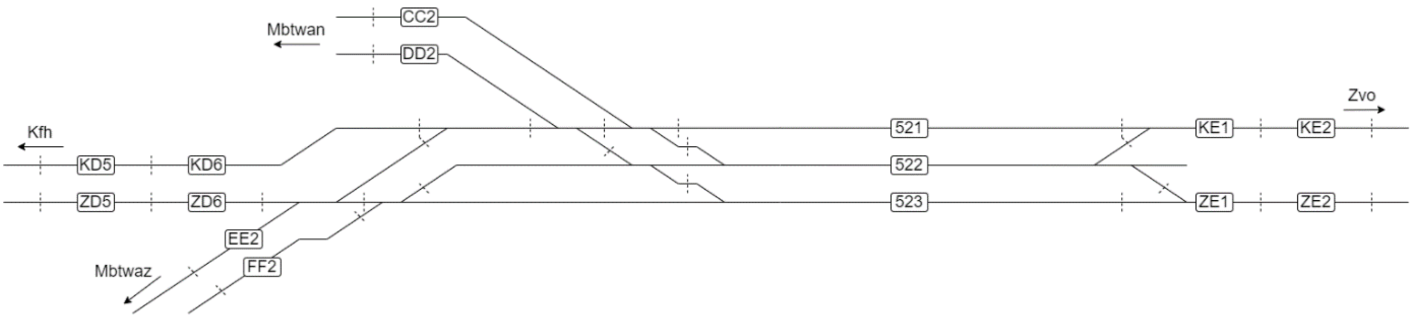


Figure 29 Track layout of BRmet

In Table 5, the typical sequence in which trains pass BRmet has been presented. Track 521 and 523 are mostly used for all ongoing trains between Kfh and Zvo. Track 522 is used as a waiting track for trains in the direction of Geldermalsen (Gdm), via Mbtwan or in the direction of Zaltbommel (Zbm), via Mbtwaz. As the A2-corridor is highly utilized, most trains have to wait some time before there is a free train path for a freight train. Train operators often make a planned stop on track 522 for a few minutes. This will ensure that the train is on time to enter the A2-corridor (Appendix G). If a freight train is more than three minutes behind schedule, the train path is given to another train, after which it takes half an hour, an hour or even more time to get a new path onto the A2-corridor (Appendix E). Freight trains entering the Betuweroute often make a planned stop at waiting tracks at Gdm when they approach from the northern direction and at Mbtwaz when they approach from the southern direciton for similar reasons (Appedix E).

Table 5 track section sequence per train direction (Appendix P)

TRAIN DIRECTION	**RAIL SECTION SEQUENCE**								
ZVO → KFH	KE2	→	KE1	→	521	→	KD6	→	KD5
KFH → ZVO	ZD5	→	ZD6	→	523	→	ZE1	→	ZE2
ZVO → MBTWA	KE2	→	KE1	→	522	→	CC2		
MBTWA → ZVO	DD2	→	523	→	ZE1	→	ZE2		
ZVO → MBTWAZ	KE2	→	KE1	→	522	→	EE2		
MBTWAZ → ZVO	FF2	→	523	→	ZE1	→	ZE2		

6.1.3 Future developments at Meteren junction: the Zuidwestboog

In future years, Meteren junction will undergo major reconstruction works. New connecting arches will be built, that allow freight trains to drive onto the Betuweroute in westward direction. These new connecting arches are commonly referred to as ‘Zuidwestbogen’. The decision to build these new connecting arches was made in 2010 (Ministry of Infrastructure and Water Management, 2010).

By constructing these new connections, freight trains that currently use the railway line Dordrecht – Breda – Tilburg – Eindhoven, commonly known as ‘Brabantroute’, will use the Betuweroute between Kijfhoek and Meteren in future years (Figure 30). More passenger trains will be able to use the Brabantroute once the number of freight trains on this route has been reduced. Furthermore, residents along the Brabantroute will experience less noise disturbance from freight trains. Finally, the Zuidwestboog increases the number of possible routes for freight trains between the Rotterdam harbour and the German hinterland, which increases the flexibility and robustness of freight train operations. Between 14 and 43 daily freight trains are expected to use the new Zuidwestboog in 2040 (Ministry of Infrastructure and Water Management, 2018c).

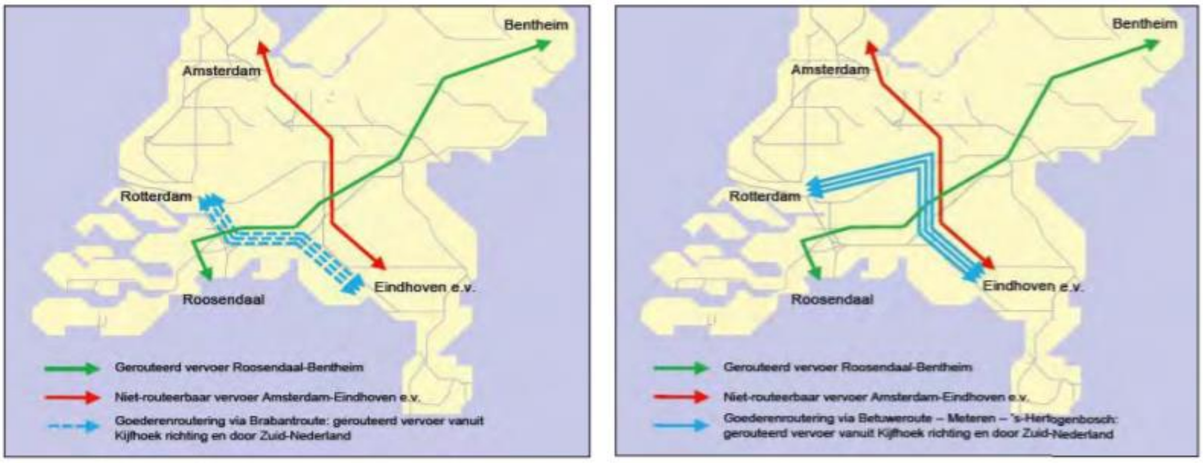


Figure 30 present and future freight train traffic flows on the Brabantroute (Ministry of Infrastructure and Water management, 2018c)

Zuidwestboog design

Multiple designs have been proposed to link the Betuweroute and the A2-corridor in westward direction, with different configurations of fly-overs, dive-unders and vertical separation. In the end, a design has been chosen with two separate arches (Figure 31). Over a distance of 2 kilometres, the Betuweroute is rerouted in order to create space for the new connecting arches (see Figure 31). The 'inner' arch is used by freight trains from Kijfhoek in the direction of Den Bosch. The arch branches off at the Betuweroute and crosses the A15 highway with a fly-over with a maximum gradient of 4.3‰ (Arcadis, 2015b). The transition between 25kV and 1.5kV is designed on top of this fly-over. After the fly-over, the line descends to ground level with a maximum gradient of 23,4‰ and connects to the Utrecht - Den Bosch railway line (Arcadis, 2015b). Directly after this steep decline, a waiting track with a length of 770 meter is present, which allows freight trains to wait on level track before continuing on the main line tracks in the direction of Den Bosch. As a design criterion, trains have to be able pass the power supply transition with a minimum speed of 15 km/h without stranding (Arcadis, 2015a). The last signal in front of the transitions should therefore be located sufficiently far away to allow trains to gain enough speed after receiving a green signal. This signal is located on the Betuweroute, 55 meter in front of the switch leading to the 'inner' Zuidwestboog (Arcadis, 2015b). Subsequently, freight trains waiting for a signal at danger will have to wait on the Betuweroute, blocking all traffic in the direction of Zevenaar.

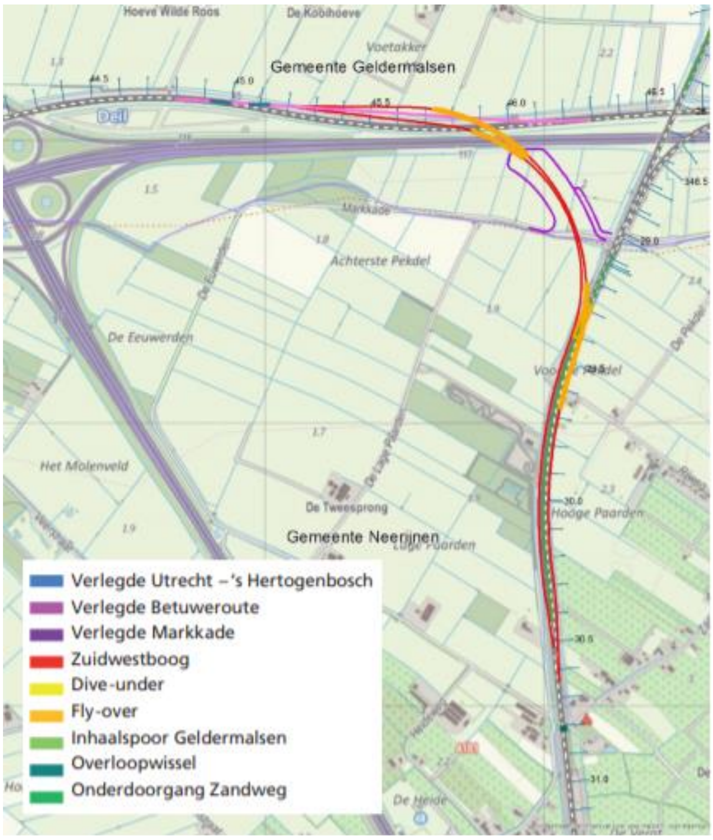


Figure 31 Zuidwestboog Meteren junction design (Ministry of Infrastructure and Water management, 2018c)

The ‘outer’ arch (see Figure 31) will be used for trains from Den Bosch in the Direction of Kijfhoek. A 770 meter long waiting track will be built in front of the connecting arch (Arcadis, 2015c). If freight trains cannot directly enter the Betuweroute, due to other rail traffic, they can wait on level track. After a steep climb with a gradient of 23,4‰ with a total height difference of 9 meter, the arch passes the A2-corridor with a fly-over. Due to the height of the fly-over, trains have to wait well ahead of the start of the fly-over in order to gain sufficient speed. The power supply system transition is envisioned on top of the fly-over (Arcadis, 2015a), similar to other power supply system transitions on the HSL-Zuid and the Betuweroute. As a consequence, the last signal in front of the fly-over and the transition from 1.5kV DC to 25kV AC, is located just over 100 meter after the start of the waiting track (Arcadis, 2015c). So when a train has to wait for a signal at danger in front of the fly-over, only the first 100 meter of the train is standing on the waiting track. The rest of the train is waiting on the Den Bosch – Utrecht main line. After the fly-over, the connecting arch continues to rise slightly with a gradient of 1.2‰ on an embankment, before arriving at a second fly-over, which crosses the A15 highway, the Markkade and the Betuweroute. Subsequently, the line drops back to the level of the Betuweroute with a gradient of 15.1‰ and branches in on the Betuweroute (Arcadis, 2015c).

6.2 TROTS section analysis

In this section, the frequency and severity of delays at Meteren junction will be investigated, using TROTS sections. The methodology used for the TROTS section analysis has been described in section 4.2. In subsection 6.2.1, the results of the data analysis are shown. In subsection 6.2.2, the TROTS sections containing operational transitions will be investigated in more detail. In subsection 6.2.3, a validation is given of a hypothesis that is formulated in subsection 6.2.2.

A total number of 1040 delays have been recorded in 2019 at Meteren junction, with durations ranging from 60 seconds (the minimum time for a disruption to be registered as such) to almost 9,5 hours. In Figure 32, the number of delays per TROTS rail section (see Figure 29 for TROTS-sections) is shown. A subdivision has been made according to time duration of the delays.

6.2.1 TROTS section data analysis

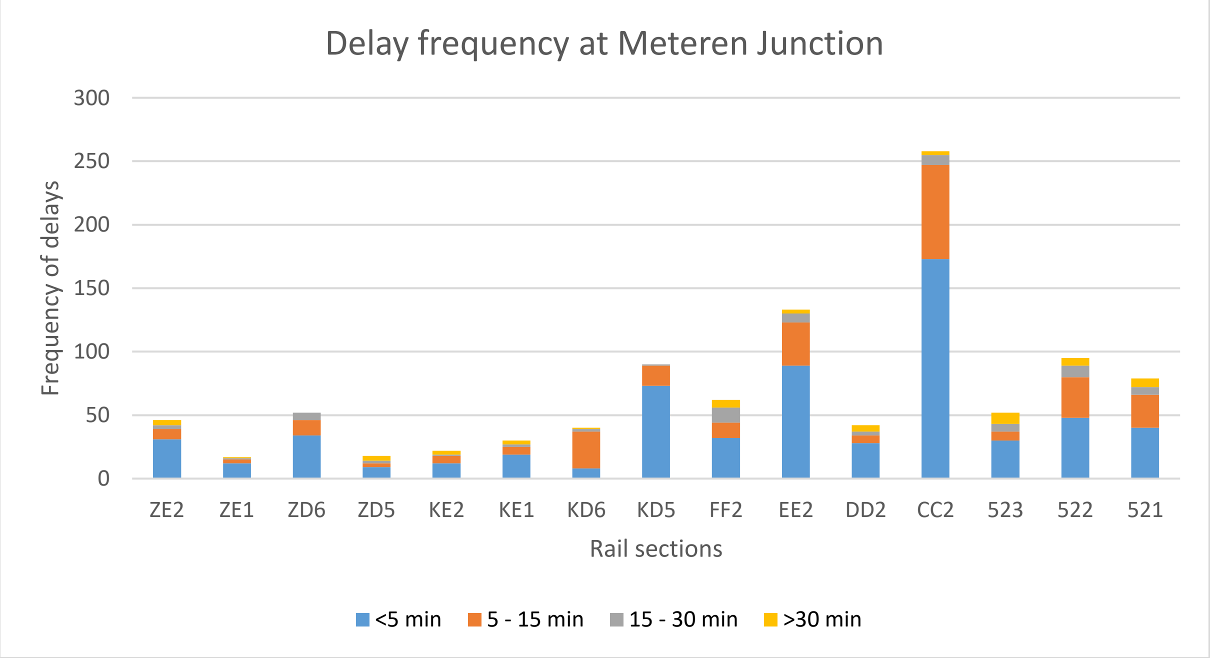


Figure 32 Disruption frequency at TROTS rail section at Meteren junction

As can be expected, most delay events have a duration of less than five minutes (638 out of a total of 1040 delays). A further 274 delays lasted between 5 and 15 minutes and 69 delays lasted between 15 and 30 minutes. Finally, 55 delays lasted longer than 30 minutes (Figure 32, Appendix P.1).

The total number of delays varies over all track sections. The number of delays at CC2 and to a lesser extent at EE2 are notably higher than the other track sections. This can be explained by the fact that these sections lead onto the A2-corridor. CC2 is the connecting arch for trains in the direction of Gdm, Utrecht and further. Similarly, EE2 is the connecting arch for trains in the direction of Zaltbommel and Den Bosch. The number of trains per year on both sections is roughly similar (Figure 28). The difference in delays frequency is therefore likely caused by the presence of a waiting track at Mbtwaz. Furthermore, south of Gdm, the frequency of passenger trains is 8 trains per hour per direction. North of Gdm, the passenger train frequency is 10 trains per hour and per direction. This means that more paths for freight trains are available south of Gdm. There is also a dedicated path for freight trains between Meteren and Den Bosch, making it easier for freight trains to enter the A2-corridor in southern direction (Ministry of Infrastructure and Water Management, 2018c).

Though the number of delays with a duration longer than 15 minutes is limited in frequency, the impact of such delays is considerable. The total delay time per TROTS rail section is shown in Figure 33. The total delay time in 2019 was 160 hours and 11 minutes. Small delays with a delay less than five minutes contributed 26:47 delay hours. A further 36:42 hours were lost to delays lasting between 5 and 15 minutes. 23:19 hours of delays were caused by delays with a duration of 15 to 30 minutes. The largest delay time, however, was caused by delays of 30 minutes and larger. 73:22 hours of delays were caused by such events.

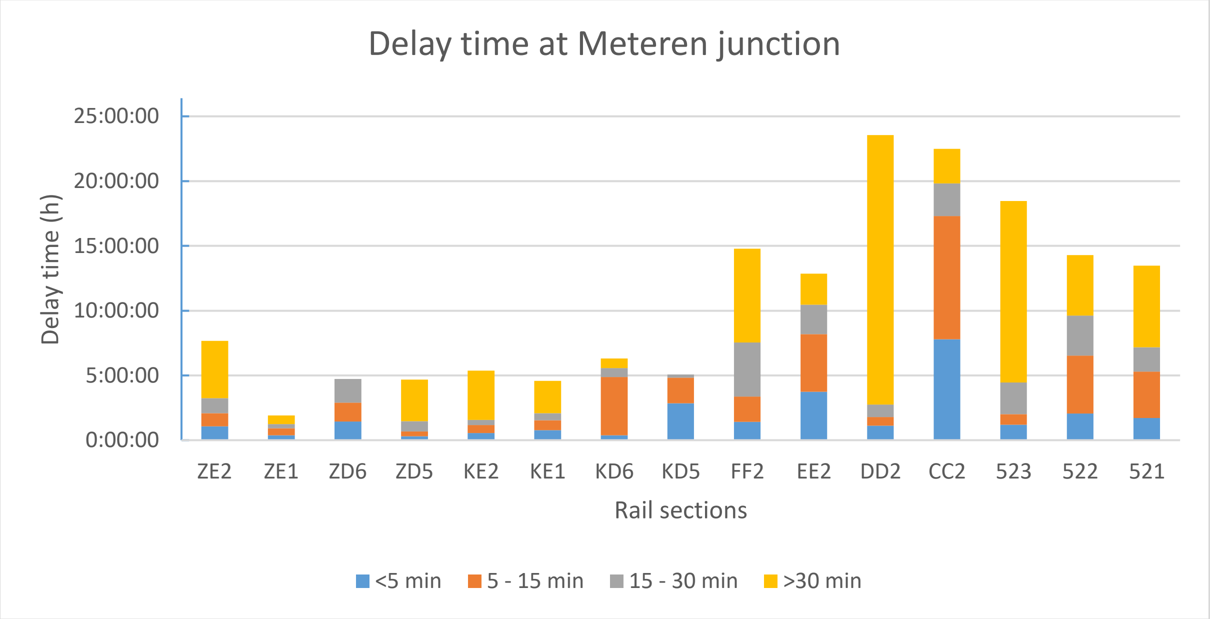


Figure 33 Total delay time per TROTS rail section at Meteren junction

While the disruption frequency and total delay time give an overview of the absolute delay frequency and severity, they do not take into account the number of trains using each TROTS section. As said earlier, the number of trains on the connecting arches is relatively limited, compared to the number of trains that travel between Zevenaar oost and Kijfhoek. At Figure 34, the delay probability is shown. This is the number of delays recorded per TROTS subsection, divided by the number of trains that used the track section. In Figure 35, the average delay per train is shown. This is the total delay time per TROTS section, divided by the number of trains that passed the section.

A sizeable proportion of trains driving on one of the connecting arches (FF2, EE2, DD2 & CC2) experience some sort of delay (Figure 34). At CC2, 36% of all trains has experienced a delay. On CC2, 24% of all trains experienced a delay less than 5 minutes, 10% experienced a delay between 5 and 15 minutes and 2% a delay of more than 15 minutes. Furthermore, 7% of all trains using track 522, the waiting track, wait longer than planned on this track section. At other sections, delay probability is less than 1%

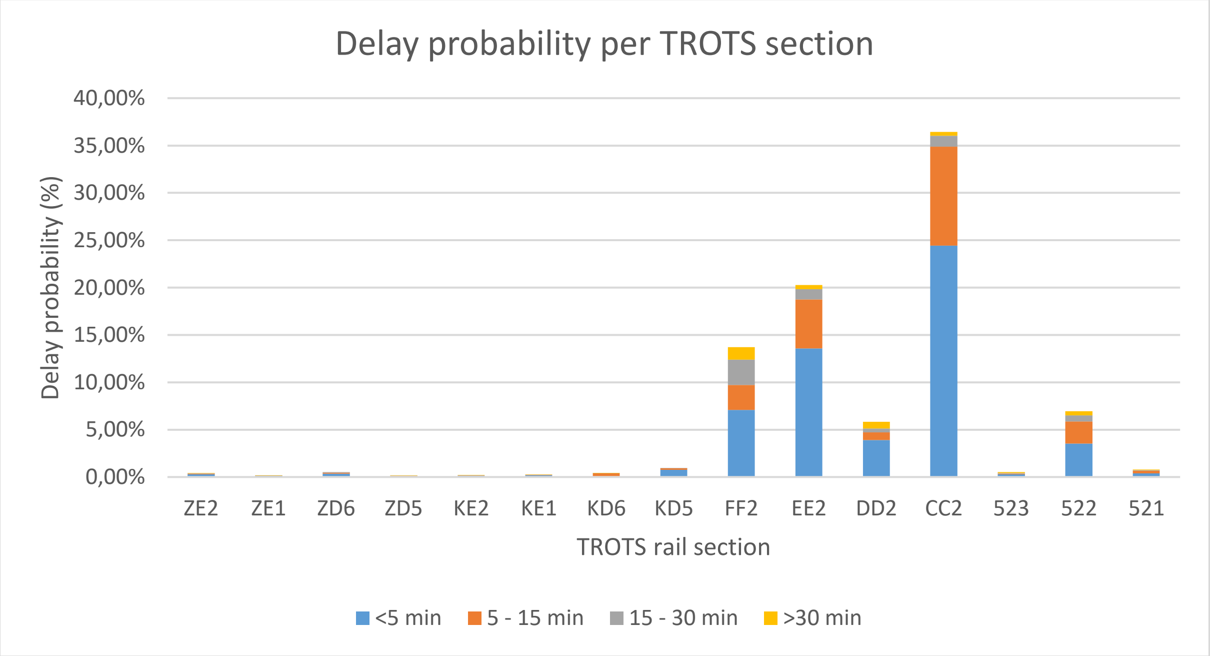


Figure 34 Delay probability per TROTS section at Meteren junction

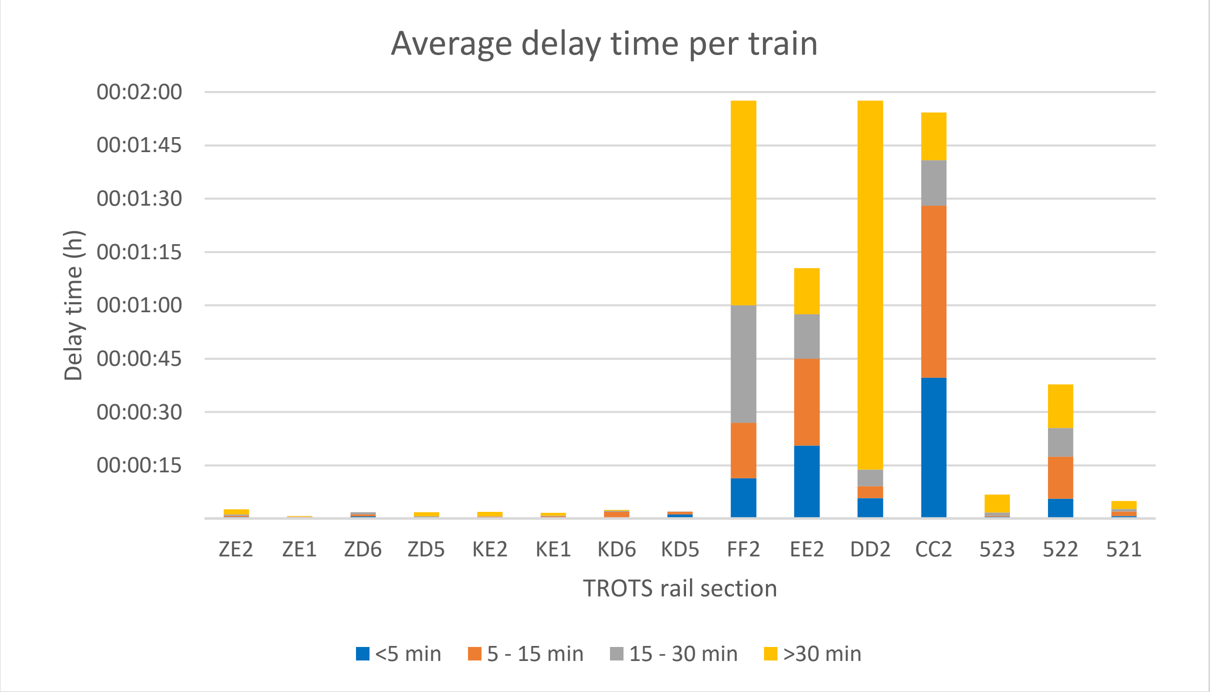


Figure 35 Average delay per train per TROTS section at Meteren junction

Similar patterns can be discovered when assessing the average train delay per rail section (Figure 35). Trains have an average delay of a few seconds on TROTS rail sections without any operational transitions or crossing rail traffic, but on the connecting arches of the Betuweroute to the A2-corridor, an average delay time up to 2 minutes can be noticed. Significant delays can also be seen on waiting track 522. Based on this figure, it can be seen that, although the number of >30 minute delays is limited (Figure 34), they contribute significantly to the total delay time per train

Although the data shows a large difference in delays between track sections with operational transitions (FF2, EE2, DD2 & CC2 in Figure 29) and track sections without any operational transitions, this does not mean that all delays can automatically be contributed to the presence of these transitions. Many (smaller) delays are most likely caused by the fact that freight trains have to wait for a free path, as the A2-corridor is a highly utilized railway line. In order the effect of operational transitions on delays more precisely, the four TROTS-sections containing the operational transitions will be studied in more detail in section 6.2.2.

6.2.2 Comparison among operational transition track sections

The sections CC2 and EE2 are both used by trains coming onto the A2-corridor and leaving the Betuweroute. DD2 and FF2 are used by trains in the opposite direction. These trains come from the A2-corridor and enter the Betuweroute. In Figure 36, the delay probability, the average delay time per train and the distribution of delay time of these four sections are presented.

When comparing these four rail sections, trains on CC2 and EE2 are more often delayed than trains on DD2 and FF2 (Figure 36). This difference is most likely explained by the frequency of trains on the A2-corridor and the Betuweroute. 8 or 10 trains per hour, per direction use the A2-corridor. The Betuweroute is used by approximately 1 or 2 trains between Kfh and Zvo per direction per hour. Trains joining the Betuweroute at Meteren simply experience less crossing traffic than trains entering onto the A2-corridor, which results in less delays as a consequence of conflicting train paths.

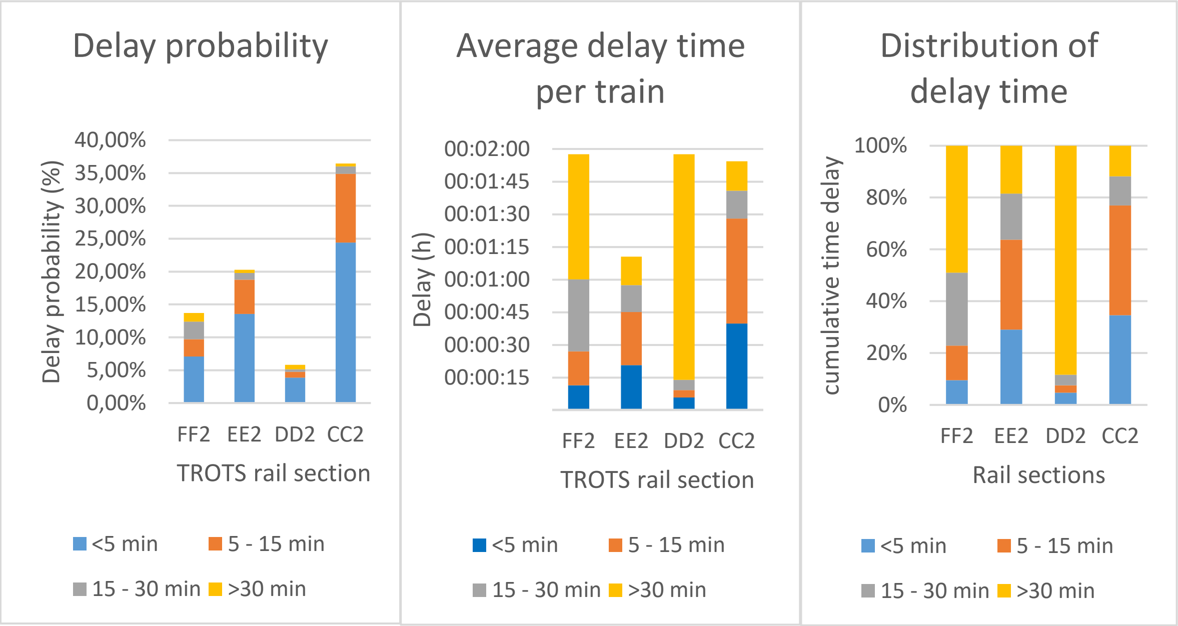


Figure 36, Delay probability, average delay time and distribution of delay time for TROTS sections with operational transitions at Meteren junction

The average delay time per train is similar for FF2, DD2 an CC2 at around 1:55 minutes per train. Lower average delays per train are seen at EE2, which is most likely caused by the presence of dedicated train paths for freight trains coming from BRmet and heading in southern direction and by the waiting track at Mbtwaz. There are less conflicting trains, making it easier for freight trains to leave the Betuweroute in the direction of Zaltbommel.

The third graph in Figure 36 in gives an overview of the distribution of total delay time. On the sections EE2 and CC2, the majority of total delayed time are caused by (relatively) minor delays up to 15 minutes, 65% and 75% respectively. In contrast, delays up to 15 minutes only make up 22% of total delay time on FF2 and only 7% on DD2. On FF2, close to 50% of total delay time is caused by delays with a length of over 30 minutes. On DD2, an even higher percentage of 90% of total delay time is caused by delays with a minimum length of 30 minutes. So although the average delay time per train is similar for at least three of the four TROTS sections, there is a large disparity in the distribution of delay durations. Trains on section DD2 especially seem to be plagued by large delays.

Based on the analysis conducted in this subsection, there is ample evidence to suggest that delays in railway operations are at least partly caused by operational transitions, although it is difficult to determine the 'pure' effect of operational transitions on delays. Especially on EE2 and CC2, most delay time seems to be caused by conflicting traffic, rather than by failed transitions. In subsection 6.2.3, a further distinction between delays caused by a signal at danger and delays caused by failed operational transitions will be made.

6.2.3 validation

In an effort to reduce the spread of COVID-19, the Dutch government has requested all citizens in March 2020 to stay at home for a prolonged period of time. Due to a large reduction in passengers and in anticipation on a growing number of sick train drivers and dispatchers, NS started offering a reduced timetable, also known as 'basic' timetable, from the 21th of March 2020 onward. In this timetable, the number of sprinter trains is reduced to two per hour, whereas most intercity trains are cancelled altogether. Between Utrecht and Den Bosch, the number of trains is reduced from 6 intercity trains and 2 sprinter trains to 2 intercity trains and 2 sprinter trains. The sprinter service Utrecht – Geldermalsen – Tiel also remained in place (NS, 17-03-2020).

In subsection 6.2.2, it is hypothesized that delays on TROTS section CC2 and EE2 are mainly caused by trains waiting for a free path to become available on the A2-corridor. As the number of passenger trains on the A2-corridor is reduced significantly, this would mean that the number and the duration of delays as a consequence of capacity constrains is reduced as well. Data has been used spanning a four-week period from Saturday 21-03-2020 until Saturday 18-04-2020 (Appendix P.3). In this time period, 58 trains used EE2, whereas 41 trains used CC2 (ProRail, 2020f). In this period, 7 delays were recorded on EE2, with a total delay time of 49:59 minutes. Furthermore, 5 delays were recorded on CC2, with a total delay time of 41:13 minutes (ProRail, 2020g). The average delay per train as well as the delay probability during a normal timetable as well as during the reduced timetable are shown in Figure 37.

During the reduced timetable period, the percentage of delayed trains on EE2 and CC2 is reduced considerably. The delay probability on EE2 has almost halved, while the delay change on CC2 is reduced by two thirds, suggesting that the delay probability is indeed largely dependent on traffic intensities on the A2-corridor, as has been hypothesized in section 6.2. The average delay time per train on EE2 and CC2 is also lower in March and April 2020, compared to 2019.

To conclude, the number of delays caused by operational transitions is usually quite low, although the impact of such delays are large. As a consequence, it is not possible to test whether the frequency and impact of delays at operational transitions remains constant, based on the four-week period data.

In section 6.3, the four TROTS rail sections containing operational transitions will be investigated in more detail at TROTS subsection less. This will also allow to differentiate between delays caused by operational transitions and other delay causes.

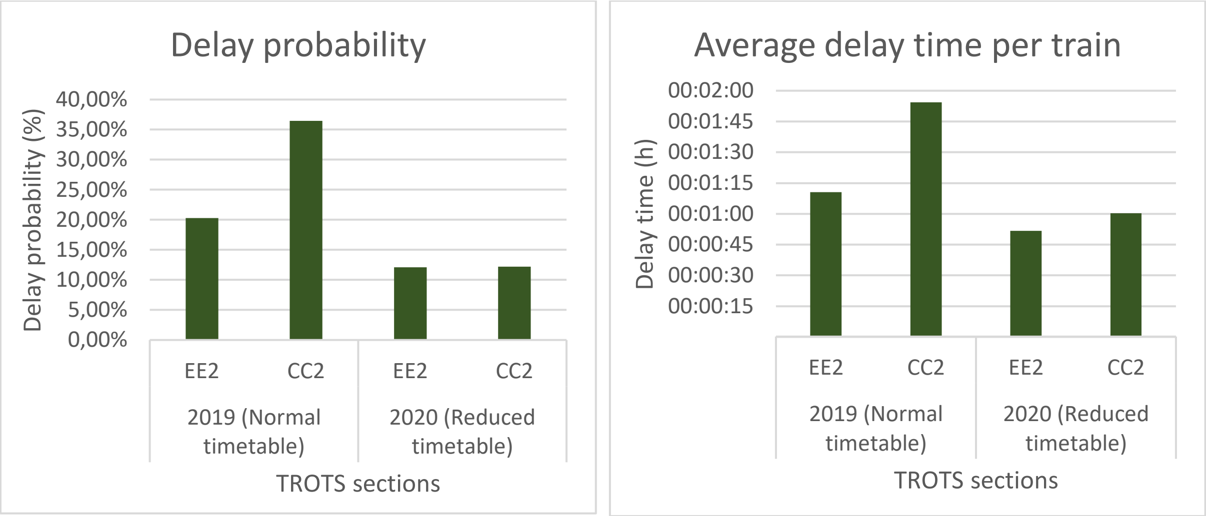


Figure 37 Delay probability and average delay time on EE2 and CC2 with a normal and a reduced timetable at Meteren junction

6.3 TROTS subsection analysis

In section 6.2, it was established that a relatively high occurrence rate of delays can be identified at TROTS sections containing operational transitions. In this section, these vulnerable TROTS sections will be investigated in more detail. Each TROTS section consists of multiple subsections with lengths ranging from 100 to 500 meter. Four TROTS sections (CC2, DD2, EE2 and FF2) will be analysed in more detail, following section 6.2. The methodology has been described in section 4.3. Table 6 contains a list with all relevant subsections per TROTS section. An overview of the number of delays per subsection and the total delay time as a result of these delays is given

In most cases, the number of delays as well as the total delay time are concentrated in one or two TROTS subsections. This information can be used to link delays and delays more closely to features in the rail infrastructure. In this analysis, subsections with a total delay time higher than one hour will be submitted to further inspection.

In TROTS section CC2, almost all delay time is concentrated in subsection 4190AT. In DD2, there are three subsections with a heightened occurrence of delays, 4192AT, 4192CT and

Table 6 Delay frequency and total delay time per TROTS subsections at Meteren junction

TROTS SECTION	TROTS SUB-SECTION	DELAY FREQUENCY	TOTAL DELAY TIME
CC2	4190AT	247	21:11:34
	4190BT	1	0:01:40
	4190CT	2	0:22:24
	4190DT	6	0:33:10
	4227T	1	0:04:15
	4231T	1	0:01:07
		258	**22:29:32**
DD2	4192AT	10	5:43:46
	4192BT	3	0:09:12
	4192CT	7	15:53:38
	4192DT	21	1:44:45
	4223T	1	0:01:16
		42	**23:32:37**
EE2	4201T	5	0:23:38
	4204T	3	0:17:23
	4205T	2	0:58:00
	4204AT	35	2:45:58
	4204BT	88	8:25:54
		133	**12:50:53**
FF2	4206T	2	0:07:58
	4206AT	31	7:31:12
	4206BT	6	0:38:14
	4206CT	23	6:29:07
		62	**14:46:33**

4192DT. The statistics on 4192CT are remarkable, as the 7 delays that occurred in that subsection caused almost 16 hours of delays.

In EE2, delays are concentrated in 4204AT and 4204 BT. Finally, in FF2, delays are equally more or less equally split among 4206AT and 4206CT. Figure 38 shows the total delay time and Figure 39 the total delay time distribution of all TROTS subsections with a total delay time higher than 1 hour in 2019.

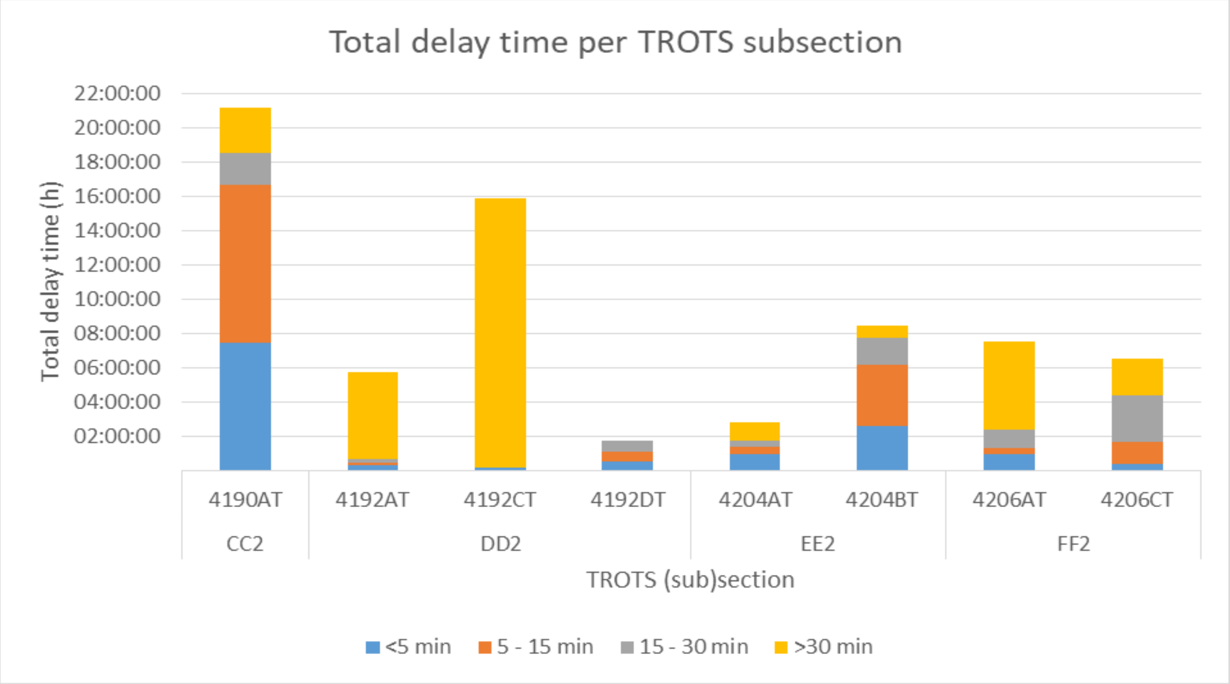


Figure 38 Delay time of a selected sample of TROTS subsections at Meteren junction

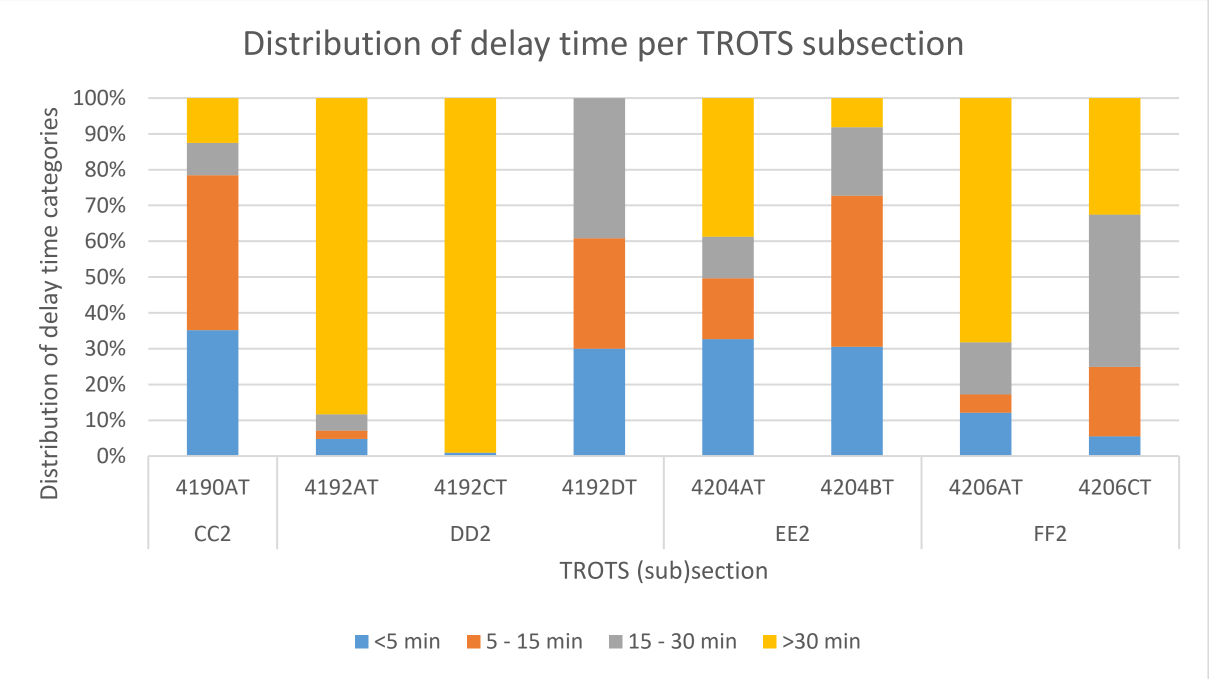


Figure 39 Distribution of delay time of a selected sample of TROTS sections at Meteren junction

The distribution of delay time varies significantly over the TROTS subsections. Subsections 4190AT and 4192DT have a relatively high amount of delays, but the length of these delays is generally limited. On the other side, the majority of delay time in subsections 4192AT, 4192CT and 4206AT is caused by delay events longer than 30 minutes. In subsection 4192CT, the three largest delays had a combined delay time of 15:44 hours. The longest of these three delays lasted approximately 9:30 hours. The remaining subsections (4192DT, 4204AT and 4206CT) are in between these two extremes and show a more mixed delay type distribution.

Table 7 Operational transitions per TROTS subsection at Meteren junction

TROTS (SUB)SECTION		**POWER SUPPLY TRANSITION**	**ATP SYSTEM TRANSITION**	**VERTICAL TRACK ALIGNMENT**	**SIGNALLING**
CC2	4190AT	25kV → 1.5kV	ETCS l2 → ATB-EG	Flat	Entry signal Ut – Ht (Northbound)
DD2	4192AT	-	ATB-EG → ETCS l2	Upward slope (8.6‰)	-
	4192CT	1.5kV → 25kV	-	Fly-over (8.6‰)	-
	4192DT	-	-	Downward slope (9.3‰)	Entry signal Betuweroute
EE2	4204AT	25kV → 1.5kV (partial)		Downward slope (10‰)	-
	4204BT	25kV → 1.5kV (partial)	ETCS l2 → ATB-EG	Flat	Entry signal Ut – Ht (Southbound)
FF2	4206AT	-	-	Upward slope (10‰)	Entry signal Betuweroute
	4206CT	1.5kV → 25kV (partial)	ETCS l2 → ATB-EG	Flat	-

In Table 7, an overview of operational transitions and other relevant features per TROTS subsection is given. Based on this information and the data in Figure 38 and Figure 39, some patterns begin to emerge. Three of the eight TROTS subsections contain upward slopes: 4192AT and 4192DT in DD2 and 4206AT in FF2. On these subsections, delays with a duration of more than 30 minutes make up between 68% and 99% of total delay time. They also contain a varying number of operational transitions, but the presence of an upward slope or crest seems to be the overarching factor that lead to the frequent occurrence of long delays. When freight trains come to a complete stop on these sections due to a failed transitions in power supply system or ATP system, it is not always possible to restart the train. Similar patterns have been described in appendix E and appendix G.

The effect of vertical track alignment on the length of delays is also supported by a comparison of 4192DT in DD2 and 4206AT in FF2. Both subsections have entry signals, protecting the entrance onto the Betuweroute. While 4192DT has a downward slope of 8.6‰, 4206AT has an upward slope of 10‰. The total delay time caused by sub-30-minute delays is similar for both subsections, just under 2 hours per year for both sections. The contribution of delays with a length of more than 30 minutes is considerably larger at 4206AT in comparison to 4192DT. The upward slope at 4192DT might be a cause for this disparity.

The subsections 4190AT in CC2 and 4204BT in EE2 show a similar built-up in total delay time (Figure 39). Between 70% and 80% of total delay time is caused by delays with a duration of less than 15 minutes. Both subsections contain exactly the same operational transitions: a power supply system transition from 25kV to 1.5kV, an ERTMS level 2 to ATB-EG transition and no (significant) upward or downward slopes. Furthermore, both subsections contain an entry signal, protecting the entrance of the A2-corridor. If no free path is available, freight trains will wait at these location until a free path becomes available. Though the distribution of delay time is similar in both subsections, the total delay time at 4190AT in CC2 is approximately 21 hours, while the total delay time at 4204BT in EE2 is about 8 hours (Figure 38). The number of trains that use CC2 and EE2 are quite even, 708 trains and 656 trains in 2019 respectively. Differences in total waiting time are most likely caused by the presence of a waiting track just south of EE2 and due to the lower passenger train frequency south of Geldermalsen, than north of Geldermalsen; something that has already been discussed in section 6.2.

6.4 Delay causes at Meteren.

In this section, the causes for delays will be studied in more detail. In subsection 6.4.1, a classification of delay causes is made. 12 categories of causes for delays have been identified. These 12 categories have been grouped in 6 groups, containing roughly similar causes for delays. Subsection 6.4.2 discusses the causes for delays per TROTS subsection. The eight TROTS subsections that have been studied in section 6.3 will be the focus of research in this section. Finally, subsection 6.4.3 investigates some large scale disruptions in more detail in order to find out why these delays lasted so long.

6.4.1 Delay classification

Based on the methodology explained in section 4.4, 12 delay categories have been constructed, which are shown in Table 8 and Table 9. For each category the frequency of delays in 2019 as well as the total delay time of those delays, has been listed. These 12 categories have been grouped into 6 groups, containing roughly similar delay causes. Appendix P.4 contains a full overview of the number of delays per delay type for each TROTS subsection.

Table 8 Delay categories Meteren Junction

DELAY CATEGORY	FREQUENCE OF DELAYS (NO.)	TOTAL DELAY TIME (HOURS)	DESCRIPTION
WORK PROCESS TRAIN DRIVER	12	1:51:16	Various causes for delays which are caused by the work process of train drivers
WORK PROCESS DISPATCHER	29	13:32:50	Various causes for delays which are caused by the work process of dispatchers
ROUTE SET MANUALLY BY DISPATCHER	28	2:40:22	The automatic route setting functionality (ARI) has not provided a train path, which had led to a train encountering approaching the end of its MA and slowing down.
WORK PROCESS	**68**	**18:04:28**	
NO CONNECTION WITH RBC	16	17:21:31	While transitioning from ATB to ERTMS level 2 or while driving under ERTMS level 2, the on-board ETCS equipment lost connection with the RBC.
ERTMS TRIP	8	1:31:58	An ERTMS trip occurs when a train is in danger of surpassing its End-of-Authority (EoA). ERTMS Trips can also occur when a (sub)system is malfunctioning (ERA, 2016).
ETCS MALFUNCTION	**24**	**18:53:29**	
ROLLING STOCK DEFECT	5	2:41:46	Due to a defect in the locomotive or in the freight wagons, the driver is forced to stop or to continue driving with reduced speed.
INFRASTRUCTURE DEFECT	12	0:47:01	Due to a defect to the track infrastructure, train operation is hindered, which leads to delays
DEFECTS	**17**	**3:28:47**	

Table 9 Delay categories Meteren Junction (continued)

DELAY CATEGORY	FREQUENCE OF DELAYS (NO.)	TOTAL DELAY TIME (HOURS)	DESCRIPTION
DELAYED BY OTHER TRAIN	238	17:19:52	Trains are delayed due to the delay of other trains. Trains have to wait until the next free path.
EARLY ARRIVAL	32	2:28:27	Trains arriving early have to wait until their reserved train path is available.
WAITING FOR SIGNAL AT DANGER	**270**	**19:48:19**	
OTHER CAUSES	44	2:34:57	
CAUSE UNKNOWN	38	7:11:16	Delays, with a minimum duration of 3 minutes, for which no clear cause could be found.
TOTAL:	462	70:01:16	

6.4.2 Delay cause per TROTS subsection

In this section, the primary causes for delays are discussed. A primary cause for delay is defined as the initial cause that led a train to come to a stop. For purposes of clarity and readability, only the six groups of delay categories are reported here. The reasons why some of these delays last a long time will be discussed in subsection 6.4.3.

Figure 40 indicates the primary causes for delays at each of the eight TROTS subsections, which have also been investigated in section 6.3. Approximately 60% of all delay events are caused by waiting for a signal at danger. Most trains have to wait at a signal because either they are late or other trains are late. In some cases, trains arrive early and have to wait for their reserved train path. As hypothesized in section 6.2 and section 6.3, most delays on 4190AT and 4204BT originate from trains waiting for the entry signals before entering the A2 corridor in northbound or southbound direction. This hypothesis is confirmed be the results as shown in Figure 40 and in Figure 41.

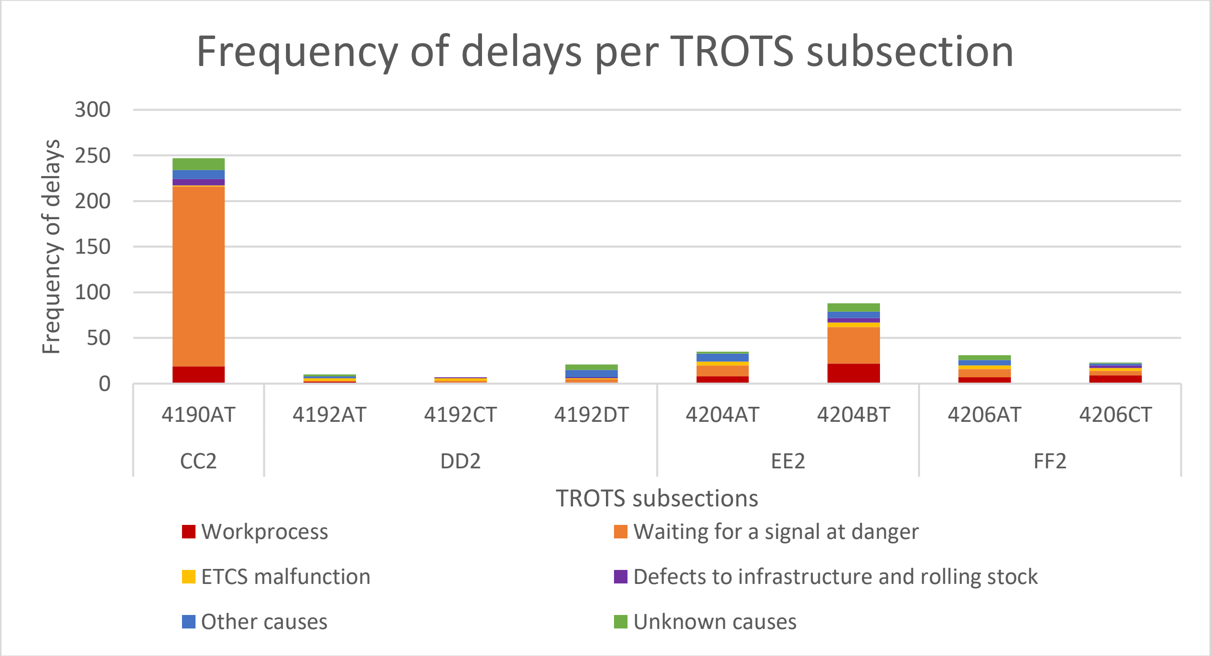


Figure 40 Frequency of delay types per TROTS subsection at Meteren junction

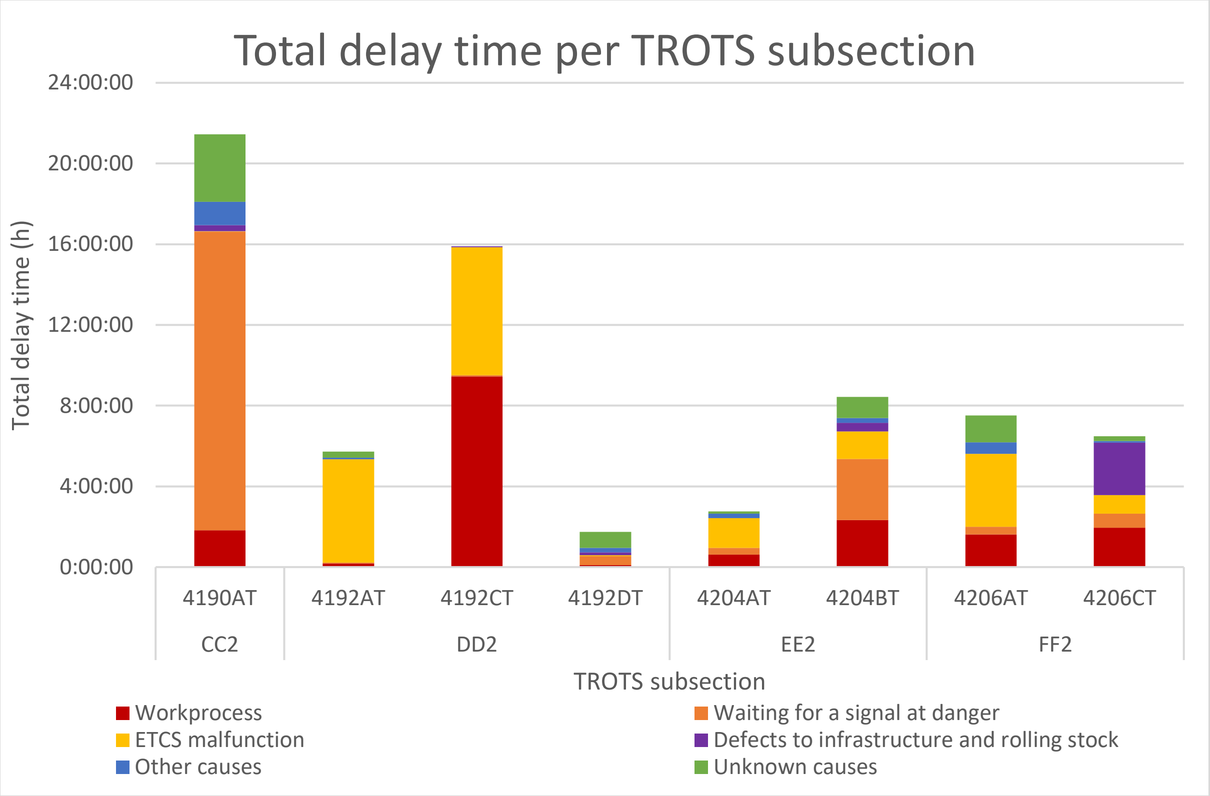


Figure 41 Total delay time per delay category and per TROTS subsection at Meteren junction

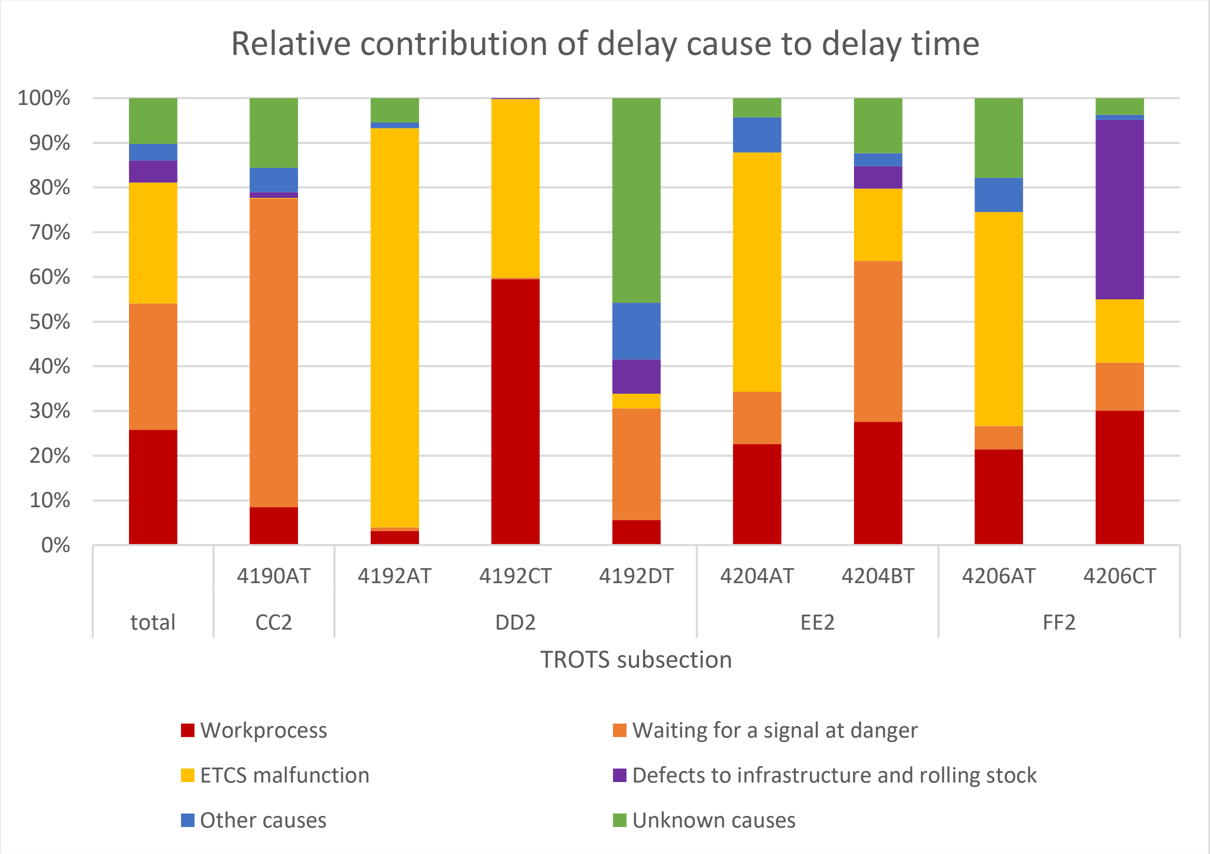


Figure 42 Relative importance of delay causes to total delay time at Meteren junction

Figure 41 and Figure 42 show the absolute and relative contribution of each delay cause category to the total delay time in each TROTS subsection. Overall, ETCS Malfunctions and waiting for a signal at danger are the largest groups of causes for delays. 50% of total delay time is caused by delays in one of these two categories. Although 60% of all delay events is caused by signals at danger, this contributes to less than 30% of total delay time. This indicates that delays caused by signals at danger are generally limited in duration. On TROTS subsection 4190AT and 4204BT, an overrepresentation of delays as a consequence of signals at danger can be seen (Figure 42). The large number of delays as a consequence of trains waiting for a signal at danger is likely caused by the entry signals for the A2-corridor in both subsections.

In contrast, ETCS malfunctions caused 24 of 462 registered delays in 2019, approximately 5% of all delays. With approximately 2500 trains using the connecting arches in 2019, this means that around 1% of all trains experiences ETCS-related transition failures. Over 25% of total delay time can be attributed to ETCS-related malfunctions. On subsection 4192AT, 4192CT and 4206AT, ETCS malfunctions have been the cause for a majority of total delay time. On these subsections, delays longer than 30 minutes also comprised the majority of total delay time, proving that delays with a long duration are indeed caused by failed operational transitions.

A third trend that can be extracted from Figure 41 and Figure 42 is the overrepresentation of Work process-related delays in TROTS section EE2 and FF2, the southern connecting arch of the Betuweroute to the A2-corridor. At each subsection, work process-related delays make up over 20% of total delays, while work process-related delays are hardly significant on the two northern connecting arches of the Betuweroute, with the exception of a spike in work process-related delays in 4192CT. This event, lasting 9:27 hours, is discussed in box 6.4.3. Most work process-related delays are caused by delayed route setting. Under normal circumstances, route setting is performed automatically, but in some cases, the dispatcher has to create a train path manually. Either when a train is too early or too late, ARI is not active and the dispatcher will have to create a train path manually (see section 3.2.5). When the dispatcher does not provide a train path in time, trains are forced to stop. Work process related delays were the cause of 69 delays in 2019, approximately 15% of all delays. 25% of delay time is caused by work process related issues. With the exception of the aforementioned outlier, lasting nine and a halve hours, less than 15% of total delay time is caused by work process related delays, so they do not seem to cause very lengthy delays on average.

Defects to rolling stock and infrastructure play a minor role in delays on the connecting arches of the Betuweroute, both in frequency of occurrence as well as in total delay time. ‘Other causes’ also play a minor role in train operations. These delays are mostly causes by humans and animals on or near the railway line. No delays have been registered as being caused by temporary speed restrictions on the connecting arches of the Betuweroute. Three delays were caused by a dispatcher mandate, lasting a couple of minutes each. Neither TSRs, nor dispatcher mandates therefore seem to have a large impact on train operations, other than a couple of minutes of delay.

6.4.3 Causes for larger disruptions

Although a primary delay cause can be identified for each delay event, this does not explain why some delays last one or multiple hours before being resolved. In this subsection, these large disruptions are studied in more detail. Spoorweb data is used to analyse delays with a length of more than 30 minutes in more detail. In 2019, 17 delays could be identified on the connecting arches of the Betuweroute that lasted more than 30 minutes. For 10 out of 17 delays, Spoorweb data was available. In Table 10, these 10 delay events are listed. For each event, it is listed what role each operational transition type has had in the delay. As noted in subsection 6.4.2, ETCS-related problems often are the primary cause for delays. In 5 out of 10 cases, the on-board ETCS equipment failed to connect with the RBC in time. In a further 2 cases, the on-board ETCS equipment failed altogether. Two delays were caused by defects to the locomotive and one delay event can be attributed to route setting problems.

Table 10 large delays at Meteren junction

TRAIN NO.	DATE	LOCATION	DELAY (HOURS)	ATP SYSTEM TRANSITION	POWER SUPPLY TRANSITION	VERTICAL TRACK ALIGNMENT	OTHER FACTORS
48734	14-06	CC2 4190AT	0:43	-	-	Flat	Defect to locomotive
42305	29-08	DD2 4192AT	4:08	OBU failure	-	Upward slope (8.6‰)	-
48781	24-12	DD2 4192CT	9:27		Train stranded in neutral section	Fly-over (8.6‰)	Signal at danger at the end of DD2
47797	02-05	DD2 4192CT	3:21	RBC connection failure	Train stranded in neutral section	Fly-over (8.6‰)	-
48747	07-03	DD2 4192CT	2:56	RBC connection failure	Train stranded in neutral section	Fly-over (8.6‰)	-
44787	17-05	EE2 4204AT	1:04	OBU failure	-	Downward slope (10‰)	
41505	03-05	EE2 4204BT	4:07	RBC connection failure	-	Flat	Defect to locomotive
42993	02-07	FF2 4206AT	0:54	RBC connection failure	-	Upward slope (10‰)	-
41505	03-09	FF2 4206AT	2:34	OBU failure	-	Upward slope (10‰)	-
41599	21-10	FF2 4206CT	2:06	-	Locomotive in front of neutral section	Flat	Defect to locomotive

When investigating the data in Table 10, several observations can be made. Only 1 out of 10 delay events took place on a downward slope (Train 44787, due to connection problems with the RBC). Eventually, after regaining contact with the RBC, the train was able to continue in southern direction. No assistance was required by another locomotive. All other events that did not involve a defect to the locomotive took place on upward slopes. Once a freight train is stopped on a sloped track, it is difficult to restart the train, as the train is heavy and the tractive effort of one locomotive is too small.

Stranded trains in the neutral section of power supply system transitions were only recorded on 4192CT, the fly-over connecting the A2-corridor to the Betuweroute. Only in one other case does the presence of a power supply transition seem to play a role. After the locomotive of train 41599 broke down on FF2 (Table 10), the train came to a halt just in front of the power supply system transition. As a consequence, an assistance locomotive had to be place to the rear end of the train in order to move the train to another location.

Assistance by other locomotives was required in 8 out of 10 cases. Trains were unable to continue without an assistant locomotive because they were stranded in or near a neutral section of a power supply system transition, because the locomotive was defect, or because the locomotive was unable to haul the train up the slope it was standing. The total duration of a stranding is heavily influenced by the availability of nearby assistance of other locomotives. When assistance is required, the railway undertaking is responsible for providing an assistant locomotive (Appendix M). When the railway undertaking cannot provide one in a reasonable time, the dispatcher lays claim on a locomotive that happens to be nearby (Appendix G).

The length of time until an assistant locomotive is present on location varies wildly and is to a large extent based on luck. Larger freight railway undertakings, such as DB Cargo often have a locomotive in the vicinity (there are usually a few locomotives stationed at Kijfhoek), but other railway undertakings have a fleet of only a few locomotives. Similarly, crew should be available to operate the assistant locomotive. These two factors, the availability of an assistant locomotive and of free crew, to a large extent determine the length of a delay when a train is stranded and cannot continue without assistance (see box 6.4.3).

Box 6.4.3 The misfortunes of train 48781

In the early morning, train 48781 left Amsterdam Houtrakpolder at 1:17 with a 2800 ton coal train headed for Mannheim, Germany. LTE was responsible for operating the train. As traction, locomotive E186 355, type TRAXX MS2, was used. The journey from Amsterdam to Geldermalsen was uneventful, the train arrived six minutes early at Meteren. At Mbtwan (Meteren Betuweroute aansluiting Noord), just in front of the start of the fly-over, train 48781 had to wait before entering the Betuweroute. No free path could be provided, as train 41734 just passed by Meteren junction in the direction of Kijfhoek. The train passed Meteren at 2:20, 8 minutes behind schedule. Once the tracks were cleared, at 2:23:00, a path was provided to train 48781.

After receiving a green signal, the train continued on to the Betuweroute. The train could not, however, attain sufficient speed to clear the neutral section of the power supply system transition and got stuck there at 2:26 AM. It was clear that an assistant locomotive was required to pull the train clear of the neutral section, but LTE did not have an extra locomotive readily available. Finally, at 3:32, LTE found a suitable engine in Rotterdam Europoort. The train driver found his locomotive at 4:02 locked in by other locomotives. As this locomotive could not be used, a plan was conceived to let the stranded train roll back to Geldermalsen. A shunter was sent to train 48781 to assist the roll-back. When the shunter arrived at the train at 5:58, it was found that the train was out of air to operate the brakes. As the locomotive was stranded in the neutral section, no power was available to power the generator for the braking system.

A second assistant locomotive, E186 941, was found at 6:15 at Waalhaven in the Rotterdam harbour area. A train driver was on its way and would depart as soon as possible. E186 941 left Waalhaven at 7:30 and arrived at Geldermalsen at 9:08. The locomotive would be attached to the back of train 48781. At 10:30, E196 941 was connected to the rear end of the train and at 11:15, the train was pulled back to a siding of Geldermalsen station. After the arrival of a replacement train driver, train 48781 departed Geldermalsen once again, this time using the other connecting arch (CC2), which is normally used for trains in the opposite direction. As a result, train 48781 had to drive on the left track until it reached crossover switches at Echteld on the Betuweroute, some 15 kilometres to the east of Meteren junction. As the track was blocked by an oncoming train, train 48781 had to wait until 12:00 until it had a free path in the direction of Zevenaar.

The transfer of trains between two dispatching centres does cause some delays. As shown in Figure 42, faults in the work process of train drivers and dispatchers account for approximately 12% of total delay time. Route setting problems and errors in the work process of the dispatcher make up about three quarters of this delay category.

6.5 Conclusion on operational transitions at Meteren junction

In this chapter, delays occurring at Meteren junction have been studied. Two sub questions have been covered in this case study, Firstly, the aim of this chapter has been to investigated to what extent operational transitions emerge from operational transitions in the railway infrastructure. Secondly, the underlying causes for disruptions have been investigated.

The analysis on the TROTS section level (section 6.2) indicated that trains on the connecting arches, containing the operational transitions, are more likely to incur delays than trains driving 'straight on'. The question arose to what extent these delays could be attributed to the presence of operational transitions and not to other factors. As the connecting arches connect to a highly utilized railway line (Utrecht – Den Bosch), delays can easily be incurred when waiting for a free train path on this line. In order to differentiate between capacity-related delays and transition-related delays, a validation has been conducted, which demonstrated a lower delay frequency during a time period with less train traffic on the A2-corridor.

Furthermore, TROTS subsections of the connecting arches have been investigated (section 6.3). The analysis of TROTS subsections allows delay events to be more closely linked to features in the railway infrastructure, such as transitions and signals. Based on the subsection analysis, it has also been possible to attribute some delays to capacity issues and other delays to transition issues with some level of certainty.

The TROTS subsections on which high total delay times were found, were used for further analysis in section 6.4. In this section, the underlying causes for delays have been investigated. Approximately 25% of total delay time could be attributed to waiting for a signal at danger, caused by other trains. On subsections with entry signals, this share was considerably higher. The highest single factor that contributed to total delay time is problems with ETCS equipment. Close to 30% of total delay time was caused by this factor. Upon further analysis, it was found that some trains with ETCS-related problems would come to a halt in or very near to the neutral section of the power supply system transition, making it impossible to continue their way without the help of an assistant locomotive. The availability of a suitable assistant locomotive and available crew with the right route knowledge is a major factor in determining the eventual duration of large disruptions. A small number of trains stranded on an upward slope without any registered ETCS problems.

Train strandings almost always occurred on upward slopes. Often, trains that stranded on these slopes were already slowed down as a result of a failed ATP system transitions, or as a result of restrictive signals. For freight trains, passing an upward slope with insufficient speed drastically increases the probability of a train stranding.

Work process related delays attributed 25% of total delay time on the southern connecting arch, while only accounting for a few percent of total delay time on the two northern connecting arches. No clear reason could be found why work process related delays play a more important role at the southern connecting arch than at the northern arches, based on the available data.

Chapter 7. Case study 3: Zaandam

In this chapter, a case study of Zaandam station and its surroundings is conducted in order to gain more insight into the effects of operational transitions on railway operations. Similar to the Meteren case study in chapter 7, two sub questions will be addressed in this case study of Zaandam. Firstly, an analysis of TROTS sections and subsections will be conducted to examine to what extent operational transitions at Zaandam have an impact on railway operations. Secondly, the underlying causes for disruptions as a consequence of operational transitions will be studied. The methodology as described in section 4.3 and 4.4 will be used in this case study. The rationale for selecting Zaandam as a case study is given in section 4.2. In section 7.1, a description will be given of Zaandam station and its surroundings. The analysis of TROTS sections is reported in 7.2. An analysis of TROTS subsections is conducted in 7.3. Delay causes are discussed in section 7.4. Some final remarks on this case study are made in 7.5

7.1 Description of Zaandam station area

In this section, the station area of Zaandam is described in more detail. In subsection 7.1.1, the historic developments that have led to the present day situation are described. In subsection 7.1.2, the current usage of Zaandam is described.

7.1.1 Historic development of Zaandam station

Zaandam was first connected by railway in 1869 as part of the railway line Den Helder – Alkmaar – Uitgeest – Zaandam. It took another nine years before Zaandam was connected to Amsterdam by rail. A large bridge had to be built over the Noordzeekanaal, which was opened in 1876, in order to connect Zaandam to Amsterdam. In 1878, the last section of the line between Zaandam and Amsterdam was finally opened. A swing bridge was used to cross the Noordzeekanaal. The bridge soon proved to be too restrictive to shipping traffic, which is why a new swing bridge was built to replace the old bridge in 1904. This bridge, the Hem bridge, had a vertical clearance for shipping traffic of 11 meter, as opposed to the four meter of the old bridge (Rail Magazine, 2013).

In 1884, the first part of the railway line Zaandam – Hoorn – Enkhuizen was completed between Zaandam and Hoorn. A year later, Enkhuizen would be connected as well. The railway line branched of the mainline just north of Zaandam station in eastward direction. Here, the railway line crossed the Zaan river with a single-track swing bridge (Rail Magazine, 2013).

In 1931, the railway line Alkmaar – Amsterdam was electrified. Zaandam – Hoorn – Enkhuizen would be served by diesel trains until 1974, when the railway line was electrified as well. Subsequently the section Zaandam and Hoorn was double-tracked between 1974 and 1983 (Rail Magazine, 2013). This meant that the single-track swing bridge over the river Zaan, just north of Zaandam station, had to be expanded with a second track. The Hem bridge, with its high clearance, remained a blockade to the ever increasing shipping traffic. Although plans to replace the Hem bridge by a tunnel had existed since 1900, serious plans to construct a tunnel date from 1964 (Rail Magazine, 2013). Eventually, it was decided to replace the tunnel with a bridge. The Hem tunnel opened in 1983, together with a new station and station layout for Zaandam. The new station was built 300 meter to the south of the old station building. The number of platform tracks was increased from 3 to 4 and a fly-over was constructed in order to create a free crossing of the railway line in the direction of Uitgeest and of the railway line to Hoorn and Enkhuizen. Finally, the old, now double-track swing bridge over the Zaan was replaced by a new swing bridge in 1991. This bridge is catenary-free (Zaanwiki, n.d.; Railwiki, n.d.).

The sidings at Zaandam station where used until the 1980s for the loading and unloading freight trains. Nowadays, these sidings are used by railway contractors to load and unload building materials.

Furthermore, the SPENO grinding train, which is used to grind the rail head profile, is stationed at the Zaandam sidings (railwiki, n.d.). An overview of Zaandam and its surroundings is given in Figure 43.

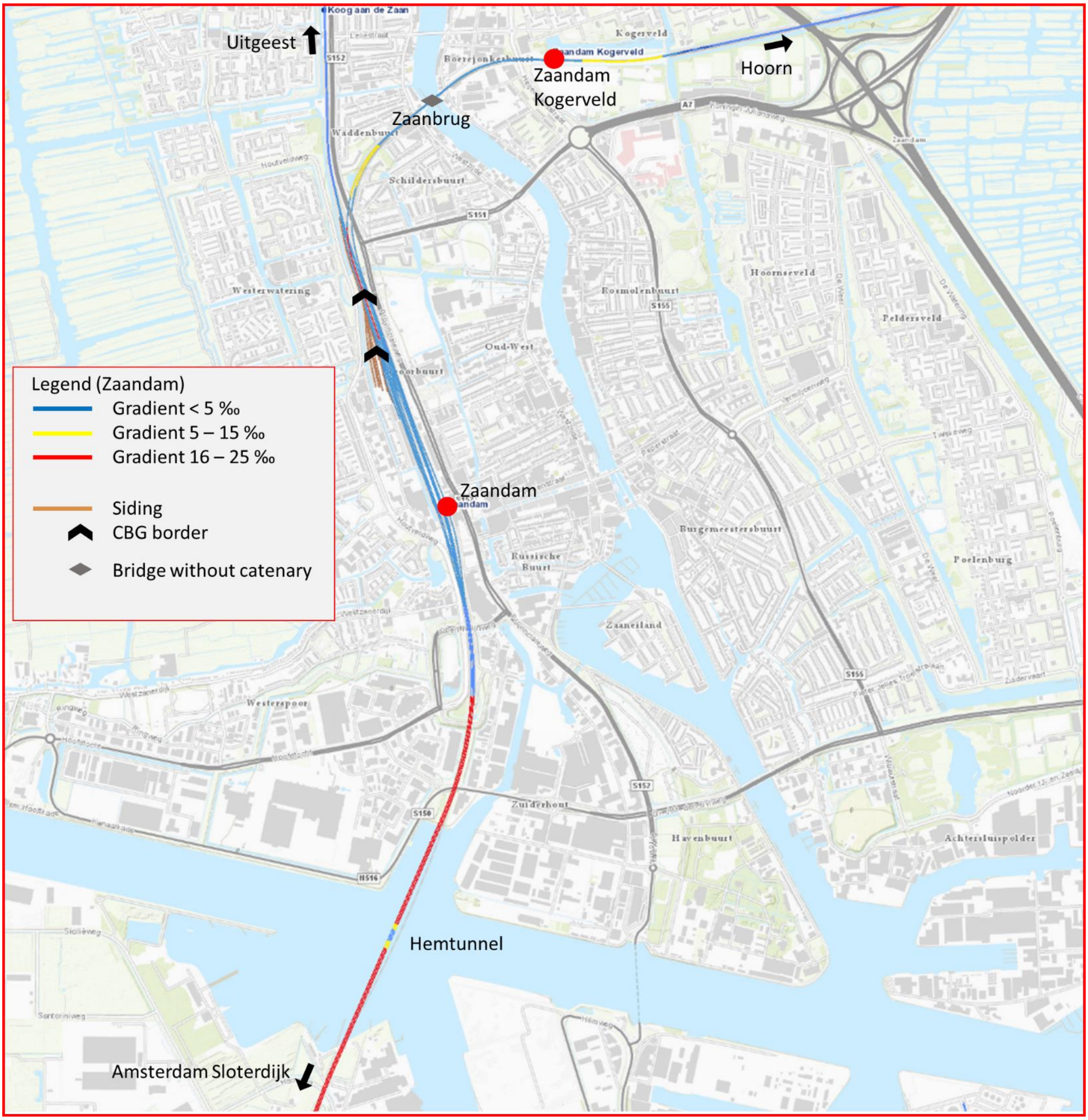


Figure 43 operational transitions at Zaandam

7.1.2 Present day and future traffic flows at Zaandam

Zaandam is served by multiple sprinter- and intercity services (Table 11). Furthermore, approximately 500 freight trains pass Zaandam each year, both directions combined. Most of these freight trains operate between Tata Steel in Beverwijk and the harbour area of Amsterdam. While all intercity trains to and from Alkmaar and Den Helder halt in Zaandam, Zaandam is only connected to Hoorn (Hn) and Enkhuizen with Sprinter trains. Intercity trains to and from Hoorn and Enkhuizen do not halt at

Zaandam, with a few exceptions. An overview of (platform) track usage in the direction of Uitgeest (Utg), Hoorn (Hn) and Amsterdam Sloterdijk (Ass) is provided in Table 11. All passenger train services listed in Table 11 have a base frequency of 2 trains per hour.

Table 11 Train services at Zaandam station

TRAIN SERVICES	STANDARD PLATFORM TRACK			COMMENT
	To Utg	**To Hn**	**To Ass**	
IC 800 DEN HELDER/ALKMAAR – MAASTRICHT	2		4	Does not operate in the early morning and evening. Is replaced by IC 2900.
IC 3000 DEN HELDER – NIJMEGEN	2		4	
S 4000 UITGEEST – ROTTERDAM	1		5	
S 7400 UITGEEST – RHENEN	2		4	
FREIGHT TRAFFIC	3		4	Mostly freight trains between Amsterdam Westhaven and Beverwijk via Uitgeest.
S 3300 HOORN – LEIDEN		1	5	
IC 2900 ENKHUIZEN – MAASTRICHT		1	5	Does not stop at Zaandam. Operates in the early morning and evening as a replacement for IC 800.
IC 3900 ENKHUIZEN – HEERLEN		1	4	Does not stop at Zaandam. Operates when IC 2900 does not operate.
IC 4500 HOORN - AMSTERDAM		1	4	Does not stop at Zaandam. Morning peak: Hoorn→Amsterdam. Evening peak: Amsterdam→Hoorn.

Due to the fly-over at the northern side of Zaandam, there is no conflict between trains to and from Uitgeest and trains to and from Hoorn. The Hem tunnel at the southern side of the station has three tracks. While track TJ is solely used for northbound traffic and Tl for southbound traffic, track TK is used in both direction on a regular basis (Figure 44).

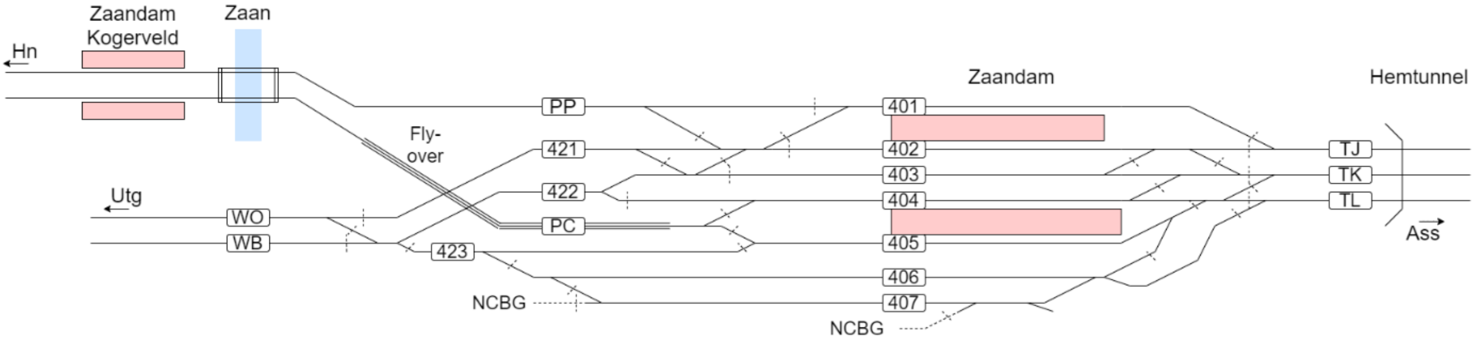


Figure 44 Track layout Zaandam with TROTS sections

On a standard weekday, 4 intercity trains and 4 sprinters operate between Amsterdam and Uitgeest/Alkmaar. Between 2025 and 2028, the frequency of intercity trains and sprinters will be increased from 4 to 6 as part of the PHS project between Amsterdam and Alkmaar (Ministry of Infrastructure and Water Management, 2019b). Together with 4 intercity trains between Enkhuizen/Hoorn and Amsterdam and 2 sprinters between Hoorn and Leiden, 18 passenger trains will stop at Zaandam or pass Zaandam each hour, per direction. Track 406 and 407 (Figure 44) will therefore be used more frequently to store unused rolling stock in future years. No significant changes to the infrastructure of Zaandam are planned to accommodate the growth of traffic.

7.2 TROTS section analysis

In this section, the frequency and severity of delays per TROTS section are analysed. An overview of all TROTS sections at Zaandam are shown in Figure 44. Figure 45 shows the number of delays per TROTS section as well as the subdivision of these delays in four time categories.

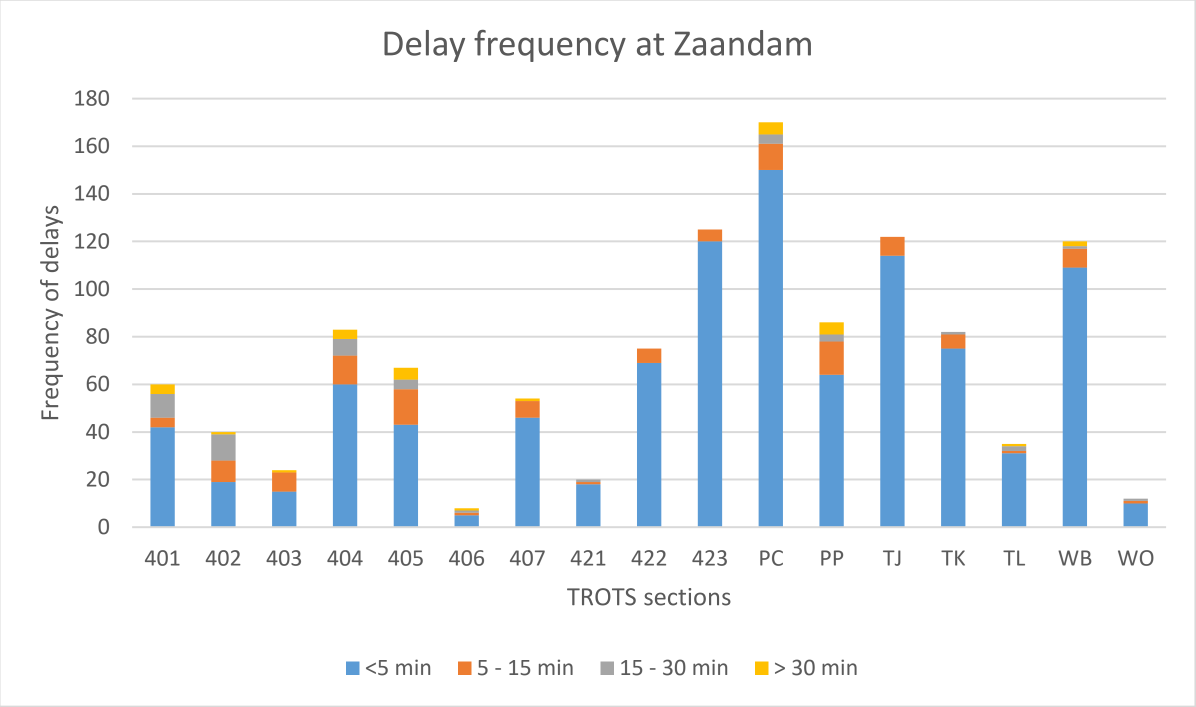


Figure 45 Delay frequency at Zaandam per TROTS section at Zaandam

The highest number of delays can be found on 423, PC, TJ and WB. These TROTS sections have in common, that are located in front of the station tracks of Zaandam, taking into account the typical driving direction. 423, PC and WB are all located on the northern side of Zaandam station. Passengers trains stopping at Zaandam on their way to Amsterdam either use track 4 or 5 (TROTS section 404 and 405). If (one of) these tracks are blocked, the subsequent train has to wait for the station track to be cleared. The high number of delays at TJ can be declared in a similar fashion, although further analysis will have to be conducted to find typical causes for delays per TROTS section.

Figure 46 shows the total delay time per TROTS section, whereas Figure 47 shows the relative distribution of total delay time per TROTS section. Although a relatively large number of delays has been recorded at the four aforementioned TROTS sections (423, PC, TJ and WB), there are large differences in total delay time and the distribution of total delay time between these four sections. While delays larger than 15 minutes have not been recorded in 2019 at 423 and TJ, the same does not hold for PC and WB, where a sizeable share of delay time is caused by delay events with a length of more than 15 minutes (Figure 46 and Figure 47).

Furthermore, a high share of delays with a length of more than 15 minutes can be seen at the station platform tracks of Zaandam station (401, 402, 404 and 405). Although the number of recorded delays at these track sections does not stand out from other sections (Figure 45), the total delay time of all recorded delays is relatively high.

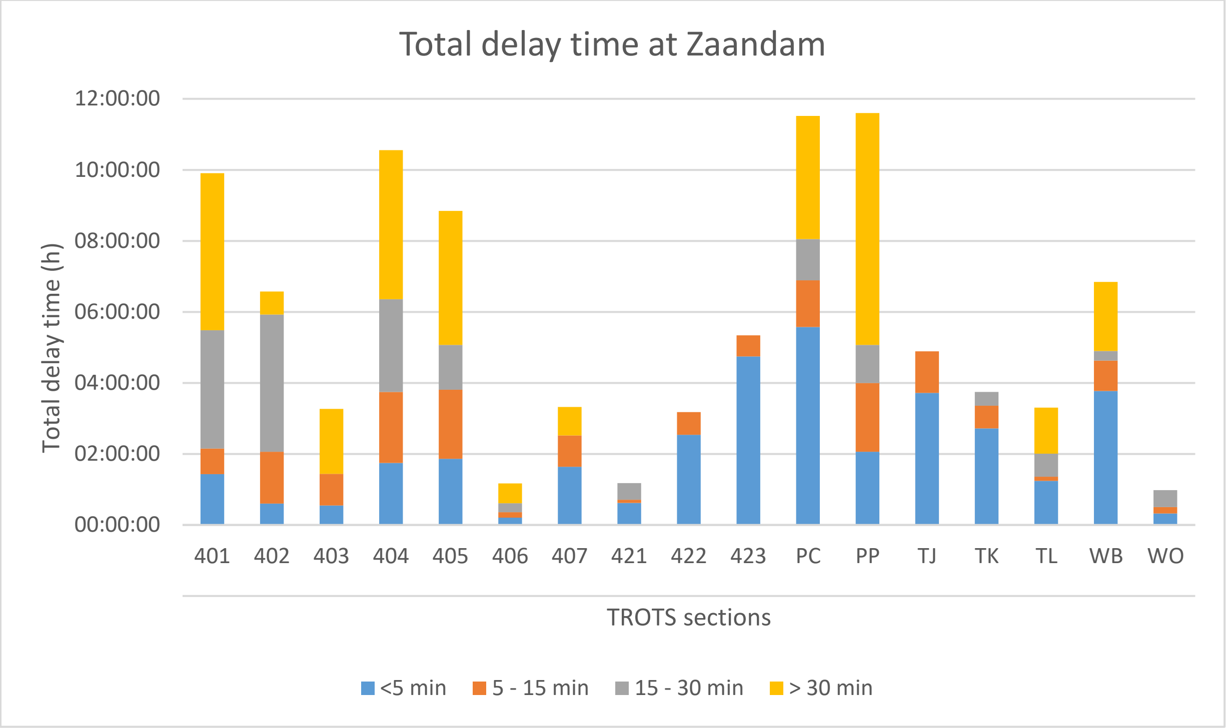


Figure 46 Total delay time at Zaandam

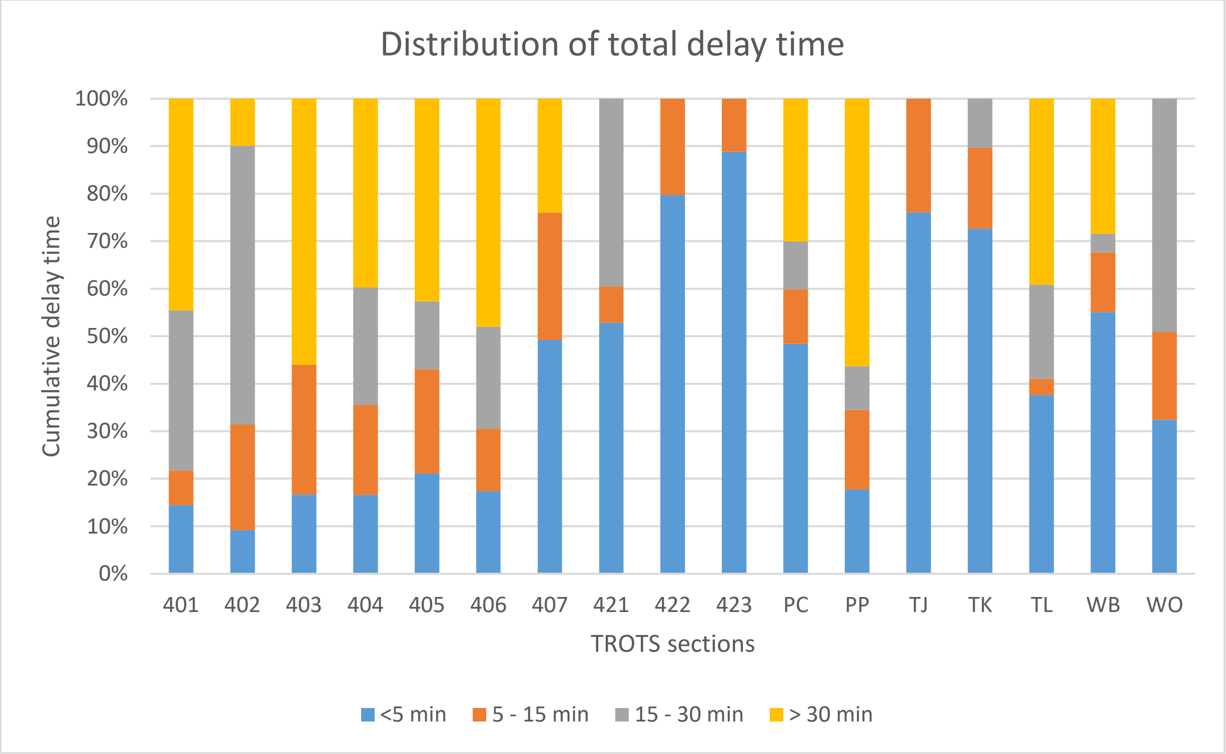


Figure 47 Distribution of total delay time at Zaandam

The total delay time on the Hem tunnel track sections (TJ, TK and TL) is surprisingly low. Even though the Hem tunnel is one of the deepest tunnels in the Netherlands with steep inclines, only one delay event with a length of more than 30 minutes has been recorded. On TJ and TK, no single delay event has even exceeded 15 minutes. It therefore seems unlikely that a train has stranded in the Hem tunnel in 2019, as actual strandings of trains at Meteren junction usually lasted more than an hour.

A final observation based on Figure 46 and Figure 47 is the high total delay time of TROTS section PP. Together with PC, both track sections are responsible for nearly 12 hours of total delay time. The traffic intensities on both sections are near identical (29.290 trains in 2019 on section PC and 28.619 on PP), which enables a direct comparison between these two track sections. Not only is the total delay time on both sections similar (Figure 46), but the distribution of total delay time is quite similar as well (Figure 47). The swing bridge over the Zaan river is located in PP and PC. Furthermore, PC contains the fly-over at the northern side of Zaandam station.

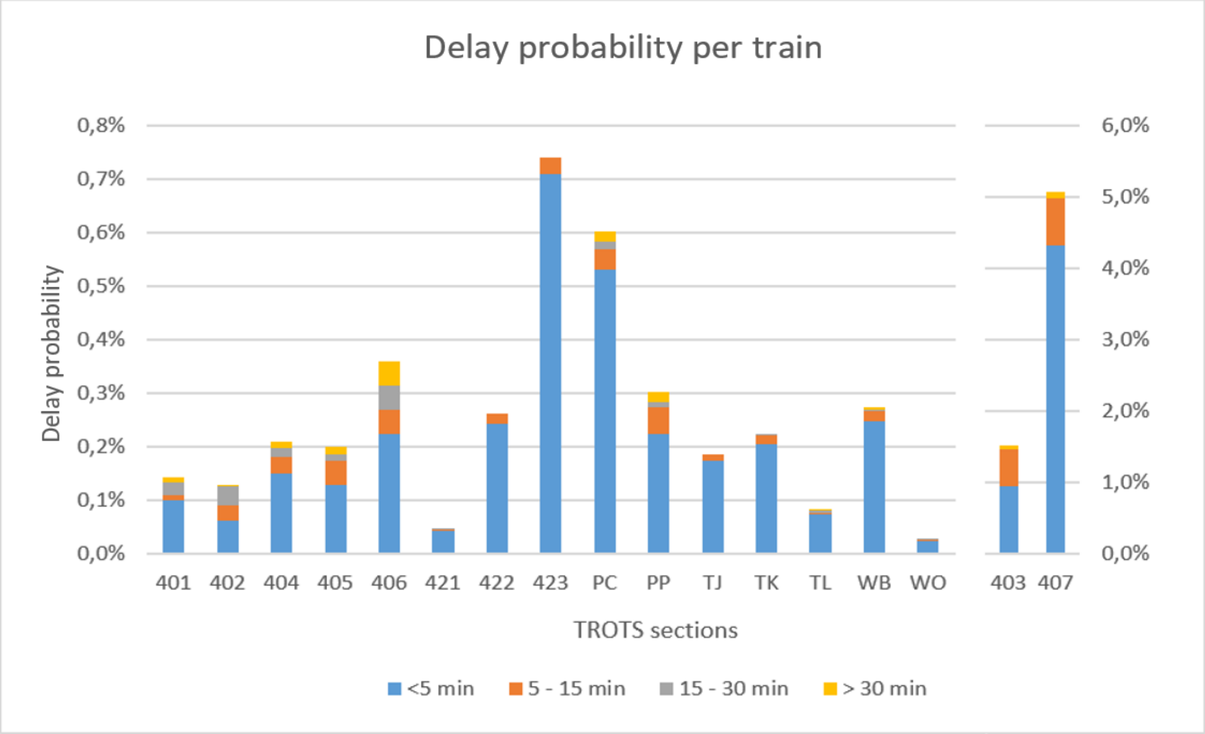


Figure 48 Delay probability per train per TROTS section at Zaandam

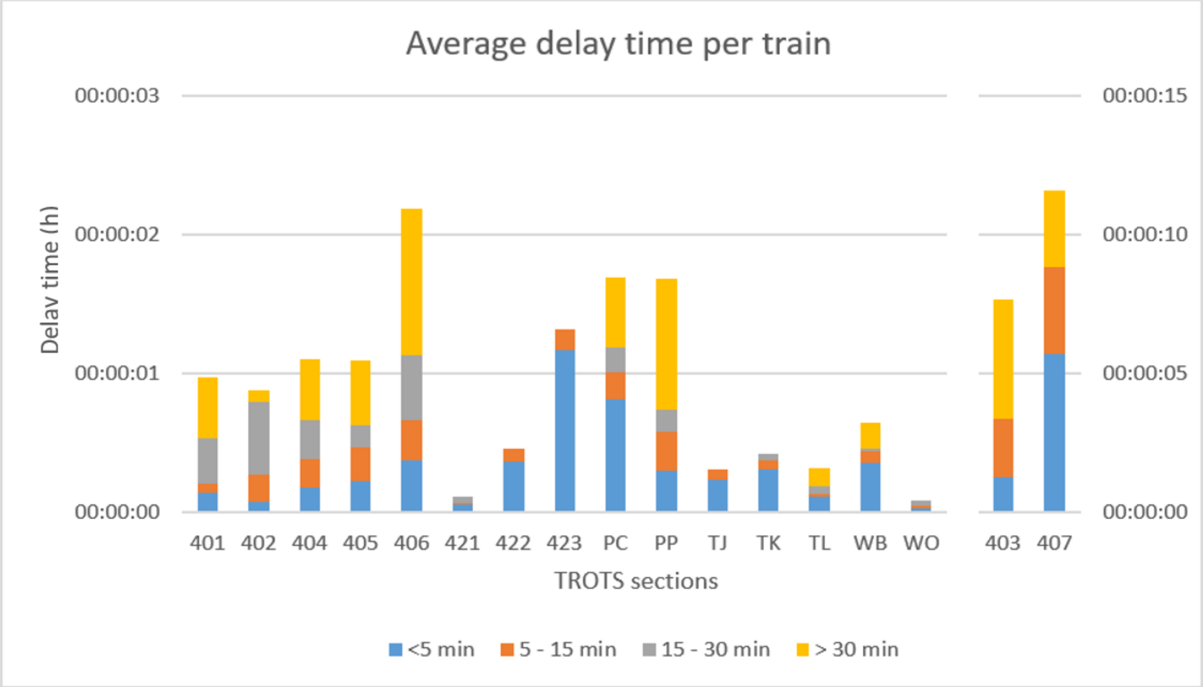


Figure 49 Average delay time per train per TROTS section at Zaandam

TROTS section selection for further analysis

In order to compare the frequency and severity of delays at all TROTS sections, the delay probability per train (Figure 48) and the average delay time per train (Figure 49) have been calculated by dividing the number of delays and total delay time by the number of trains that have used each TROTS section. In both figures, the delay probability and average delay time at TROTS sections 403 and 407 are shown in the right side of the graph with a different scale, as these two sections have a considerably larger delay probability and average delay time.

Section 403 is used by most freight trains passing through Zaandam. Apart from that, 403 can be used by intercity trains between Enkhuizen/Hoorn and Amsterdam that do not stop at Zaandam. The relatively high probability of a delay could be caused by freight trains, waiting for a free path to Uitgeest, or for a free path through the Hem tunnel. As noted before, the Hem tunnel is equipped with X/G-signals, which prohibit heavy trains, including most freight trains, from entering the tunnel, unless a free path throughout the entire tunnel can be guaranteed.

TROTS section 407 was used by 1.065 trains in 2019, approximately 3 trains per day. The track section is used for storing rolling stock, for shunting and for reaching the NCBG area at Zaandam (see Figure 44). TROTS section 406, on which a relatively high average delay time is measured as well, similarly is used for storing rolling stock and for shunting. It is unlikely that these delays are related to operational transitions. A further analysis of TROTS section 407 might provide useful insight into the effect of a NCBG-CBG transitions, which is why this section will be studied in more detail in section 7.3.

Leaving aside the outlier sections 403, 407 and (to a lesser extent) 406, some observations can be made based on Figure 48 and Figure 49. First, the platform tracks of Zaandam station (TROTS section 401, 402, 404 and 405) all have a similar average delay time of around 1 second per train (Figure 49). Delay probabilities between these four sections are more varied (Figure 48), but the delay probabilities are nearly equal for sections used in northern direction (section 401 and 402) and for sections used in southern direction (404 and 405). The distribution of average delay time among the four platform sections indicate that most delay time on these sections is caused by delays events lasting more than 15 minutes. As the built-up of average delay time is similar for all four sections, TROTS section 405 will be studied in more detail in section 7.3.

The TROTS section TJ, TK and TL represent the Hem tunnel, as noted before, only a small amount of delays is recorded on these sections and the duration of delays on these sections is limited, even though the Hem tunnel is one of the deepest tunnels in the Netherlands. One of these sections, TROTS section TL, will be studied in more detail in 7.3.

Setting the outliers aside, TROTS sections PP and PC have the highest average delay time among all other section. The distribution of delay time differs slightly in both sections. Short delays up to 5 minutes make up a larger share of delay time on section PC than on PP (Figure 49). As a result, the delay probability is significantly higher on PC in comparison to PP (Figure 48). As stated earlier, this is most likely caused by the delay of other trains at Zaandam station. Track section PP will be studied in more detail in section 7.3.

Based on the results of the analysis of TROTS sections in this section, no definitive conclusions can be drawn on the impact of operational transitions on train operations. Four TROTS sections have been selected for further analysis in order to find out to what extent operational transitions are a cause for delays and disruptions in railway operations.

7.3 TROTS subsection analysis

In this section, four TROTS sections (sections 405, 407, PP and TL) will be analysed in more detail using TROTS subsection data. As the physical distance between the three operational is large, it is unlikely that the three operational transition types have a significant influence on each other. Moreover, since each operational transition is different, a direct comparison of delays per subsection is of limited value.

The main purpose of the TROTS subsection analysis in this case study is to find common locations for delay events within each TROTS section. These sections will be analysed in more detail in section 7.4, where the causes for delays are analysed. The number of delays per TROTS subsection as well as the total delay time as a result of these delays are shown in Table 12. In contrast to the TROTS subsection analysis of Meteren (section 6.3), delays are not registered per TROTS subsection, but in groups of subsections. 278A-ET for instance, part of TROTS section PP, consists of five TROTS subsections and 194D/ET consists of the subsections 194DT and 194ET. This makes it more difficult to attribute delays to features in the railway infrastructure. Subsections with a total delay time of more than one hour in 2019 will be used for further analysis in this section and in section 7.4. A description of each (group of) TROTS subsections, that fulfil this requirement is shown in Table 13.

Table 12 Delay statistics for TROTS subsections at Zaandam

TROTS section	TROTS subsections	Number of delays	Total delay time (hours)
405	260A/BT	77	7:58:13
	295BT	2	0:05:25
		79	**8:03:38**
407	A264/281T	51	3:50:26
	285AT	2	0:12:29
		53	**4:02:55**
PP	278A-ET	59	4:19:31
	194A-CT	1	2:37:32
	194D/ET	26	4:38:50
		86	**11:35:53**
TL	705C/DT	2	0:24:51
	715BT	29	2:39:07
	296BT	3	0:07:25
	705A/BT	1	0:06:52
		35	**3:18:15**

Table 13 Description of TROTS subsections at Zaandam

TROTS (SUB)SECTIONS		**DESCRIPTION**
405	260A/BT	Platform track at Zaandam station. At the end of 260BT, an exit signal is located.
407	A264/281T	Level track with two switches, leading to a NCBG-area
PP	278A-ET	This combination of five TROTS subsections, with a total length of approximately 800 meter, is made up with an estimated gradient of 10‰ and a height difference of approximately 4 meter. At the end of 278ET, a signal is placed, protecting the passage of the bridge over the river Zaan.
	194A-CT	Swing bridge over the river Zaan. Bridge is constructed without catenary. At each end of the bridge, signs, ordering the train driver to turn off the traction, are placed.
	194D/ET	The two subsections are located after the Zaan bridge. Station Zaandam Kogerveld is located in 194DT. A signal is placed at the end of 194ET. The track is built with a slight downward gradient.
TL	715BT	715BT is located on the southern side of the Hem tunnel. 715BT is partly located on an upward slope with a gradient of 25‰, while the last 400 meter of the subsection is located on level track. At the end of 715BT, a signal is located.

For three of the four TROTS sections, 405, 407 and TL, delays are clearly concentrated in one (group of) subsection(s). On TROTS section PP, delays are more equally distributed over the entire length of the section. In Figure 50 and Figure 51, the delay frequency and the total delay time of the six remaining subsections are shown.

Some observations can be made on the results of Figure 50 and Figure 51, especially with respect to TROTS section PP. Firstly, only one delay was recorded on subsection 194A-CT, the swing bridge over the river Zaan. As this delay lasted two and a half hours, this delay is responsible for a considerable share of total delay time on the entire TROTS section (section PP). This indicates that stranded trains are a rare event to happen on the Zaan bridge, although the consequences of such events are large. Secondly, most delay events occur in front of the bridge, rather than after passing the bridge. 59 delays were registered on subsection 278A-ET, while only 26 delay events were registered on 194D/ET. However, the total delay time of delays that have occurred on 194D/ET is slightly higher than the total delay time on 278A-ET. Most delays in front of the Zaan bridge are most likely caused by trains waiting for a signal, while delays after the bridge might have other causes. These hypotheses will be tested in section 7.4.

TROTS subsection 715BT in TL shows little delays, both in frequency as in total delay time. Only one delay event lasting more than 30 minutes is registered at the subsection. The number of disruptions at the Hem tunnel therefore seem to be limited. For the two remaining TROTS subsections, it is difficult to see what causes these delays and delay patterns.

In section 7.4, the six TROTS subsections that have been selected in this section will be discussed in more detail. The primary causes for delays at these subsections will be investigated. Furthermore, large-scale disruptions that occurred at these subsections will be investigated in more detail, in order to gain more insight into the sequence of events causing large-scale disruptions.

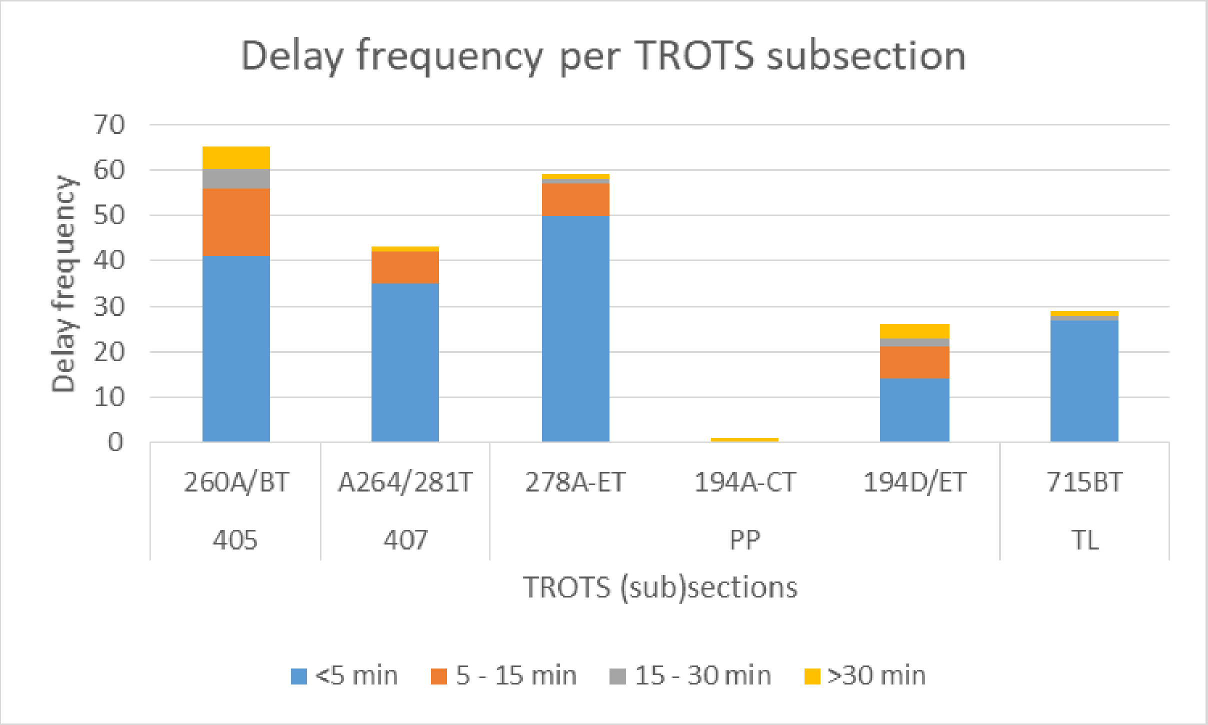


Figure 50 Delay frequency per TROTS subsection at Zaandam

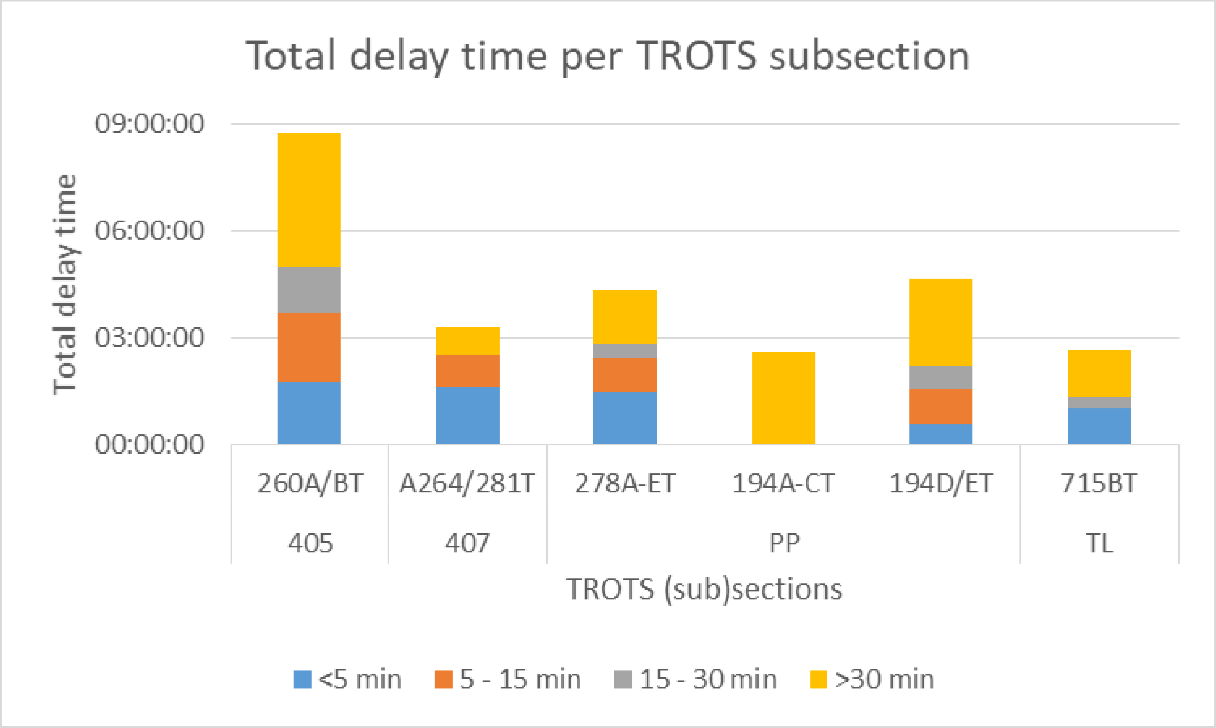


Figure 51 Total delay time per TROTS subsection

7.4 Delay causes at Zaandam

In this section, the underlying causes for delays are investigated. In subsection 7.4.1, a classification for delays will be presented. In subsection 7.4.2, the primary causes for delays at six TROTS subsections are investigated. In subsection 7.4.3, some large-scale disruptions are investigated in more detail.

7.4.1 Delay causes classification

For each delay event that took place in 2019 on one of the six TROTS subsections, a primary cause for delay has been determined. Several data sources have been used to determine the most likely delay cause. A comprehensive description of the used data sources as well as the methodology to determine the most likely delay cause are provided in section 4.4.

The delay categories that have been used to classify delay events are partially overlapping with the categorization used in the Meteren Case study. However, some delay types, such as delays caused by passengers, are unique to Zaandam, just as ETCS connection issues are unique to Meteren. In total, 13 delay categories have been constructed, which have been combined into seven groups of delay types (Table 14). The total number of delays as well as the total delay time per delay group are highlighted in bold. Some delay categories have not been merged into a group, in which case they are highlighted in bold as well. In Appendix Q.4, for each TROTS subsection, the number of delays per delay type is reported, as well as the total delay time per delay type.

Table 14 Delay categories at Zaandam

DELAY CATEGORY	FREQUENCE OF DELAYS (NO.)	TOTAL DELAY TIME (HOURS)	DESCRIPTION
WORK PROCESS TRAIN DRIVER	2	0:03:58	Various causes for delays which are caused by the work process of train drivers
WORK PROCESS CONDUCTOR	1	0:15:21	Various causes for delays which are caused by the work process of conductors
ROUTE SETTING (DISPATCHER)	28	1:22:20	The automatic route setting functionality has not provided a continuous train path, which had led to a train encountering yellow and red signals and being forced to slow down.
DISPATCHER MANDATE	7	0:12:58	Dispatchers can order train driver to adjust their regular driving behaviour for several reasons
WORK PROCESS	**38**	**1:54:37**	
ROLLING STOCK DEFECT	10	4:36:27	Due to a defect to the locomotive or to wagons, the driver is forced to stop or to continue driving with reduced speed.
INFRASTRUCTURE DEFECT	4	2:09:12	Due to a defect to the track infrastructure, train operation is hindered, which leads to delays
DEFECTS	**14**	**6:45:39**	
DELAYED BY OTHER TRAIN	61	4:57:50	Trains are delayed due to the delay of other trains. Trains have to wait until the next free path.
EARLY ARRIVAL	17	1:08:37	Trains arriving early have to wait until their reserved train path is available.
SIGNAL AT DANGER	**78**	**6:06:27**	
CONSTRUCTION WORKS	**6**	**2:23:28**	Due to construction works, some large delays are recorded on TROTS (sub)sections when maintenance rolling stock is stationary on these sections for a long time.
PASSENGER-CAUSED DELAYS	**3**	**1:08:43**	Passenger behaviour can cause delays. These delays are mostly found at station platforms.
MINOR DELAYS	68	1:55:48	Small delays up to three minutes, for which no specific cause for delay could be found.
VARIOUS CAUSES	4	1:56:38	Other delays that do not fit into any of the aforementioned categories
OTHER CAUSES	**72**	**3:52:26**	
CAUSE UNKNOWN	**12**	**4:07:12**	Delays, with a minimum duration of 3 minutes, for which no clear cause could be found.
TOTAL:	**223**	**26:18:32**	

7.4.2 Delay causes per TROTS subsection

In this subsection, the delay causes for the six TROTS subsections are presented. Figure 52, shows how often each delay type has occurred at each TROTS subsection in 2019. In Figure 53, the total delay time caused by these delay events in each subsection is shown. Figure 54 displays the relative contribution of each delay category per TROTS subsection. The seven delay categories that have been constructed in subsection 7.4.1 have been used.

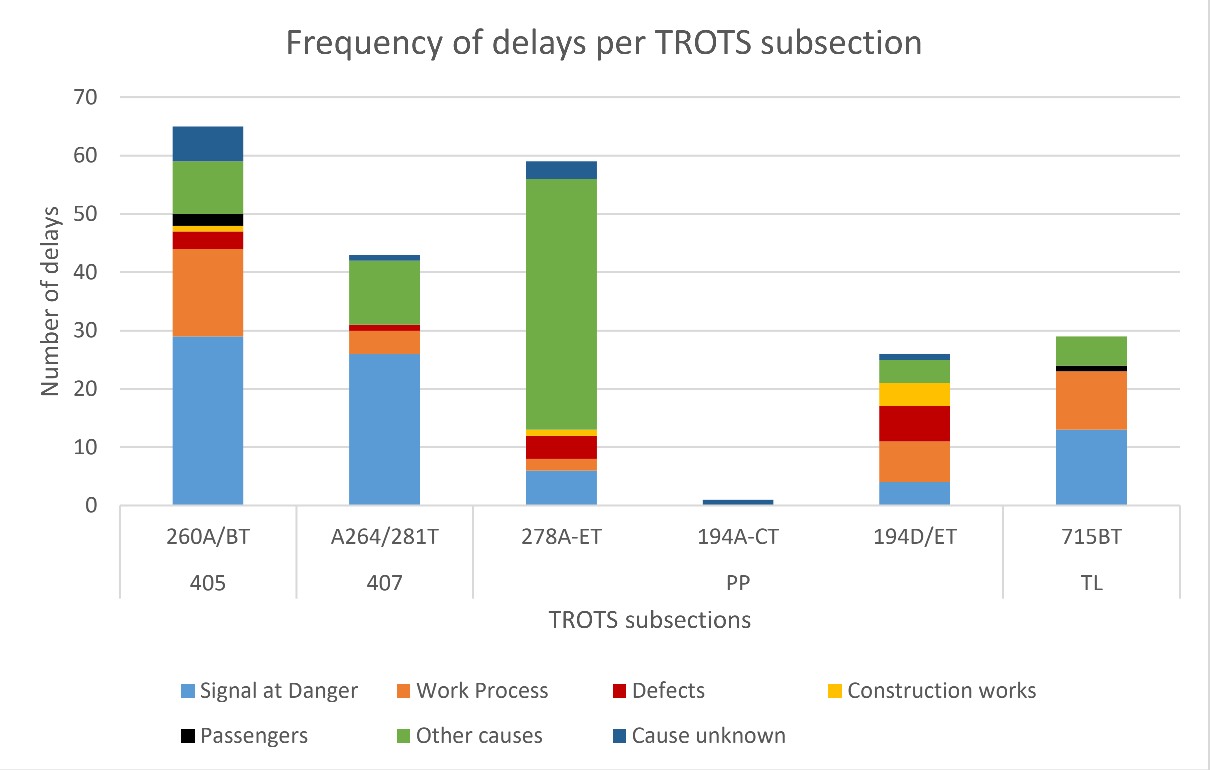


Figure 52 Frequency of delay types per TROTS subsection at Zaandam

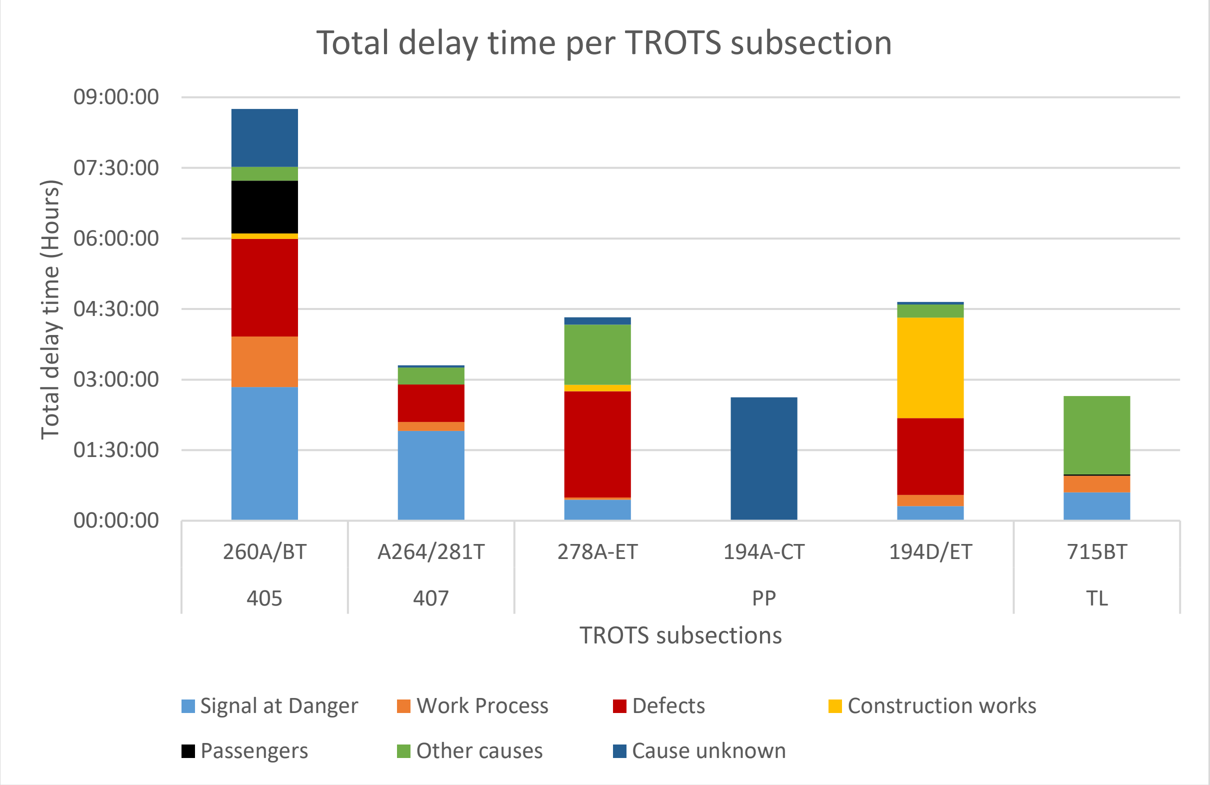


Figure 53 Total delay time per delay type and per TROTS subsection at Zaandam

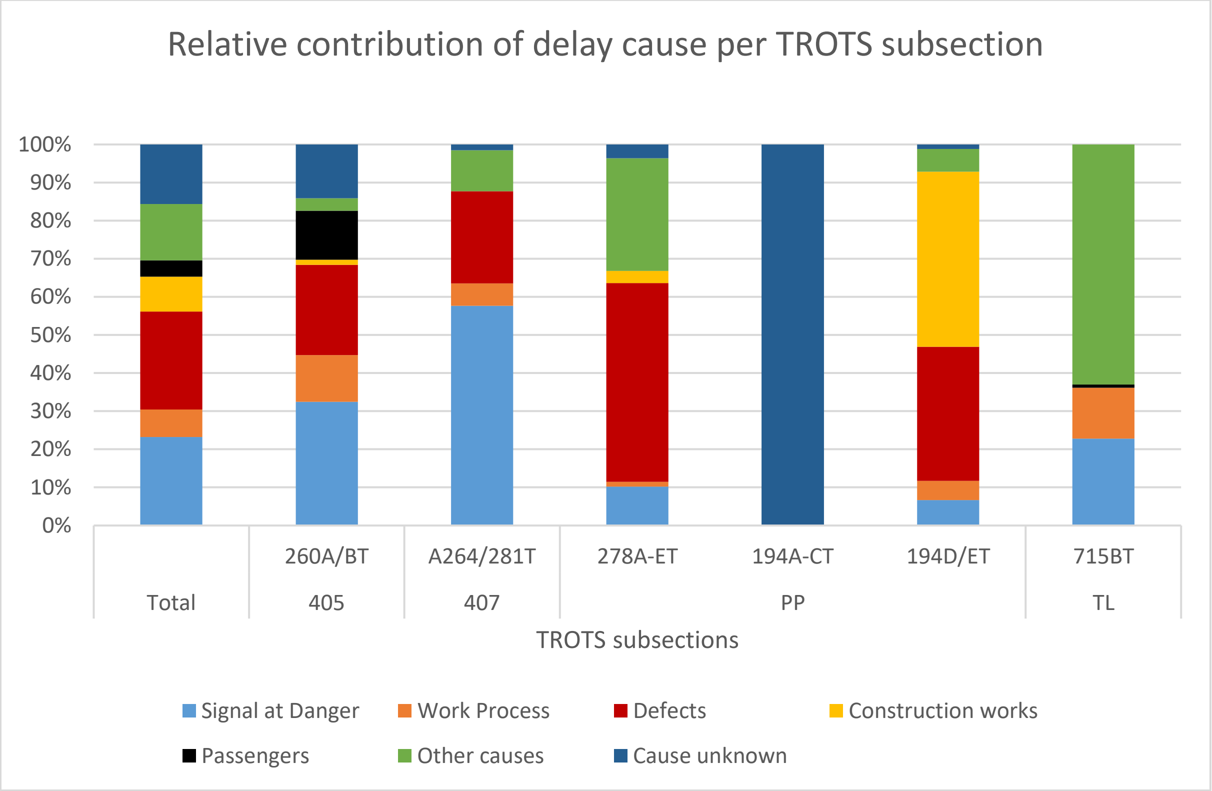


Figure 54 Relative contribution to total delay time per delay cause per TROTS subsection at Zaandam

Most delay events are caused by three delay categories. Of 223 registered delays in 2019, 78 delay events were caused by trains waiting for a signal at danger, usually caused by conflicting train paths. Furthermore, 72 delays were caused by ‘other delays’. Of those 72 events, 68 are registered as ‘minor delays’, delays lasting less than 3 minutes, for which no clear cause could be found. Finally, 38 delay events are a result of the ‘work process’ of one or multiple actors.

At TROTS subsection 260A/BT, platform track 5 at Zaandam station, most delay events are caused by waiting for a signal at danger and the work process of various actors in railway operations (Figure 52). Although these delays make up approximately two thirds of all delays, they only account for 45% of total delay time (Figure 53). Defects to rolling stock and infrastructure, passenger behaviour and construction works make up an almost equal share of total delay time (close to 40%) at 260A/BT, although only six delay events were registered in one of these categories. Passenger-caused delays with a relevant impact on train operations are only found at 260A/BT, which is logical for a platform track.

The main aim of a more detailed analysis of TROTS subsection A264/281T, TROTS section 407, is to find if transitions from CBG to NCBG would cause disruptions to train operations. However, train movements are not registered in NCBG areas. It is therefore not possible to find out to what extent this transition has any impact on train operations with this data. Trains entering the NCBG area from section 407 ‘vanish’, which is why delays cannot be registered. Most of the registered delays are of trains heading in the direction of the Hem tunnel, similar to trains on TROTS section 405 (Figure 54). This might explain why the relative importance of delay categories on both sections shown some resemblance, although passenger-caused delays were not registered on subsection A264/281T.

Significant differences can be seen between the three subsections that make up TROTS section PP. Only one delay event was registered at subsection 194 A-CT, the swing bridge over the river Zaan. However, this delay event lasted over two and a half hours. A train came to a standstill on the bridge without a clear reason, but as the locomotive was standing on the bridge, the train could not move under its own power. This event is described in more detail in box 7.4.3. The other two subsections, 278A-ET and 194D/ET have a higher rate of delay events. On 278A-ET, two infrastructure defects and two rolling stock defects were registered (Appendix Q.4) These four defects make up half of total delay time. The remaining delay time is caused by relatively small events. Six rolling stock failures were registered on 194D/ET. At least three of these rolling stock failures where caused by problems with the door mechanism of SNG (Sprinter Nieuwe Generatie) sprinter trains stopping at Zaandam Kogerveld, which is located in this subsection. Almost half of total delay time on 194D/ET is caused by trains used for construction works and maintenance tasks. As these tasks are mostly carried out during the night when no trains are scheduled, these trains have no effect on other trains or railway operations in general.

Finally, some small delays and one large disruption are observed on 715BT, the southern tunnel end of the Hem tunnel. Small delays are caused by signals at danger at the end of subsection 715BT, or by work process related factors. The one large delay event is caused by a freight train that was unable to make it through the tunnel. The train stranded on the upward slope of the Hem tunnel. The cause for this disruption was a lack of power of the locomotive pulling the train. Whether the locomotive was not powerful enough, had a technical problem leading to power loss or the train entered the tunnel with a too low speed is unclear. The disruption of this track lasted one hour and 18 minutes. As the total delay time on 715BT is less than three hours in 2019, this event has a large effect on the overall performance statistics of trains on this subsection.

7.4.3 Disruption causes at Zaandam

In subsection 7.4.2, the primary causes for delays have been discussed and analysed. In order to determine why some delays last a long time, it is useful to analyse the sequence of events that led to these long delays. In this subsection, delays with a duration over 30 minutes will be analysed in more detail. A different approach has been used in comparison to the Meteren case study (subsection 6.4.3), where the relevant operational transitions are listed for each delay event. In Table 15, for each delay event lasting more than 30 minutes, a short description is given. Spoorweb data has been used to determine the event sequence for each delay.

Of the 11 delay events, four occurred at TROTS subsection 260A/BT, track 5 at Zaandam station. Furthermore, one delay occurred on subsection A264/281T (TROTS section 407) and another delay event occurred on subsection 715BT (TROTS section TL). The final five events occurred on the three separate subsections of TROTS section PP, one on 278A-ET, one on 194A-CT and three on 194D/ET.

At subsection 260A/BT, two disruptions occurred as a consequence of passenger (mis)behaviour. One delay at this subsection, train 303073, was caused by a fire in a substation. The final delay over 30 minutes was caused by a defect door mechanism of the train. None of these delay events seem to have any connection with operational transitions at either the Zaan bridge or the Hem tunnel.

As stated in subsection 7.4.2, movements between CBG and NCBG areas are not registered, which means that no delay events as a result of this transition have been found at A264/281T (TROTS section 407). The single delay event that has been recorded on subsection A264/281T is caused by the aforementioned fire in a substation, prohibiting trains from continuing their journey.

One large delay event lasting more than 30 minutes was recorded on subsection 715BT in 2019. Train 60604, heading from Beverwijk to Amsterdam Westhaven via Uitgeest and Zaandam, reportedly did not have sufficient power to make it up the upward slope of the Hem tunnel. Train 60604 is a regular train between these two places, with an average frequency of 3 or 4 trains per week in 2019. Freight trains to Beverwijk are planned to be driven by BR 189 freight locomotives. The train weight of this train service varies between 250 tons and 2300 tons. On February 7th, the train was headed by a BR189 locomotive and the train weight was 1843 tons. It is therefore unlikely that the train stranded as a consequence of an overweight train or a lack of power from the engine. As a complete train path was available for this train throughout the Hem tunnel, route setting issues are unlikely to be the cause of this stranding either. Some remaining options are: a technical defect to the locomotive (either hardware of software), an intervention by ATB-EG causing the train to slow down and misjudgements made by the train driver.

Table 15 Causes for delays lasting more than 30 minutes at Zaandam

TRAIN NO.	DATE (2019)	LOCATION	DELAY (HOURS)	DESCRIPTION OF DELAY
74024	9-5	405 260A/BT	0:55:08	Due to earlier delays at Amsterdam Sloterdijk caused by passengers, train 4024 did not complete its journey to Uitgeest, but was turned around at Zaandam. The turnaround time was 55 minutes.
3363	19-11	405 260A/BT	0:46:56	Delay caused by behaviour of passengers. Train continued after incident was settled.
303073	22-4	405 260A/BT	0:43:28	Train was delayed by defect infrastructure. A fire had broken out in a substation. Similar delay cause as for train 89289.
3377	23-12	405 260A/BT	0:42:47	The door mechanism of the train did not function properly, prohibiting the train form leaving Zaandam.
89289	22-4	407 A264/281T	0:47:51	Train was delayed by defect infrastructure. A fire had broken out in a substation. Same delay cause as for train 303073.
61604	7-2	TL 715BT	1:17:37	Train 61604 passed Zaandam via TROTS section 407 with a complete train path throughout the Hem tunnel available. The train did not make it up the upward slope of the Hem tunnel. A lack of power was reported as the primary cause for this disruption. An assistant locomotive was attached to the rear of the train to push it out of the tunnel.
4552	20-8	PP 278A-ET	1:28:02	Shortly after departing Zaandam, train 4552 developed problems with the in-train circuit breaker (Dutch: snelschakelaar). An assistant locomotive was called in to move the train.
4529	8-4	PP 194A-CT	2:37:32	Train stranded on one the Zaan bridge for unclear reasons and therefore was not able to move under its own power. An assistant locomotive was called in to move the train.
56144	2-5	PP 194D/ET	1:12:00	Maintenance train that remained on subsection 194D/ET for a longer period of time. No other trains where influenced or disrupted by this train as this event happened during the night.
3310	30-8	PP 194D/ET	0:43:11	The door mechanism of the train did not function properly, prohibiting the train form leaving Zaandam Kogerveld.
57180	1-8	PP 194D/ET	0:31:06	Maintenance train that remained on subsection 194D/ET for a longer period of time. No other trains where by this train as this event happened during the night.

A technical defect to train 4552 at TROTS subsection 278A-ET led to a delay of one hour and 28 minutes. There is no apparent connection between problems with the on-train circuit breaker and the Zaan swing bridge, a couple hundred meters further on. At subsection 194A-CT, one train has stranded on the Zaan bridge, unable to continue. The train was driving toward Zaandam on the left-side track (which is not common) in order to overtake another train that was stranded on the other track of the Zaan bridge (see box 7.4.3). It is unlikely that a too low line current caused this stranding, as no such events have been recorded at the Zaan bridge (see box 3.2.3).

Finally, three delay events lasting more than 30 minutes occurred on 194D/ET. Two of these events where caused by maintenance trains standing for a long period of time during the night in this section. No disruption was therefore caused. One delay was caused by the failing door mechanism of a commuter train. This defect became apparent at station Zaandam Kogerveld, which is why the delay is registered in this subsection.

Box 7.4.3 Double trouble

On its approach to Zaandam, train 3327, a sprinter service from Hoorn to Leiden, developed difficulties with the braking system of the train. Air was escaping from the brake cylinder, which meant that the brakes where applied to the train. The train, three coupled SNG-units, came to a halt on the Zaan swing bridge at 8:03 AM. The pantograph of the first unit did not touch the catenary as it was standing on the catenary-free part of the bridge. After consulting the dispatching centre of Alkmaar, the train driver decided to let down the pantograph of each of the three units, walk to the other side of the train, raise the pantograph of the rear unit, which was not standing on the bridge and reverse the train of the bridge.

At 8:40, train 3327 reversed of the bridge and stopped at Zaandam Kogerveld, where it had left 40 minutes earlier. Meanwhile, other traffic was led around the stranded train, including train 4529, consisting of an electric locomotive type 1700 and 4 DDM double-decker coaches. For unknown reasons, this train too came to a standstill on the Zaan bridge at 8:24. As only the locomotive has a pantograph in this train composition and the locomotive was standing on the catenary-free part of the bridge, assistant traction was required to remove the train from the bridge. At 9:27, a diesel locomotive of DB Cargo left Amsterdam Westhaven for Zaandam. The assistant locomotive, type 6400, arrived at Zaandam at 9:53 and was couple to train 4529 at 9:57. Due to busy train traffic, train 4529 was moved off the Zaan bridge toward Zaandam station at 10:51. The assistant locomotive was decoupled at Zaandam and returned to Amsterdam Westhaven. Train 4529, now renumbered as train 89290 continued its journey towards Amsterdam central station at 11:30

7.5 Conclusion on operational transitions at Zaandam

In this chapter, a case study of Zaandam station and its surroundings has been conducted with the purpose of analysing multiple operational transitions in the vicinity of Zaandam station. Three operational transitions have been studied: the catenary-free swing bridge over the river Zaan, the Hem tunnel and the transition between CBG and NCBG areas. Section 7.2 and 7.3 have been used to answer the second sub question: ‘To what extent do disruptions emerge from operational transitions?’.

Using data analysis of the number and duration of delays per TROTS section, it could be established which TROTS sections have a high delay probability or a high average delay time (section 7.2). In absolute terms, none of the TROTS sections showed notably high numbers on either of these metrics, certainly not if compared with the delay statistics on some TROTS sections at Meteren junction. Moreover, some TROTS sections had a relatively low delay probability and average delay time, even though an operational transition was located on this section. This is especially the case with the Hem tunnel, where a relatively small number of delays with a limited total duration have been observed. This is not only true for TROTS section TL, which was subjugated to further analysis, but also for the other two tracks running through the Hem tunnel.

At the Zaan bridge, a relatively high delay probability and average delay time could be observed, which is why one of the tracks over the bridge, TROTS section PP, was used for further analysis. The delay probability and average delay time of TROTS section 407 were very high compared to other sections at Zaandam. Finally, section 405 was also selected for further investigation in order to find out what type of delays can be observed at platform tracks.

In contrast to the Meteren case study, delay data for individual TROTS subsections could not be used. Data is reported for groups of subsections, which limits the accuracy with which delays can be attributed to features in the railway infrastructure, such as transitions and signals. Nonetheless, using this analysis, six (groups of) subsections from the four aforementioned TROTS sections have been selected for further analysis (section 7.3).

The results from the TROTS section and TROTS subsection analysis are mixed with respect to the second sub question. Although a slightly higher delay probability and average delay time can be observed at the Zaan bridge and at TROTS section 407 (near the CBG-NCBG transition), this does not hold for TROTS section TL (Hem tunnel). The operational transitions do not cause a lot of delays and are not responsible for a large share of total delay time on their (sub)sections.

In section 7.4, a delay cause analysis was conducted in order to answer the third sub question of this research for the Zaandam case: What are the underlying causes for failed operational transitions?

First, CBG-NCBG transitions could not be investigated using this method. As train movements between CBG and NCBG are not registered, delays on these (sub)sections are not registered as well. No conclusions can therefore be drawn on the effect of this transition type with this method. Observations at NCBG locations and interviews with train drivers and dispatchers may provide more insight into the effect of CBG-NCBG transitions.

Second, the catenary-free Zaan bridge has been the cause of some stranded trains. Two of these events are described in box 7.4.3. One of these events was the result of a technical failure, unrelated to the transition at the bridge. For the second stranding, no clear cause could be found. The train was operating under a dispatcher mandate, which allowed the driver to drive on the left track past the previously stranded train on the bridge. To what extent the dispatcher mandate had any influence on the stranding of the second train is unclear. In general though, the number of stranded trains on the bridge is limited. Some defects to rolling stock and infrastructure at subsections at either side of the bridge have caused considerable delays. These defects are not connected to the functioning of the bridge or to the transitions required by the train driver when passing this bridge. In some cases, delays occur when the bridge is opened for longer periods of time or when it opens on irregular times, but this has no connection with the operational transitions of this bridge.

Third, the steep inclines of the Hem tunnel hardly cause any large delay events. Only one delay event lasting more than 30 minutes was recorded in 2019 on the three tracks of the Hem tunnel. Analysis of this events suggests that a defect to rolling stock, intervention by ATB-EG or mishandling of the situation by the train driver are possible causes for this event, but this is not certain. A couple of delay events of passenger trains where caused by an ATB-EG intervention, leading to trains coming to a standstill in the tunnel. These trains where, however, able to continue without assistance of other trains. The limited number of stranded freight trains in the Hem is most likely the result of the X/G-regime at the Hem tunnel.

Another factor that may influence the number of delays in the Hem tunnel is the functioning of the ATB-EG system. The maximum speed in the Hem tunnel is 120 km/h. ATB-EG intervenes when the train speed exceeds 130km/h, due to the limited number of enforceable speed limits (see section 3.2.2). The speed limit for freight train entering the Hem tunnel is 40 km/h in southern direction and 30 km/h in northern direction. In both cases, an entry speed limit of 40km/h is enforced by ATB-EG. When the driver of a freight train adheres to the tunnel entry speed, the estimated speed at the bottom of the tunnel is 80 km/h, well under the ATB-enforced speed limit of 130 km/h at the bottom of the tunnel. The result of this is, that the number of ATB-interventions as a result of overspeed is limited. Although this is not necessarily desirable from a safety perspective, it does mean that slight and medium overspeed at the bottom of the Hem tunnel do not directly lead to an intervention by the ATP system.

Chapter 8. Case study 4: Human factors in ATP system transitions

In this case study, the role of human factors in failed ATP system transitions will be investigated in more detail. In chapter 5, it was established that this is a major cause for disruptions at the HSL-Zuid and the Betuweroute. The case study of Meteren junction (Chapter 6) confirmed that connection issues with the RBC are a major cause for delays.

The main focus will be on ATB – ERTMS transitions, but other transition types will be briefly mentioned as well. As the number of transitions between ATB and ERTMS is expected to increase in the upcoming years (see chapter 1), investigating train driver behaviour can help to identify factors that influence the vulnerability of this operational transition type. In this chapter, both the initial causes for failed ATP system transitions will be investigated as well as the way in which these failed transitions are resolved. Interviews are used as data for this case study. In Appendix A, an overview is given of the conducted interviews. Section 8.1 focusses on the initial causes for transitions failures. Section 8.2 will cover the means by which these transition failures are resolved. In section 8.3, conclusions are drawn on the role of human factors in ATP system transitions.

8.1 Primary causes for ATP system transition failures

In the context of ATB-EG – ERTMS transitions, the term 'primary causes' is defined as the cause for a train to start slowing down as a result of an unsuccessful transition in ATP system. Braking is therefore not initiated by the train driver, but by the on-board ETCS or ATB-EG equipment. There are multiple reasons that can cause an intervention by the on-board unit during a transition: a failure to acknowledge the transition, technical failures and GSM-R signal interference.

When the same type of failure occurs frequently, train drivers are better able to anticipate on these failures and to come up with workarounds to prevent such failures form happening. In the final part of this section, some comments are made on the role of human factors as primary cause of failed transitions.

Technical defects

Some technical issues or defects can prevent trains from connecting with the RBC. Of these technical defects, a failure of the on-board modem, which is responsible for receiving GSM-R signals, is the most common one (Appendix H; Ministry of Infrastructure and Water Management, 2014b). When no connection to the RBC can be established, the train will come to a complete stop. A modem malfunction may be caused by actual defects, which the train driver is unable to fix. Modem malfunctions can also be caused by loose or dusty adapters in the modem, which occasionally occur (Appendix F, Appendix J). Due to the large variety of possible defects or the modem, identifying the exact nature of the malfunction and subsequently solving it requires a high level of experience of the train driver with this kind of situations (Appendix L). When a train comes to a stop as a result of a lacking connection between on-board unit and RBC, several attempts are made to create a connection automatically. Only when attempts to create a connection with the RBC repeatedly fail, the train driver checks the modem if it has any malfunctions.

When a NS train driver cannot create a connection between the on-board unit and the RBC, he or she can call on specialized helpdesks, which have been set up by NS in order to support train drivers that experience difficulties with ERTMS (Appendix F, Appendix L). While NS has a dedicated helpdesk available for train driver, smaller railway companies often have to rely upon less formalized communications between train drivers (Appendix J, Appendix K).

ETCS-related problems can be solved by the train driver if he or she knows how to solve the problem. While a defect modem primarily impacts one train, defects to the RBC itself impact all trains that are connected to it. Although RBC failures are rare (Appendix J), their impact on train operations is very large, as no train is able to receive new movement authorities when the RBC is not functioning properly.

GSM-Railway signals

Malfunctioning technology for transmitting and receiving radio signals are not the only reason why a connection between RBC and on-board ETCS unit cannot always be established. GSM-R is used as a means of data transmission between trainside and trackside systems. The frequency bands of GSM-R are 876 to 880 MHz and 921 to 925 MHz. In the EU, public GSM networks operate in the frequency bands of 880 to 915 MHz and 925 to 960 MHz. Furthermore, each individual member state of the EU can use the 873 to 876 MHz and 918 to 921 MHz bands for domestic usage (European Commission, 2016; see Figure 55). In the Netherlands, these national bandwidths are exclusively used for military aviation purposes (Ministry of Economic affairs, 2014).

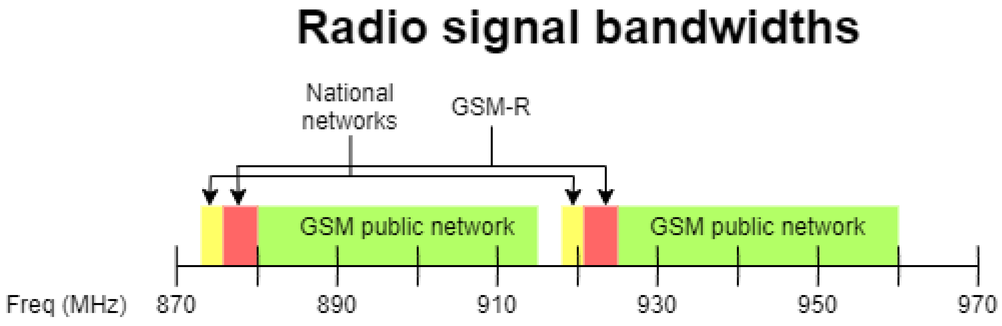


Figure 55 Radio signal bandwidth of GSM-R, public GSM and national networks in the EU

Due to the close proximity of bandwidths used for other networks, the GSM-R signals and signals of other networks occasionally interfere with each other (ERA, n.d.). As a result of these interfering signals, no stable radio connection between the RBC and the on-board ETCS unit can be established and no movement authority can be sent to the train. The degree to which other signals are able to interfere with GSM-R signals are very much dependent on local circumstances. A single misplaced or even misaligned antenna can cause a great deal of signal interference (Appendix F). The relative strength of GSM-R signals in comparison to the signal strength of other, public networks also influences the degree to which signals are interfered (Appendix I). Similarly as signals of public networks are able to interfere with GSM-R signals, GSM-R signals interfere with public network signals. Increasing the strength of GSM-R signals will therefore decrease the quality of public networks, which makes simply increasing the strength of GSM-R signals to overcome the interference by other signals an unsuitable solution.

One of the ways in which the issue of signal interference is being addressed, is by improving the radio frequency filters of on-board modems (Appendix I; ERA, n.d.). The main purpose of a radio frequency filter is to remove signals with a frequency out of the accepted frequency bands of 876 to 880 MHz and 921 to 925 MHz. New rolling stock is being equipped with upgraded modems, containing better radio frequency filtering abilities (Appendix I). Industry standards for modems radio frequency filtering have also been upgraded in order to reduce the impact of signal interference on the reliability of radio communication with GSM-R (EIRENE, 2015).

Anticipating on transition failures

During an ATB – ETCS transition, the role of the driver is limited to acknowledging the transition, if this is required by the on-board ETCS unit. In the case of known transition problems (Box 8.1), the driver can act in advance to reduce or eliminate the risk of a specific transition failure from happening. Anticipating on transition failures is possible when the conditions that cause transitions to fail are known. When these condition are known, the train driver can prevent these conditions from occurring (Appendix M).

Box 8.1 GSM-R registration at border crossings (based on Appendix K and Appendix L)

Although the scope of this research is operational transitions in the Netherlands, it is interesting to see an example of a failed ATP transition on a track section at the border. Trains do not only use GSM-R for communication with the RBC, but for radio communication in general. When a train is made ready for service, a connection with the GSM-R network that is available is made. International trains, for instance, driving from Germany to the Netherlands, would register to the German GSM-R network. When entering into another country, the train would have to be reregistered to the GSM-R network of the other country. A balise group would give the order for registration to the domestic GSM-R network. At the Zevenaar border crossing, this balise was not present for some time. Trains entering the Netherlands would retain their connection to the German GSM-R network. Eventually, when entering the first tunnel on the Betuweroute, trains would lose connection with GSM-R Germany and subsequently lose their connection with the RBC. Network registration balises were added to resolve the issue at the border crossing. Before the extra balise group was added, train drivers would often reset the train radio after passing the border, in which case the radio would connect to the network with the strongest signal, which often was the Dutch GSM-R network.

Paradoxically, such workarounds can be come up with and used without knowing why the workarounds actually work. In some cases, workarounds are discovered accidently. An example of such workarounds is used by train drivers operating G2000 diesel locomotives, which are used by multiple freight operators in the Netherlands. In this locomotive, ETCS and ATB are not integrated into a single DMI. A separate ATB-EG unit is present, which is connected to the on-board ETCS unit via a Special Transmission Module (STM). During transitions from ETCS to ATB-EG, situations occur in which the on-board ETCS unit does not recognise the STM, so that no connection can be established with the on-board ATB unit and the train will be forced to a stop (Appendix M).

Eventually, a solution was found for this problem. When the train driver would start preparing the locomotive for service at the beginning of his or her shift, the driver would active the emergency brake before starting the preparations. When this procedure is followed, the aforementioned connection problems with the STM would not occur. Although the solution is successful in eliminating connection issues between the on-board ETCS unit and the STM, it is not clear to the train drivers or support staff why this workaround solves the connection issue (Appendix M). This is only one example of a workaround used by train drivers to deal with potential transition failures. Train drivers know multiple workarounds for preventing certain failures. Often, they do not know why they prevent failures, but they use them nonetheless (Appendix M).

The role of human factors as primary cause for transition failures

Both technical defects and GSM-R connection issues can hardly be attributed to (a lack of) actions of the train driver, leaving aside the situation described in Box 8.1, which is an exceptional situation that has been solved in most cases. Train driver behaviour does, however, play a role in (un)successful transitions when the transition has to be acknowledged. Although the task of acknowledging a transition from ATB-EG to ERTMS is a relatively simply one, there are multiple circumstances, in which the acknowledgement could lead to a failed transition.

When transitioning from any ETCS level to level NTC (National Train Control), acknowledgement of this transition by the train driver is always required, as NTC is considered to offer a lower safety level than ETCS (ProRail, 2018b; Appendix I; Appendix J). Within 5 seconds after receiving the notification of the transition, the driver has to acknowledge the transition to ATB-EG. When the driver does not acknowledge the transition in time, the service brake will be applied. The brake is released when the driver acknowledges the transition (ProRail, 2018b). When transitioning from ATB-EG to ETCS, acknowledgement is only required for trains that are equipped with specific types of on-board ETCS equipment. The ETCS equipment of some manufacturers require an acknowledgement by the driver when transitioning from level NTC to ETCS and vice versa in all circumstances (Appendix J; ProRail, 2018b). Other manufacturers only require acknowledgement by the train driver when transitioning from ETCS to NTC (Appendix I, ProRail, 2018b). As the safety level of ETCS is considered higher than ATB-EG, an acknowledgement of the transition is not required.

Currently, most train drivers on the HSL-Zuid regularly drive one type of train: the bombardier TRAXX MS2. The Bombardier-fabricated on-board ETCS equipment requires acknowledgement in all cases, when transitioning from ERTMS to ATB-EG and vice versa. Train drivers of NS International operate TRAXX MS2 locomotives for the Benelux services as well as Thalys trains between Paris, Brussels and Amsterdam. The TGVs used for the Thalys train service have been built by Alstom, who also built the on-board ETCS equipment for that train. NS International train drivers also partially operate the ICE train services between Amsterdam and Frankfurt, which uses the ETCS-equipped Amsterdam to Utrecht railway line. NS international train drivers, as well as train drivers of freight railway companies with a mixed fleet of locomotives, have to work with different on-board ETCS units with different operating conditions. This is only a small proportion of the entire population of active train drivers. Most train drivers that operate on ETCS-equipped trains only have to work with one ETCS system. In future years, when the number of trains and railway lines that are equipped with ETCS will expand, train drivers will have to become accustomed to varying types of on-board ETCS units and possibly with varying types of ETCS infrastructure. Although on-board units and infrastructure are constructed to the same baseline, manufacturers can make different choices in the design of their products.

While TRAXX MS2 locomotives require the acknowledgement of the train driver in all cases when transitioning between ETCS and ATB (Appendix J; Appendix L), SNG sprinter trains, constructed by CAF, only require driver acknowledgement when transitioning from ERTMS to ATB-EG (Appendix I). As ERTMS has a higher safety level than ATB, no transition is required when transitioning form ATB-EG to ERTMS (Appendix I). The differences in operating principles might become problematic when train drivers will operate both train types and experience both ETCS systems. Situations can occur where the train driver is not aware that the transition from ATB to ETCS has to be acknowledged, as he or she implicitly or explicitly assumed that no acknowledgement is required for this specific train type. When the driver realises that acknowledgement is required, possibly after a short period of confusion over the unexpected signal, the five second acknowledgement time may have already passed and the train will start braking.

Parallels can be seen between the aforementioned hypothetical situation and the finding of Large, Golightly and Taylor (2014), who found that Driver Advisory Systems (DAS) can increase driver workload as these systems sometimes give conflicting information with the drivers internal representation of the situation. The temporary high level of workload will mean that the driver will focus on the ATP system transition and focus less on other possible transitions such as power supply system transitions, as is the case on the entrances of the HSL-Zuid and Betuweroute. Furthermore, Pickup et al. (2005) noted that driver effort, does not directly respond when workload increases, this may lead to the driver missing information. Similarities can also be seen between the unexpected acknowledgement of an ATB to ERTMS transition and automation surprises, in which drivers of autonomous cars or pilots required quite some time to regain full control of the situation after an automation surprise had occurred (Merat et al., 2014; Stoop & Van Kleef, 2015; Sarter, Wood & Billings, 1997; De Boer & Dekker, 2017).

Whether surprises occur in aviation, while driving autonomous vehicles or while operating a train, the operator needs time to readjust their mental state to a new situation. If this time is not available, in situations where multiple transitions are combined for instance, the train driver may not be able to successfully accomplish the other transitions, even if he or she acknowledges the transition from ATB to ERTMS in time. The fact that the concentration of the train driver has been diverted by an unexpected event increases the chance that more errors will be made. Different operating principles of different on-board ETCS units can therefore lead to an increased probability of failed transitions from ATB to ERTMS. Especially when the driver is already distracted before the transition point by other factors, uncertainties in operating conditions are undesirable. More research, however, is required to investigate to which extend differences in operating conditions of on-board ETCS units influence the probability of a failed ATP system transition acknowledgement.

8.2 Consequences of failed transitions and recovery strategy

As described in section 8.1, the role of the train driver as a primary cause for failed operational transitions is limited. A hypothetical situation has been described where human factors could play a role, but further research will have to point out whether train drivers may be confused as a result of different operating principles of different on-board ETCS units. Prior to the ATP system transition, however, train drivers can perform certain actions are use ‘workarounds’ that reduce or eliminate the probability of a failed transition. In this section, the consequences of failed transitions are described. Also, the effects of driver education and experience on coping with failed transitions are discussed. Finally, the most common means by which failed transitions are solved are described.

Train driver skills and support

The number of possible defects or malfunctions when transitioning from ATB-EG to ERTMS is large. Therefore, it is often unclear to the train driver what the exact cause of a failed transition is. Furthermore, the on-board ETCS unit gives little information on the exact nature of the failure via the DMI and even less information on how the system failure could be solved. A distinction should be made between NS train drivers on the one hand and the train drivers of other railway operators that have to deal with ATB – ERTMS transitions on the other hand (Appendix M).

NS train drivers facing ETCS-related problems in operation have to capability of contacting a designated helpdesk, which can help the train driver to solve the issues at hand. This helpdesk is staffed with experienced train drivers (Appendix J). This helpdesk has access to real-time information on the vehicle status of each locomotive on the HSL, information that is inaccessible for train drivers. With the help of the helpdesk staff, NS train driver stranded on the HSL, are able to resolve most problems (Appendix F; Appendix M). The helpdesk plays an important role in solving ETCS-related issues. As a result, a lot of knowledge is accumulated in the helpdesk staff. As train drivers are expected to contact the helpdesk, their education for driving on the HSL is limited, much to the dissatisfaction of the train drivers in question, who consider their own education for driving on the HSL inadequate (Bremmer, 13-03-2019; Appendix M).

In contrast, train drivers of other (mostly freight) railway operators lack any form of structural support during failures. These drivers therefore have to rely more on their own experience and knowledge. The in-door education of train drivers for smaller railway operators is therefore more focussed on technical knowledge of locomotives and rolling stock. Drivers of smaller railway operators are also more inclined to solve the problems themselves initially, rather than contacting anyone for help. Only when the attempts of the driver turn out to be fruitless, will the driver contact others. Usually, train drivers contact colleges from the same railway operator or alternatively, they might contact befriended drivers of other operators (Appendix M).

A general lack of information, either through insufficient education or because the on-board ETCS unit provides little information to the driver, can cause safety issues if this lack of information is combined with a lack of motivation by the driver (Keckland, 2001). Informing the driver, even if he or she is not able to solve the problem, may keep the driver more involved in the entire process of recovery.

Apart from acquiring knowledge through education and through external support, train drivers get more experienced through repeatedly encountering the same situations. As stated by Rajabalinejah, Maartinetti & Van Dongen (2016), the number of fault made by drivers decreases with increasing levels of experience. Very experienced drivers might become complacent and pay less attention to details, thereby making more faults. Similar patterns can be seen in recovering from failed transitions. Experienced drivers know better how to solve certain issues, as they've encountered those transition issues before. Furthermore, they know whom to contact in case they are not able to solve the problem themselves (Appendix J; Appendix M).

Solving failed transitions

As the number of possible defects or malfunctions is sizeable, train drivers often do not try to find out what the cause of the failed transition is, but rather they focus on a speedy recovery. As the failure cause is often unknown, train drivers often simply reset the entire on-board ETCS unit, which takes approximately 15 minutes (Appendix K; Appendix L). By resetting the system, all potential issues are resolved at once. When the train driver does not reset the entire ETCS unit, but tries to identify and solve the exact cause for the failure, other failures often occur while trying to recover. Often, multiple software problems occur at once. Resetting the entire system is the easiest way of recovering in those circumstances. In case similar defects occur frequently at the same location or with the same locomotive type, smaller railway companies will try to find a solution in coordination with ProRail or, when no solution can be found, workarounds will be used to reduce the frequency of these malfunctions, as described in section 8.1 (Appendix M).

Occasionally, the on-board ETCS unit will give a detailed explanation of the type of malfunction and of the actions the train driver has to undertake in order to resolve a failure. Not all on-board ETCS unit types give these indications. If this information is provided by the on board ETCS-unit, the train driver mostly follows the instructions given by the on board ETCS-unit, rather than resetting the entire system (Appendix M).

External factors influencing driver behaviour

Train driver behaviour is not solely influenced by the available information and the driver's own knowledge and skill, but also by their ability to withstand pressure and to deal with stress. When a train is delayed as a result of a failed transition, this can have large consequences for the rest of the journey. For passenger railway operators, even minor delays can cause passengers to miss their connection. For freight operators, delays often lead to freight trains losing their train path. These trains have to wait until the next free train path becomes available (Appendix M).

For train drivers of both passenger and freight railway operators, there are clear incentives to stick to the timetable. When a failure occurs that leads to delays, not all train drivers possess the patience and stress resistance to wait before the system has been reset. Drivers might not wait until the system has been fully reset, a process which can take several minutes up to 15 minutes and attempt to restart the train even though the system reset has not been completely finished (Box 8.2; Appendix M).

Pickup et al. (2005) refer to this situation as an increase in internal workload, a component of workload that refers to the goals and objectives of each individual train driver. Some drivers may want to prevent delays to passengers and goods no matter what it takes, while other drivers are more complacent in these matters and take delays as a fact of life that they occasionally have to deal with. If the total workload exceeds the mental capacities of the train driver, he or she has a higher probability of making suboptimal decisions that would not have been made when total workload was lower.

Box 8.2 PZB – ATB transition at Venlo station (Appendix M)

As described in more detail in Appendix M, BR193 locomotives are not capable of transitioning from the German PZB ATP system to ATB-EG while driving at the Venlo border crossing. BR193-hauled trains therefore have to stop on the Venlo shunting yard to switch from PZB to ATB. As there is no scheduled stop for these trains in Venlo, the train comes to a stop in front of a green signal. The switchover from PZB to ATB takes a few minutes. Meanwhile, the dispatcher of Venlo contacts the train driver, inquiring the cause of the unexpected stop. If the delay lasts too long, the dispatcher may recall the train path and the train will have to wait until the next train path becomes available. Some train drivers, stressed out by the prospect of a long delay, may try to continue their journey before the entire transition process is sorted out by the on-board computer. As a result, a malfunction will occur and the train will not be able to start driving or will come to a stop again, leading to an even longer delay.

8.3 Conclusion on human factors in ATP-transitions

The role of human factors in ATP-transitions differs significantly between different time phases. Prior to the actual operational transition, the driver can take actions that reduce or remove the risk of specific transition failures. Examples have been given of measures that were taken at the start of a train driver shift, potentially multiple hours before the actual transition takes places. Other precautions, such as limiting the train speed during a transition (Appendix M) are taken just minutes in advance of the actual transition. For specific transition failures, workarounds can be applied.

During the transition itself, the driver has a minor role. When transitioning from ATB to ERTMS, the driver has to acknowledge the transition, depending on the type of on-board ETCS unit. Acknowledgement is always required when transitioning from ETCS to ATB. The driver can forget to acknowledge the transition or may be unaware that the train type he or she is operating requires an acknowledgement when transitioning from ATB to ETCS. The effect of a late acknowledgement on the train braking behaviour is largely dependent on the type of train brakes fitted to the train (Appendix N).

Once a failure has occurred, irrespective whether they are caused by technical failures, human errors or other factors, it is generally difficult for the driver to find out what the cause of the failed transition is and if he or she can do anything to resolve the issue. Drivers are generally ill-informed by the on-board ETCS unit. NS drivers have the option of contacting a dedicated helpdesk which has real-time information on the status of each on-board ETCS unit. Apart from that, information and knowledge is limited. Furthermore, time pressure inhibits the driver to conduct a thorough examination of possible failures. In case no specific cause can be found, the driver resets the entire on-board ETCS units, which works in most cases.

Multiple aspects of the framework provided by Pickup et at al. (2005) could be linked to findings based on the interviews and panel group discussions. The concept of internal load has been applied to the recovery phase of a failed transition. Furthermore, literature on automation surprises has been used to underpin the possible effects of unexpected acknowledgements of transitions. In all three phases, the knowledge (Keckland, 2001) and experience (Rejabalinejah, Maartinetti & Van Dongen, 2016) plan an important role.

Chapter 9. Case study synthesis

In this chapter, the contribution of all operational transition types to delays and disruptions in train operations is investigated, based on the results of the four case studies (chapter 5, 6, 7 & 8). By combining the results of multiple case studies, the findings of the case studies are more generalizable.

Table 16 Operational transition types per studied location

Operational transition types	**HSL-Zuid (Ch. 5.1-5.2)**	**BR & Hsp (Ch. 5.3)**	**Meteren junction (Ch. 6)**	**Zaandam station (Ch. 7)**	**Human factors (Ch. 8)**	**Section**
ATP system	X	X	X		X	9.1
Dispatching centres		X	X			9.2
Vertical track alignment	X	X	X	X		9.3
Power supply system	X	X	X			9.4
Moveable bridges				X		9.5
Dispatcher mandates			X	X		9.6
TSRs			X	X		9.6

Table 16 gives an overview of the operational transition types that have been covered in each case study. As no train movements could be measured on CBG – NCBG transitions, no conclusions are drawn for this transition type. The findings per transition type are discussed in section 9.1 to 9.6. In section 9.7, a conclusion is given on the role of operational transitions in train operations and on the effects of combined operational transitions.

9.1 ATP system transitions

Transitions between ATB-EG and ERTMS can fail due to a lack of contact between the on-board ETCS unit and the RBC. Without this connection via GSM-R, MAs cannot be provided to the train, resulting in trains coming to a complete stop. Connection problems with the RBC have been reported at the entrances of the HSL-Zuid and the Betuweroute. Transition failures are mostly caused by on-board modem failures, the failure of other on-board hardware and software, GSM-R signal interference, RBC failures (which are rare) and by failures to acknowledge a transition from ATB-EG to ERTMS and vice versa. During ATP transitions, failures are mostly caused by technical defects, rather than by human factors. The role of human factors in ATP system transitions is further explained in chapter 10.

The case study of Meteren junction confirms that connection failures with the RBC are indeed a major cause for delays at the connecting arches between the Betuweroute and the A2-corridor. In total, 24 out of 462 delay events at Meteren junction in 2019 could be attributed to ETCS-related malfunctions. With approximately 2500 trains using the connecting arches at Meteren, this means that 1% of all passing trains experience ETCS-related malfunctions as primary delay cause. The total delay time as a consequence of these 24 delays is almost 19 hours, which is close to 30% of the total delay time registered at Meteren junction. The large contribution of ETCS-related delays to total delay time is caused by the fact that trains with ETCS-related failures often strand in a neutral section or on an upward slope at Meteren junction. When trains do not get stranded, ETCS-related failures are often solved in 10-15 minutes. Most ETCS-related failures are solved by resetting the on-board ETCS unit.

9.2 Dispatching centre handovers

Transitions between two dispatching centres can lead to delays when a train path is not provided to a train in time. Under normal circumstances, route setting is performed automatically by ARI (Automatische Rijweg Instelling). When a train has deviated too much from its original schedule, route setting has to be done manually by dispatchers. As demonstrated in chapter 5 and 6, route setting delays regularly occur during transitions between dispatching centres. When a train path is not available in time, the train driver has to start slowing down, leading to delays and to the propagation of delays. In some circumstances, delayed route setting can cause trains to come to a stop at undesirable locations, such as on upward slopes, or close to neutral sections and catenary-free bridges. In those cases, delayed route setting can be the cause for major disruptions. Delays as a consequence of manual route setting delays are not limited to transitions between dispatching centres. Similar delays can also occur at transitions between two PPLGs (Primair ProcesLeidingsGebied), controlled by different dispatchers within the same dispatching centre.

9.3 Vertical track alignment

Large height differences in the vertical track alignment, especially at tunnels, are challenging obstacles for trains, freight trains in particular. Due to the large weight of freight trains and the relatively limited tractive effort of the locomotives hauling them, it is often not possible to get a freight train moving again once it has come to a stop on an upward slope. At several tunnels on the Betuweroute and Havenspoorlijn, steep upward slopes caused trains to strand. Passenger trains often do not experience these problems, as the train weight of passenger trains is lower. Upward slopes can, however, contribute to other types of failed transitions, for instance when upward slopes are combined with power supply system transitions, as is the case at the HSL-Zuid, but also at the Betuweroute. At locations where power supply system transitions are combined with upward slopes, these inclines increase the probability of a train stranding in the neutral section of the power supply system transition. Due to the presence of upward slopes, the minimum speed to clear the neutral section of the power supply system transition increases, as trains lose more speed when going uphill. The higher minimum speed decreases the speed margin between minimum speed and normal operating speed, increasing the probability of trains being unable to pass the neutral sections.

In order to prevent trains from coming to a halt at the bottom of a tunnel or on top of fly-overs and bridges, X/G-signals or L- and H-signals are used to ensure a free train path for the entire length of the tunnel, bridge or fly-over. Partially as a result of the presence of a X/G-regime, the number of train strandings is very limited at the Hem tunnel near Zaandam. A drawback of the X/G-regime is the reduction in infrastructure capacity, as a long track section has to be reserved for one train.

Another reason why the number of stranded trains is limited in the Hem tunnel has to do with the presence of ATB-EG. For freight trains, the average speed at the bottom of the tunnel is 80 to 90 km/h, while ATB-EG supervises a speed limit of 130 km/h. The entry speed of the tunnel is also supervised by ATB-EG for freight trains at 40 km/h. As a result, it is near impossible to overspeed at the bottom of the tunnel, as there is a lot of margin between the normal operating speed at the bottom of the tunnel and the supervised speed limit. Under ETCS, this margin is much smaller. At the bottom of the Botlek tunnel on the Havenspoorlijn, ETCS supervises a speed limit that is much closer to the actual operating speeds at the tunnel. As the margin between operating speed and maximum speed limit is small, overspeed at the bottom of the Botlek tunnel regularly occurs, leading to the application of the train brake at the bottom of the tunnel by the on-board ETCS unit and causing train strandings in the tunnel. Although ETCS offers more safety protection, it also decreases the margin for operating errors in comparison to ATB-EG, leading to more train strandings.

9.4 Power supply system transitions

Failed power supply system transitions are rare to occur by themselves. During transitions, train drivers can raise the pantograph too soon, in the neutral section separating both power supply systems. In this case, the system would be short-circuited. These failures occasionally occur at the HSL-Zuid, where the neutral sections are 600 meter long. It is, however, more common for trains to strand in neutral sections as a result of external factors. The probability of a train stranding in a neutral section increases significantly when a train is not able to pass the neutral section with sufficient speed. Trains are forced to slow down when they encounter restrictive signals or when they near the end of their EoA close to the neutral section. This can be caused by crossing traffic and by delayed route setting by the dispatcher. Trains also slow down when driving on steep upward slopes. Finally, trains can be forced to brake when ATP system transitions fail, for instance when no connection with the RBC can be established during an ATB-EG to ERTMS transitions. All these factors decrease the passage speed of neutral sections and thereby increase the probability of a train stranding.

At the HSL-Zuid, with its long neutral sections, around 1 in 1500 passages of neutral sections by TRAXX locomotive hauled trains fail. These trains end up getting stranded in one of the neutral sections on the HSL-Zuid. With 120 daily trains hauled by TRAXX locomotives on the HSL-Zuid, this means that approximately every 2 weeks, a train is stranded in every one of the five neutral sections of power supply system transitions at the HSL-Zuid (Van Gompel, 10-10-2019). For the Betuweroute, similar problems occur at power supply system transitions, even though the neutral sections are much shorter (30 meter, rather than 600 meter). At Meteren junction, four events occurred where trains were stranded in or very close to the neutral section. With 2500 trains using the connecting arches at Meteren in 2019, this means that around 1 in 600 trains strand in the neutral sections of power supply system transitions, significantly more than at the HSL-Zuid. The differences may be explained by the fact that the maximum speed at Meteren junction is lower than at most HSL-entrances (80 km/h and 140 km/h respectively) and by the differences in train characteristics. Due to their large weight, freight trains are less ‘manoeuvrable’ in terms of speed, which they cannot get up to speed very fast in comparison to passenger trains.

Finally, locomotive characteristics also play a large role in power supply system transitions. For some locomotive types, it requires more than 2 minutes to transition from one power supply system to another. So even though the neutral section between two power supply systems may be short, the consequences of such a transition can be large. When combined with a long and steep upward slope, such as at the Sophia tunnel, the slow power supply system transition may lead to trains stranding on the upward slope of the tunnel, as the train driver is unable to apply traction for more than 2 minutes.

9.5 Moveable bridges

Similar to power supply system transitions, moveable bridges are rarely a cause for failure by themselves. There are multiple variants of moveable bridges with different operating rules for train drivers. Some bridges can be passed without any restrictions. Other bridges must be passed with traction switched off, in order to prevent the occurrence of electric arches. Finally, some bridges do not have catenary on the moveable part of the bridge. These bridges should be passed with traction switched off as well. Similar to neutral sections at power supply system transitions, trains can strand on the catenary-free section of moveable bridges. At Zaandam, multiple instances have been recorded where trains stranded on the catenary-free section of the bridge over the river Zaan, though no structural causes have been found for these events. The lack of any other features in the direct vicinity of the Zaan bridge is the most likely explanation for this.

Similar to neutral sections, train strandings on moveable bridges are most likely caused by external factors, such as ATP system transitions, route setting delays and other factors that decrease overall train speed or force trains to brake near catenary-free bridges. Although such combinations do not currently appear on the Dutch railway network, a similar pattern of train strandings will likely be uncovered at combined transitions that include a moveable bridge and at combined transitions of power supply system (neutral section), ATP system transition and dispatching centre handover.

Whereas some trains require a lot of time to transfer between two power supply systems, as described in section 9.5, this problem is not expected for moveable bridges, as the train does not have to transfer between two systems. At both sides of the bridge, the same power supply system is present.

9.6 Temporary speed restrictions and Dispatcher mandates

Temporary speed restrictions (TSRs) and dispatcher mandates have not been found to be a major contributor to delays and disruptions at other operational transitions. Naturally, some delays occur as a result of reduced train speeds, but TSRs or dispatcher mandates did not lead to any significant delays at Meteren junction or at Zaandam. A dispatcher mandate could be linked to one disruption of Zaandam, but it is unclear to what extent this dispatcher mandate has actually contributed to this delay event. This does not mean that there are no situations in which TSRs or dispatcher mandates could be a primary cause for a failed transition of another type, but no structural patterns have been discovered where TSRs or dispatcher mandates have been the cause for major disruptions.

9.7 Conclusion on operational transitions

In this chapter, the effects of each operational transition type on train service reliability have been described, based on four case studies that were conducted. Based on these findings, two categories of operational transition types emerge. On the one hand, there are neutral sections of power supply system transitions, bridges without catenary and upward slopes. These features in the railway infrastructure can cause trains to strand under certain conditions. These features are, however, often not the primary cause for the stranding. Often, strandings are caused when trains are not able to pass these features with sufficient speed or when trains are forced to slow down or brake in the vicinity of these features. When this occurs, the probability of a train stranding increases significantly.

On the other hand, some transition types cause trains to slow down or even to stop. Unsuccessful transitions in ATP system can result in trains coming to a complete stop, for instance when no connection with the RBC can be established. When transitioning from ATB-EG to ERTMS Level 2, connection failures with the RBC regularly occur. Dispatching centre handovers can also cause trains to slow down, when route setting is delayed. When operating under ATB-NG or ETCS Level 1, signalling information is only sent to the train at intermittent locations. When the route has not been set before the train passes the ATB-NG beacon or ETCS L1 balise, the train will have to slow down until it reaches the next beacon. Upward slopes also decrease train speed due to increased gravitational resistance. Finally, TSRs and dispatcher mandates cause trains to slow down and thereby increase the probability of a train stranding in neutral sections, catenary-free sections and on upward slopes.

These two categories of operational transition types, (1) transition types that can cause train strandings and (2) transition types that can cause trains to slow down or stop, when combined, lead to frequent and severe disruptions in train operations. Transition types of category 2 also lead to delays, but these delays are much more limited in duration. Once a connection with the RBC has been re-established, once a route has been set and once the dispatcher mandate has expired, trains can continue running at normal speed. While failed category 2 transitions result in limited delays, failed transitions of category 1 can result in large-scale disruptions in train operations. The probability of such a failure is low when they are passed with sufficient speed, but this probability increases significantly when category 1 transitions are combined with category 2 transitions.

Chapter 10. Conclusion, Discussion and Recommendations

In this chapter, the main conclusions of the entire research are formulated in section 10.1. Section 10.2 contains a discussion of the results and the conclusions, a comparison of the results with literature and an overview of the limitations of this study. Finally, in section 10.3, recommendations are made.

10.1 Conclusion

The aim of this thesis has been to investigate the concept of operational transitions and to establish the relationship between operational transitions in the railway infrastructure and disruptions and delays in railway operations. At some locations, these transition types are combined. This research has taken the train driver perspective as main point of view. As little information is available on this topic, an exploratory research methodology has been applied, using a combination of grounded theory approach and mixed methods research. Following the research goal, a research question and four sub questions have been formulated in chapter 1. These questions can now be answered. The main research question of this thesis is:

> *What is the relation between operational transitions and disruptions in train operations?*

First, the four sub questions will be answered. Then, the main research question will be answered.

1. *What types of operational transitions can be identified?*

The first step in investigating operational transitions has been to identify operational transition types and to locate them on the Dutch railway network. In order to identify transition types, first, the concept of operational transition types has been defined. Operational transitions are defined by two characteristics. Firstly, they are physical locations in the rail infrastructure. Secondly, operational transition require the driver to switch between two systems, or to change his/her behaviour significantly. Based on this definition eight operational transition types have been identified. Often, subdivisions could be made within each transition type. When possible, their location has been determined on the Dutch railway network. The identified transition types are:

- Transitions between power supply systems
- Transitions between ATP systems
- Moveable bridges
- Changes in vertical track alignment
- Handovers between dispatching centres
- Transitions between centrally controlled and non-centrally controlled areas
- Temporary speed restrictions
- Dispatcher mandates

The identification and localisation of operational transition types has been used to identify locations where multiple transition types coexist or where multiple transitions are combined. Some of these locations have been used for case study analysis.

2. *To what extent do delays emerge from operational transitions?*

The extent to which delays emerge from operational transitions depends on two factors: (1) the frequency and severity of delays that are caused by the operational transitions type itself and (2) external factors that influence the probability of a transitions failure. When operational transitions are constructed without any features in its vicinity that can influence the probability of a delay or the severity of a disruption, the frequency and severity of delays is limited. At Zaandam, where all operational transitions are relatively isolated, delays on track sections containing operational transitions are not significantly higher than on track sections without these transitions. Moreover, delays in the Hem tunnel were even lower than average, most likely due to the presence of a X/G-tunnel regime.

When multiple transitions are combined or when a transition is close to other features that influence its performance, both the frequency and severity of delays increase rapidly. At Meteren junction, on average between 6% and 36% of the trains using the various connecting arches were delayed. While most of these delays were caused by a signal at danger, a considerable amount of delays was caused by failed operational transitions. Around a quarter of all delays (4-5% of all passing trains) can be attributed to operational transitions. The delays caused by these transition failures were relatively long, as they made up more than 50% of total delay time registered at Meteren. In isolation, the hindrance of operational transitions caused to train operations is limited, but when transitions are combined, they pose a significant burden to reliable train operations.

3. What are the underlying causes for failed operational transitions?

As stated earlier, transition failures hardly ever happen in isolation. Transition failures are often caused by external factors. Train strandings in neutral sections of power supply system transitions, in catenary free sections, or on upward slopes mainly occur when they are passed either too slow or (in some cases) too fast. At Meteren junction, at the other entrances to the Betuweroute and at the entrances of the HSL-Zuid, strandings often occurred after a ATB-ERTMS transition had failed or when trains were held up, either as a result of delayed route setting or because the track section ahead was still blocked by another train.

ATB-ERTMS transitions often fail when no connection with the RBC can be established. Due to a lack of MA, trains that are not connected to the RBC are forced to stop. Bad-functioning modems, GSM-R signal interference, weak GSM-R signals and other technical failures are all causes for connection losses with the RBC. ATB-ERTMS transitions can also fail when the transition is not acknowledged by the train driver. Route setting delays occur when routes are not set automatically by ARI, but have to be set manually by dispatchers. When dispatchers are busy, for instance when a disruption in train services has occurred and they're occupied with managing that disruption, they can forget to set routes manually for approaching trains, forcing these trains to slow down or even stop. Temporary speed restrictions and dispatcher mandates have not been found to cause disruptions.

4. What is the role of human factors in failed operational transitions?

The role of human factors has been specifically examined in ATP system transitions. It was found that the role of human factors for this specific case is most prominent before the transition takes place and after the transition, when a failure has already occurred. The role of human factors in the actual failure during an operational transition is limited, as most ATP system transition processes are automated. Most failures during ATP-transitions are caused by technical failures, but the driver is able to anticipate on some of those failures and act accordingly. Prior to the transition, certain precautions can be taken by the driver and workarounds can be used that reduce or eliminate the risk of a specific transition failure from occurring. Drivers can apply these tricks, often without knowing exactly why they work.

When failures occur during ATP-transitions, it is often unclear to the driver why the failure has occurred and what steps the driver should undertake to recover. Furthermore, the number of possible defects or malfunctions is large. Due to the lack of information provided by the on-board ETCS unit, drivers often simply reset the entire system, a process which takes up to 15 minutes. Due to time pressure, drivers also do not have time to examine the exact causes of failed transitions. Their main priority is to get the train moving as soon as possible. Time pressure may also lead to manual transitions being rushed and it to operating errors being made by the driver as a result.

> *Research Question: What is the relation between operational transitions and disruptions in train operations?*

The Dutch railway network contains a large number and variety of operational transitions. In the future, the number and variety of transitions is expected to grow even further. Ensuring that these transitions do not cause hindrances to train traffic is important in order to guarantee a safe and reliable railway service to passengers and freight operators. Often, however, these transitions can cause delays to passing trains. Especially when certain types of operational transitions are combined, large disruptions can occur frequently. The initial causes for these disruptions can be caused by technical factors, but also by human factors. Actors in the railway sector are, however, also able to anticipate on possible transition failures and prevent failures from occurring.

Disruptions often occur at neutral sections, catenary-free sections and on upward slopes, although these features are seldom the primary cause for train strandings. When these features in the railway infrastructure are combined with other features in the infrastructure that influence train speed, such as dispatching centre handovers and ATP system transitions, large disruptions will occur frequently. In isolation, however, neutral and catenary-free sections and upward slopes in vertical track alignment hardly cause any disruptions. Ensuring that these three features are not combined with any other transitions or constructed close to railway junctions and that trains are able to pass these features unhindered by other traffic or restricted signals will greatly reduce the number of disruptions of future operational transitions that are to be constructed.

10.2 Discussion

This study has investigated the relation between operational transitions in railway infrastructure and the reliability of train operations. In the introduction (Chapter 1) of this study, it was stated that the knowledge on operational transitions is limited and fragmentary. Eight types of operational transitions have been identified and the relation that these transitions have to disruptions in train operations has been explained.

The degree to which delays and disruptions occur, varies widely depending on the exact configuration of operational transitions. While some (combinations of) transitions hardly increase the number of delays on a track section, others significantly increase the frequency and severity of delays and disruptions. These major delays often occur at neutral sections, catenary-free sections and upward slopes. These findings, based on quantitative research, are in line with the interviews that were held with train drivers, data analysts and other experts.

The type of delays that were being found in the case studies often aligned well with the operational transitions that were present at these locations. At Meteren junction, it proved to be possible to distinguish between delays that were related to any of the present operational transitions and delays that were caused by other, unrelated causes, such as other delayed trains. At Zaandam, most delays were unrelated to any of the operational transitions present at that location.

The investigation into the role of human factors in ATP-transitions has provided new insights that were not necessarily expected. The general lack of understanding why certain failures occur in ATP-transitions was not expected. Train drivers apply workarounds that reduce or prevent failures during operational transitions, but they often do not know why these workarounds reduce failures. As described in chapter 8, often, there is no logical connection between workarounds and the problems they solve.

Based on the findings in this research, it has been possible to formulate a general theory for the relation of operational transitions and disruptions: frequent and severe disruptions occur when trains are forced to slow down or to stop at locations where they cannot drive away under their own power. This theory has been applicable to the various case studies that were conducted. Furthermore, this theory will most likely remain useable when more operational transition types are added in future research and when more case studies are conducted.

Implications of findings

The findings have several implications for the design of future infrastructure, for the design of trains and for the education of staff working in the railway sector. When designing new infrastructure and particularly if operational transitions are involved, the design should ensure that neutral sections, catenary-free sections and upward slopes are well separated from any other type of operational transitions. It should be acknowledged that these three features are and will remain vulnerable points in railway infrastructure. New infrastructure should be designed according to this insight.

This research has also shown that transitions problems can be caused by the interaction between train and infrastructure. Certain train characteristics do not coincide neatly with the way in which the infrastructure is designed. When train operators order new trains, criteria that regulate train behaviour during transitions should be formulated. In this way, the behaviour of trains during transitions can be controlled more precisely and the interaction between train and infrastructure will be improved.

Finally, the education of train drivers and dispatchers has to focus more on the role of operational transitions in train operations. Train drivers often lack the knowledge and experience to act effectively when an operational transition fails. This is especially the case in failed ATP system transitions. Due to the lack of knowledge and of information provided by the on-board ETCS unit, drivers are often unable to perform quick recoveries from failures. Dispatchers should be more aware of the problems that train drivers encounter during operational transitions. An increased understanding between driver and dispatcher can help to increase coordination and to decrease the length of delays.

Relation of the findings to the literature

Both human and technical factors play a role in failed operational transitions. In the case studies of the HSL-Zuid, Betuweroute and Havenspoorlijn (Ch.5), Meteren junction (Ch.6) and Zaandam (Ch.7), most attention has been given to the technical factors leading to failed operational transitions, for which there are two causes. Firstly, most failures seem to be caused by technical failures of some sort. Secondly, the data sources that were used for determining delay causes, especially in Ch.6 & Ch.7 focused mainly on the technical aspects. Nevertheless, human factors play a significant role in failed transitions, as demonstrated in chapter 8.

Route setting delays are the most notable example of this. For example, during busy periods, dispatchers are not always able to provide a route manually in time, leading to delayed trains. As stated by Pickup et al. (2005), high workload can influence the performance of operators. According to Young et al. (2015), both overload and underload decrease performance. Faults can therefore also be made dispatchers have little to do. Due to underload, dispatchers are more easily distracted, leading to the dispatcher forgetting to set a route in time. According to Baysari, McIntosh & Wilson (2008) and Kyriakidis et al. (2012), distraction of crew is one of the primary cause for incidents and accidents. It is therefore not unimaginable that delayed route setting may be caused by dispatcher distraction, although no empirical evidence has been found for this in the research.

In chapter 9, the role of human factors in ATP system transitions has been researched. The role of drivers during the transition turned out to be limited to acknowledging the ATP system transition. As acknowledgement of an ATP system transition is not standardised, drivers can be surprised by an unexpected acknowledgement. Currently, this is not reported as a major problem by train drivers, as most train drivers that operate under ETCS usually only driver with one train type, the TRAXX MS2. In future years, when more train types will use ETCS, unexpected acknowledgements might become more problematic. On this point, parallels have been drawn with the concept of automation surprises in aviation (Sarter, Wood & Billings, 1997; De Boer & Dekker, 2017) and autonomous car driving (Merat et al., 2014; Lu et al., 2016), where pilots and drivers are unexpectedly confronted with a reduction on automation. When driving (in) an autonomous car, regaining full control after an automation surprise required more than 40 seconds. Pickup et al. (2005) also touched upon this point by pointing out that driver effort is often slow to catch up when driver workload is suddenly increased. Train drivers may also experience automation surprises in the future, although no empirical evidence has been found for this during ATP system transitions.

Prior to the ATP system transition, drivers showed various signs of anticipation in order to reduce the probability of a transition failure. In doing so, train drivers can reduce the number of failed transitions. Branton (1993) listed anticipation on future events as one of the skills that drivers require for a good execution of their job. Drivers often anticipated by deviating from normal operating rules and procedures. These deviations can be classified as ‘situational violations’ of operating rules (Bieder & Bourrier, 2013), due to the exceptional circumstances at some transition points. Drivers deviate from the rules as the operating rules do not apply in these exceptional circumstances.

When ATP system transitions fail, drivers try to recover and get their train moving again. In doing so, some drivers experience a high level of stress, or a high perceived load as Pickup et al. (2005) would characterise it. Due to the high workload caused by stress, drivers make more mistakes in recovering from failed transitions. This is in line with the findings of Young et al. (2015) and Kecklund et al. (2001), who found that high workload of drivers and dispatchers increases the possibility of mistakes. Individual driver characteristics play an important role here, as some drivers are more resistant to stress than others (Pickup et al., 2005). Finally, a limited level of information during a failed ATP system transition contributes to mistakes being made (Kecklund et al., 2001).

Limitations of the research

In this research, two research approaches have been combined: grounded theory approach (GTA) and mixed methods approach (MMA). The GTA has become apparent in this report, not necessarily in the report writing itself, but in selecting new topics and cases to investigate. While this approach has made the entire research process flexible, it also means that the decision on what to research next is biased by the interests of the author and by the interests of those closely involved in the process of this research. Although this does not necessarily make the conclusions of this research less valid or less reliable, it is a point that should be acknowledged.

It should also be acknowledged that the selection of case studies itself has a large effect on the overall findings of this research. Other, possibly contradicting information might have been found in other case studies. This underlines the necessity to conduct more of these case studies, as a larger sample size can make the findings of studies on operational transitions more generalizable. This does not only apply to the selection of case studies, but to the identification of operational transition types as well. Although the rationale for identifying certain features in the railway infrastructure as operational transitions has been given, this process remains biased by decisions made by the author.

Case studies have been chosen based on the presence of ‘permanent’ operational transitions. This has made it more difficult to study the effects of temporary speed restrictions, as these transitions can occur anywhere on the railway network. In future research, this could be changed by selecting a location on which, for instance, a TSR has been present for a prolonged period of time.

Due to the combination of an exploratory research method and a wide scope, many topics that have been touched upon have not been investigated to the fullest extent. In this research, the width of the research has been prioritized over research depth. Although this does mean that a relatively large number of topics and transition types have been covered, it does mean that information that could significantly alter the results of this study could have been missed. In that respect, this research is never fully finished.

The two quantitative case studies of Meteren and Zaandam were able to provide useful information with regard to the effect of operational transitions on train operations. The reliability of the various data sources for determining the cause of delays differs significantly. Spoorweb, STIPT and monitoring have been used as data sets for this purpose. The involved actors often do not have sufficient time to report delays while they are occurring. Reporting is therefore done in hindsight, which inhibits the reliability of the Spoorweb and monitoring data sources. STIPT uses an algorithm to provide causes to delays automatically, based on a large number of data sources. For smaller delays, the declarations offered by STIPT often do not make much sense or are irrelevant. In the case studies, a combination has been made of purely quantitative methods and of more qualitative, interpretive methods. Using a combination of these methods, a comprehensive view on transitions could be constructed. This method can be used in future case studies, without much alterations.

Finally, the gathering of qualitative data has been hindered by governmental measures to reduce the spread of Covid-19. Although it has been possible to make formal appointments and have interviews online, it heavily limited informal communication, discussions and chats that are important for advancing the course of the research. These informal chats often provide new insights and new topics for research. The inability to have such chats therefore has been a limiting factor of this research.

10.3 Recommendations

Based on the findings of this research, several recommendations can be made on the future design of operational transitions. In subsection 10.3.1, policy recommendations are made. In subsection 10.3.2, recommendations for further research are given.

10.3.1 Policy recommendations

- Neutral sections, catenary-free bridges and upward slopes have proven to be vulnerable to disruptions. Therefore, it is recommended not to combined these features with any other transitions types, or to construct them closely to junctions. Keep these features isolated from any other relevant features in the railway infrastructure.
- the probability that train drivers successfully perform a transition between two systems is maximised if the required tasks for that transition are standardised as much as reasonably possible. Currently, the way in which transitions are carried out can vary per train type. Furthermore, the tasks required for accomplishing a transitions can vary as a result of variations in the infrastructure design of operational transitions. Standardising on-board equipment and infrastructure will minimise failures as a result of human errors.
- In the upcoming years, ERTMS will be gradually installed on the Dutch railway network. In the same time period, the 1.5kV power supply system may be replaced by a 3kV power supply system. During this transition period, a large number of operational transitions for both systems is required. It is advised not to combine these transitions in order to prevent that

failed ATP system transitions can lead to failed power supply system transitions. This has been recommended earlier (NS & ProRail, 2016).

- Continuous train paths have proven to be effective in preventing strandings of freight trains in tunnels. Similar arrangements could be used in locations, where a too low train speed could result in a train stranding. Continuous train paths decrease the overall capacity of a railway line as the headway between trains has to be larger than under normal circumstances. A right balance between capacity and reliability should therefore be found.
- The interaction between train and infrastructure has proven to be problematic occasionally. When ordering new trains, criteria on their behaviour during transitions should be made part of the tendering process. In this way, the misalignment between train and infrastructure can be reduced for future trains. The same applies to new software updates of locomotives and EMUs. Software updates can significantly alter train behaviour during transitions. After a software update has been applied, the train behaviour during transitions should be tested in order to prevent that these updates lead to more transition failures.
- When transition failures occur, train drivers are often ill-informed on the causes of the transition failure. This is the case for ATP system transitions and probably for other transition failures as well. It is therefore recommended to inform the driver better on the causes of transition failures. Furthermore, the driver should be able to interpret and use this information in such a way that he or she is able to act based on that information. Additional education of the driver may be required.

10.3.2 Recommendations for further research

- A lot of information has been acquired by talking to freight train drivers and freight operators. It is advised to intensify and institutionalize discussions with freight operators in order to gain more information on the (dis)functioning of trains during operational transitions. While data on transition failures is at the HSL-Zuid is collected by NS, no such authority exists that collects transition failure data for freight operators and other railway undertakings. Collecting this data will help to increase knowledge on operational transitions and to increase their reliability.
- In this research, eight operational transitions types have been identified. There may, however, be other features in the railway infrastructure that might be classified as such. Therefore, further research is advised with the aim of identifying any eventual other operational transition types. Interviews and panel group discussions with train drivers could be used to identify additional transition types, assuming the train driver perspective is used.
- Four case studies have been conducted in this research, which is a relatively small number. It is advised to conduct more case studies in order to get a better understanding on the effect of operational transitions on the reliability of train operations. Using this data, new patterns could be discovered. These additional case studies can also be used to gain more information on the role of temporary speed restrictions and dispatcher mandates on train service reliability.
- For CBG/NCBG transitions, no quantitative data was available. It is, however, recommended to investigate this transition type anyhow. Investigating this transition type will most likely require qualitative data in the form of interviews with involved actors and through observations.
- Temporary speed restrictions and dispatcher mandates have not been found to cause a significant number of disruptions. The research methodology, however, was not very suited for investigating the effect of TSRs and also dispatcher mandates on the reliability of train operations. Conducting case studies specifically aimed at these two transition types is therefore recommended.

- It has been advised to standardise infrastructure and on-board equipment as much as possible in order to minimize the probability of human failures during transitions. It is, however, unclear to what extent variations in in-cab design and variations in operating principles influence the probability of human failures. More research is advised on this point.
- the role of human factors has been investigated for ATP system transitions. It was found that there is a lot of interaction between what seem to be purely technical causes for failed transitions and the role of the train drivers. Technology is not only capable of intervening when human fault might occur, but human ingenuity is also vital when technology does not function as intended. This is one of the lessons of the investigation of human factors in ATP-transitions. Investigating the role of human factors in combination with other transition types is therefore advised.
- This research has been conducted from the train driver perspective. Other perspectives can, however, also be investigated. Operational transitions could also be studied from the perspective of dispatchers or other staff in the railway sector.
- Relatively little information has been gathered through interviews on the role of dispatching centre handovers on the reliability of train operations. It is therefore advised to conduct more research on this topic.

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Appendices

Appendix A. Interview guide

Most qualitative data gathering in this research is done through semi-structured interviews (SSI). In SSIs, the interviewer prepares an interview guide or topics list to be discussed in the interview with the interviewee. The purpose of this list is not, however, to cover each question in the right order, but to provide some structure to the discussion between interviewer and interviewee. The interview guide or topics list helps to create some structure in the interview so that all relevant topics are covered in the interview. Open-ended questions should be asked, which allow the interviewee to give elaborate explanations. Follow-up questions can be asked to prolong the discussion of a topic. The combination of open-ended and follow-up questions makes SSI ideal for exploratory research (Barriball & While, 1994).

The interview guide should be designed to cover all relevant topics for research. In most cases, not all topics or questions are relevant to the interviewee, so the interview should be focussed on a subset of topics. Prioritising questions, due to time constraints, is also advisable (Newcome, Hatry & WHoley, 2015).

Interviewee guide

Interviews are used as data for the case study of the HSL-Zuid, Betuweroute and Havenspoorlijn in chapter 5. Furthermore, in chapter 8, the role of human factors in ATP transitions are investigated, using interviews as data. In chapter 5, four transition types are covered: power supply system transitions, ATP system transitions, transitions between dispatching centres and changes in vertical track alignment. Roughly three types of interviewees have been interviewed. Managers have been interviewed to provide general information on operational transitions. Furthermore, researchers and data analysts are interviewed. This second category of interviewees usually possesses more in-depth knowledge on transitions. Finally, operators (in this case train drivers) are interviewed on their direct experiences with certain types of operational transitions. In chapter 5, interviews with managers and researchers/data analysists are mostly, though not exclusively, used (encircled in yellow in Table 17). In chapter 8, interviews from researchers/data analysts on ATP system transitions have been mostly, though not exclusively, used (encircled in green in Table 17).

Table 17 provides information on the role/profession of interviewees and on the transition types they have provided information for. Interviewees highlighted in green are connected or acquainted to train operations on the HSL-Zuid and interviewees highlighted in red are connected or acquainted to train operations on the Betuweroute and Havenspoorlijn. Interviewees highlighted in black are not particularly connected to any railway line. Under the heading 'dispatching centre transition' the ~-symbols indicate that informal discussions have been conducted on this topic with various people. Although these discussions have not been recorded in any interview, they have provided suggestions for literature on dispatching centres, which has been used in this report. More research into the role of dispatching centre handovers on the reliability of train operations is advised. Table 18 gives an overview of the present-day functions of the interviewees.

Table 17 Interviewee positioning with respect to operational transitions

	Power supply sys. transition	ATP sys. transition	Dispatching centre transition	Vertical track alignment
Managers	2	2,3,8,11	-	-
Researchers/ data analysist	1,4	1,4,7,9,10,12	7,~	1,4,7
Operators	5,6,13-16	5,6,13-16	~	5,6,13-16

Table 18 Interviewee functions

APPENDIX	INTERVIEWEE	FUNCTION
B	1	Rail traffic engineer
C	2	Corridor manager HSL
D	3	Interface manager ERTMS program
E	4	Specialist capacity management
F	5, 6	Train drivers at NS Reizigers
G	7	Data analyst Performance Analysis Office
H	8	Project leader improvement program HSL-Zuid
I	9, 10	Project managers at CAF
J	5	Train drivers at NS Reizigers
K	11	Manager education at DB Cargo
L	12	System specialist ERTMS
M	13, 14, 15, 16	Train drivers various freight operators

Interview guideline

An overview is given of the question types that were asked during the interviews. Not all questions have been used for every interviewee and the exact wording varies per interviewee and per topic.

Introductory questions

- What is your current function?
- Can you describe the work you do?
- How is your work related to operational transitions in rail infrastructure?

Infrastructure-specific questions

- What are the challenges of this specific track section?
- What problems/difficulties are present on the track section?
- Do others experience similar problems?
- To what extent have these problems been resolved now?
- How have problems with this track section been resolved?
- Have operating conditions improved since the problem has been addressed?

Operational transitions

- Can you identify operational transitions on track sections?
- Do you experience problems/operating difficulties at these locations?
- What do you do to prevent problems at operational transition points?
- What happens when an operational transition fails?
- What is your role in resolving a failed transition?

Human factors in operational transitions

- Are you able to anticipate on (planned) operational transitions?
- Are you able to anticipate on unplanned events during operational transitions?
- Are you satisfied with the current design of operational transitions?
- How could the design of these points be improved?
- Do you find this specific (combination of) transition(s) difficult in daily operations?
- How do you communicate with other actors?
- Do you encounter problems with communications with other actors?

Appendix B. Interview with interviewee 1

29 januari 2020, 14:30 – 16:00
De Inktpot, Utrecht

Defining operational transitions

Defining transitions is not an easy task. Mostly, when we think of transitions, we think of situations where a transition is made between two different systems. Well known examples of such transitions in the Netherlands are transitions in power supply system and transitions in train protection system. In some cases, transitions are carried out automatically and in other cases, the train driver has to actively switch between two systems. These kind of transitions are quite clear, there are clearly defined systems and system boundaries and the driver has to undertake certain tasks in order to successfully transition between two system.

In some cases, transitions are more subtle than aforementioned transitions. The two systems between which the transitions takes places may not be as well defined, nor is it clear where the system boundaries are located. Some transitions may not require the train driver to perform certain tasks, but rather to make a change in his mind set. An example of this is the signalling system. When a signal indicates a green aspect, the driver is assured of the fact that the track section between the green signal and the upcoming signal is clear of other traffic and that no other traffic can use that track section. Furthermore, the train driver is assured that the interlocking is functioning properly, which means that signals and switches are locked in position and that they cannot be changed until the train has passed those points and cleared the next signal. Similarly, a signal at danger assures the train driver that the next track section contains danger in the form of other trains, crossing train paths, opened bridges, etc.

When the train driver encounters a flashing yellow signal, ambiguity in the meaning of a signal aspect start to appear. A flashing yellow signals informs the driver to ‘drive-at-sight’, as there are possible obstacles on the track section, or there are other potentially dangerous situations. In these circumstances, the driver has to change his state of mind and prepare for an increased level of uncertainty. The driver has to change his attitude from passive to active and proactively look out for danger, more than he is used to. These changes in mind set are not limited to this field, but they may appear in all kinds of transitions.

Meteren

At Meteren junction, the Betuweroute and the railway line Utrecht – Den Bosch, also referred to as the A2-corridor, are connected with each other with a set of connecting arches. In practice, these connection arches were constructed too small. Ideally, it should be possible for freight trains entering and leaving the Betuweroute at Meteren to wait on the connecting arches until a free train path is available to continue. Most of the connecting arches are, however, too short to accommodate full length freight trains.

New connecting arches will be constructed at Meteren that allow freight trains to and from Venlo to access the Betuweroute in western direction, in the direction of Kijfhoek and the Rotterdam harbour. Currently, these freight trains use a route via Tilburg, Breda and Dordrecht, known as the Brabantroute. The new connecting arches, also referred to as 'Zuidwestboog', will be long enough in order to allow freight train to wait on the arches for a free train path to become available.

Constructing the new connecting arches, however, will not be easy due to the presence of the A15 highway. The current design for the Zuidwestboog leads the railway line over the highway. As a result, steep inclines are necessary in order to attain sufficient height to clear the highway. The maximum gradient of this track section is 17‰. The large inclines pose the question where the waiting track should be located. A waiting track just in front of the incline would not be possible, as freight trains are not capable of accelerating up the steep incline. Furthermore, where should the transition between ATB-EG and ERTMS and the transition between 1.5kV and 25kV take place?

A waiting track after the fly-over over the A15-highway is not an option either. It would require the train driver to accelerate up the hill, while the ETCS braking curve is forcing the train speed down. Ideally, it should be possible for the train driver to gain sufficient speed before the fly-over without the ETCS braking curve forcing the train speed down. On top of the level section of the fly-over, the neutral section of the power supply system transition would be located, as ProRail regulations prescribe these transitions to be constructed on level tracks.

During the same period as the initial design stage, the bad performance of the HSL-Zuid combined transitions came to light. The idea was therefore to make the transition point between ATB and ERTMS earlier, so that there would be no interference between both transitions. The waiting track in front of the connecting arch has therefore been extended by 1 kilometre, so that the transition could be made on that track section. Transitioning from ATB to ERTMS on the A2-corridor was considered unacceptable by some parties involved.

In the future, the A2-corridor will be equipped with ERTMS, just as the Betuweroute. The baseline will however be different. Furthermore, it is likely that a different manufacturer will equip the A2-corridor with ERTMS than the manufacturer who installed ERTMS on the Betuweroute. Trains on the A2-corridor will most likely also be connected to another RBC than trains on the Betuweroute. Therefore, some sort of transition will always be required when driving from the A2-corridor onto the Betuweroute and vice versa.

DSSA

In future years, the capacity of the tracks in and around Amsterdam will be expanded as part of the DSSA project (DoorStroomStation Amsterdam). Around the station area of Amsterdam, the distance between consecutive signals will be reduced significantly in order to increase the capacity of the tracks leading up to the station of Amsterdam. The average distance between signals will be reduced from 1500-2000 meter in normal circumstances to approximately 500 meter in the new situation. The effects of these measures on train driver could be quite large. The maximum speed is limited to 80 km/h. As a result of the shorter track sections, the average braking curve of a train, especially of freight trains, will be larger than 500 meter. Normally, a train driver is always able to stop his or her train in front of the next signal, even at full speed.

A different behaviour is required by the train driver when entering the 500-meter-section area. Instead of looking at the next signal, the driver might have to take into account the aspects of the upcoming two or three signals. Another change that will be made is to the signals themselves. The signals will be smaller than normal signals and they will be placed lower to the ground than normal. Due to the smaller size of the signals, reducing the signal height is possible.

Various organisations representing train drivers and their interests have opposed these plans as they do not think that train drivers are capable of operating safely in this new environment. They fear that the adjustment increase the work load of train drivers as they encounter a lot more signals than normal. At 80 km/h, the train driver will encounter close to three signals per minute.

Different signals and significantly smaller track sections can also be seen as a form of operationaal transitions. The driver mind set has to change. Instead of driving at 140km/h and encountering a signal once every minute, the driver now has to driver at 80 km/h and encounter 3 signals per minute. Is the driver capable of doing this?

Similarly, the driver has to change his or her mind set on the Havenspoorlijn, which is equipped with ETCS level 1. When entering a shunting yard, no active train protection is present. All driving aids are switched off and the driver has to rely fully on his own senses. This could be considered a transition as well, even though no action is required by the driver to make this transition.

Appendix C. Interview with interviewee 2

24 februari 2020, 12:00 – 13:00
De Inktpot, Utrecht

The performance of trains on the HSL-Zuid is generally poor. In comparison to the main line network (HRN), trains are more often delayed, are less punctual and more trains are cancelled. Improving the performance of the HSL-Zuid is therefore a major task. There are multiple causes why the HSL train services performs so badly.

For instance, there are software problems with the locomotives that are currently being used on the HSL-Zuid. These locomotives were designed as freight locomotives and are therefore not very suited to the conditions on the HSL. With the introduction of new rolling stock in 2021 (the ICNG), these problems are expected to be solved, as this train is especially designed with the HSL-Zuid in mind.

In an attempt to increase the performance of the HSL, all relevant processes surrounding the HSL have been examined and, where necessary, streamlined. By improving these processes, solving malfunctions becomes easier and disruptions are resolved faster than they are now. By moving the locations where maintenance and repair crew are standing by closer to the HSL, the time between the start of a malfunction and the moment the disruption is solved can be reduced significantly. Furthermore, small and cheap adjustments to the infrastructure help to solve local problems. In this way, the reliability of train services on the HSL is improved step by step.

The HSL has been constructed by Rijkswaterstaat. The quality of their work is good. The infrastructure has an availability of 99,97%. The HSL, however, is constructed without much regard for possible changes to the infrastructure. If the infrastructure has to be changed, the costs of such an undertaking is enormous. Structurally changing the infrastructure is therefore only a long-term solution.

Part of the reason why there are systematic flaws in the design of the HSL, is the fact that there was very little experience with systems such as ERTMS at the time of the development. People were not aware, as they are now, that transitions between ATB and ERTMS are potentially vulnerable. In the design process, a great deal of attention was given to the technical components of the line, but the user of the line, the train driver, was not in the picture when designing the line.

One of the weaknesses of the HSL design are the transitions between the HSL and the HRN. Their weakness is not technical in nature, as the built quality of the HSL-Zuid is generally good. The weaknesses are caused by the combination of transitions. Once one of the transitions is not going according to plan, it is very difficult for the train driver to figure out what has happened and how he or she can solve the problem at hand. Disruptions are not necessarily caused by faults made by train drivers. The Thalys trains automatically transitions between systems and they face similar problems.

It is very difficult to structurally improve the reliability of the HSL. This can only be done by investing heavily in the line and replacing some of the systems entirely. Most attention is therefore focussed on reducing the impact of delays. Smaller measures can be taken that significantly reduce the delay time. By installing cameras, for instance, defects can be detected much quicker. By implementing small changes, small and local problems can be resolved. It remains, however, difficult to come to grips with the large disruptions that happen on the HSL, as they require extensive and expensive reconstruction works.

The only way in which the structural improvements in reliability can be made is by structurally changing the technology of the HSL, as only structural changes to the infrastructure can increase the reliability of operational transitions permanently. In practice, this means removing transitions between the HRN and HSL. The HRN will be equipped with ERTMS in the near future. In theory this removes the ATP system transition entirely. However, the HRN will be equipped with a different ERTMS version than is currently installed on the HSL. A transition will therefore have to take place anyway. Furthermore, as the HSL is equipped with a non-standard ERTMS version, no transition between the HSL ERTMS version and the new HRN version has been defined in regulations. One of the solutions is by using an 'ATB-island', in which a dual transition is made. First from ERTMS HRN to ATB-EG and then from ATB-EG to ERTMS HSL. This solution was found to be politically unacceptable. Other solutions will therefore be devised. The ATB-island will remain as a back-up option in case other options fail. Consultation with the Belgians has learned that they have similar plans to implement similar 'island' if they cannot find another alternative.

In order to make the current transitions as doable as possible for train drivers, several measures have been taken. The infrastructure has been standardised as much as possible in order to prevent any confusion to the train driver. Another measure that has been taken is the creation of a helpdesk for train drivers. If drivers do not how what to do or how to cope with a certain situation, he or she can call an experienced train driver for assistance. These experienced train drivers know most failures and they know how they can be solved. These train drivers are now also involved in the education and training of new train drivers, so that their knowledge can be transferred to these new train drivers.

Appendix D. Interview with interviewee 3

27 februari 2020, 15:00 – 16:30
Van Sypestein, Utrecht

In the coming years, the first couple of lines of the main line network (HRN) will be equipped with ERTMS level 2, baseline 3.6.0. The HSL has been equipped with ERTMS level 1 & 2, baseline 2.3.0c. As baseline 2.3.0c is a non-standard ETCS version, no seamless transition between these two systems can be made. The ERTMS version on the HSL is non-standard, as no standards existed at all when the system was designed. In order to solve the problem, five solution directions where conceived out of a brainstorming session.

In the current situation, trains travelling from the HRN to the HSL transition from NS ’54 signalling and ATB-EG to cab signalling with ETCS baseline 2.3.0c. Over the years, upgrades have been applied that allow locomotives equipped with ETCS baseline 2.3.0d, which is a standard ETCS version, to use the HSL. An odd feature of the HSL is the inclusion of short ETCS level 1 sections between ATB-EG and ETCS level 2. Some of the balises on the HSL are active balises, which can be used for ETCS level 1 on the entire HSL as a back-up.

Option 1: ATB-island

In this solution, a double transition is proposed. Transitions from ATB-EG to ERTMS baseline 2.3.0c are possible as shown at the current HSL entrances. Furthermore, transitions between ATB-EG and ERTMS baseline 3.6.0 are technically possible as well. This would result in a double transition, in which trains operating on the HRN under ERTMS baseline 3.6.0 would first have to transition to ATB-EG and subsequently transition to ERTMS baseline 2.3.0c as used on the HSL. In contrast to the current transition, no level 1 section will be used when transitioning from ERTMS level 2 baseline 3.6.0 to ATB-EG, as this is a standard transition that should be done flawlessly. Technically, this transition is almost certain to work. It is, obviously, undesirable to have two transitions so close together from a user point of view.

Option 2: RBC gateway

The main problem of a transition between baseline 2.3.0c and baseline 3.6.0 is the communication between both respective RBCs. As the software differs, communication between both RBCs is difficult. One way in which this can be solved is by using a gateway for communication between both RBCs. The gateway is responsible for translating signals of one RBC in signals that the other RBC can understand. A gateway has been used for the RBC handover on the Dutch/Belgium border. No RBC gateway has, however, been developed for this specific problem. It is therefore unclear whether such a gateway is technically feasible. If it is feasible, it would be the preferred solution to the transition problem. If it does not work, other solutions have to be considered.

Option 3: ETCS level 1-island

A level 1 island between both level 2 section prevents that a direct handover between two RBCs is necessary. The movement authorities are provided via active balises and LEUs. An advantage of this option over the ATB-island is that the transitions take place within ERTMS. This means the train driver can still use the DMI for signalling information. Under level 1, the different software versions are not much of a problem. This solution may be problematic from a human factors point of view, as the transitions still require the attention of the train driver and divert his attention from the ever present transition in power supply systems.

Option 4: replace ERTMS on the HSL

A very obvious option is to replace ERTMS baseline 2.3.0c with baseline 3.6.0 altogether. In this way, the software versions are similar and only a standard RBC handover is required. The only remaining risk is that the ETCS equipment for the infrastructure, including the RBCs can be constructed by different manufacturers. The HSL is owned by Infraspeed, who will most likely ask Thales/Siemens to construct the new equipment. In theory, there should be no operating differences when the baseline is similar, but in practice, differences do exist between manufacturers.

Option 5: one RBC for HRN and HSL

Due to improvements in RBC technology, the number of trains that can be handled by one RBC has increased significantly in the last few years. Whereas it was first believed that 20 or 30 trains could be handled simultaneously, there are now examples where the number of trains on one RBC reaches 100. In Austria, there are examples of 92 trains being connected to the same RBC. It could therefore be possible to control the trains running on the HSL with the future RBC for the northern part of the Randstad. In this way, a transition of any form is eliminated, which would be the best possible option.

Other transitions

NCBG to CBG transitions are very important for train drivers. In an NCBG area, the train driver is the sole responsible for the train. The driver has to rely on its own senses and his actions are not warranted by any systems. When leaving an NCBG area, it depends on the local situation what a train driver has to do. In some cases, he has to stop and contact the dispatcher. In other cases, the driver may continue directly into CBG area if he has a clear order from the dispatcher.

Another transition type that is more subtle happens during construction works. When entering an area designated for construction works, the responsibility of the train is transferred from the dispatcher to head workplace safety (leider werkplekbeveiliging of WBI). Within this area, other rules apply. Furthermore, work trains can now be operated by non-qualified train drivers. These drivers know how to operate the train, but have no knowledge of signalling and national rules. This is a very special type of transition.

In some countries, railway or tramway lines are only partially equipped with catenary. In this case, a train or tram has to change between running on energy supplied via catenary and energy supplied by a battery or diesel engine. In the Netherlands, these transitions do not occur, but they might become relevant if battery-powered trains are going to be used on the Dutch railway network. These trains might use the catenary to recharge their battery and to power the train while running under catenary.

Appendix E. Interview with interviewee 4

2 March 2020 13:00 – 13:45

De Inktpot, Utrecht

When the Betuweroute became operational in 2007, no electric locomotives were available that could operate under 1.5kV and 25kV in the Netherlands. In the early months of operations, operators therefore used diesel traction. Furthermore, the 25kV installation of the Betuweroute and Havenspoorlijn were not operational in the first few months of operations. Similarly, a limited number of locomotives was available that could operate under ETCS at the time. It took a few years before railway operators had adjusted to the new systems. For smaller operators, the increased leasing cost of these multi-system engines was a heavy burden to carry.

In the first planning stages of the Betuweroute, the Betuweroute was planned to be equipped with ATB-NG as no operational ERTMS version was available in the time. Furthermore, the line would be electrified with 1.5kV DC instead of 25kV AC. Under 1.5kV DC, the maximum power is limited by the maximum amperage of 4000a. Especially for heavy coal trains, more power was needed. Among other reasons, this was a reason to choose 25kV over 1.5kV. However, as the Betuweroute was not originally supposed to be equipped with 25kV or with ERTMS, these systems needed to be implemented into the design of the infrastructure at a later stage. Transitions between systems were therefore never fully incorporated in the design of the Betuweroute from the start of the entire design process.

As a result of these intermediate changes, transitions were placed at locations that later turned out to be not suited for these transitions. An example is the Sophia tunnel at Kijfhoek. Within the tunnel, a transition from 1.5kV to 25kV is located. Furthermore, a transition from ATB-EG to ERTMS was present at the Kijfhoek end of the tunnel. This transition has been removed as ERTMS has been applied on the Kijfhoek shunting yard now.

When passing the power supply system transition, the traction has to be shut of first, which takes some time. Then, the neutral section in the tunnel has to be passed. And finally, the pantograph can be raised and the power reapplied. The train driver would prefer to accelerate at the bottom of the tunnel to make it up the incline, but this is not possible due to the power supply system transition. Even without transitions, it is difficult to keep the right speed at the right time when passing through a deep tunnel with steep inclines. The extra tasks that are required as a result of the transitions only add to the complexity.

Ideally, the design of multiple transitions is carried out in an integral manner. In practice however, decisions on the design of the Betuweroute were made at different moments in time. If you design a transition, the design of another transition might already have been finished and finalized. In that case, you have to work around that. For complex projects such as the Betuweroute, it is very difficult to keep in mind the integrity of the design.

As a result of the weaknesses in train operations that the Sophia tunnel poses, the capacity of the entire Betuweroute was limited by this tunnel. Only one train per direction was allowed in the tunnel simultaneously. When a train had cleared the tunnel, the next train was allowed to enter the tunnel. As a result, the capacity of the Betuweroute was limited to four trains per hour. The operational rules have been changed in the years thereafter. A follow-up train is now allowed to enter the preceding train is certain to be able to leave the tunnel without any problems. As a result of these measures, the capacity of the Sophia tunnel has increased from 4 to 6 trains per hour and direction.

At some tunnels, special tunnel regimes are present that ensure a continuous train path throughout the entire tunnel. The Willemspoortunnel at Rotterdam, for instance, has an X/G regime. An X-signal indicates that a freight train has to stop before the tunnel. When the X-signals turns into a G-signal, the train is allowed to enter the tunnel. The X/G-regime ensures that a continuous train path is available for the freight train, so that it does not have to slow down or come to a stop inside the tunnel. This reduces the risk of train strandings. At the Sophia tunnel, an L-signal is present. This signal has a different function. It prevents that trains enter the tunnel with a too high speed. When the entry speed of a freight train is too high, the train will overspeed at the bottom of the tunnel.

Appendix F. Visit to the ProRail railcenter / Panel group discussion with interviewee 5 & 6

05-03-2020 13:00 – 17:00

ProRail Railcenter, Amersfoort

The ProRail Railcenter is a recently-opened facility where multiple actors in the railway sector cooperate to improve the quality of the railway system. The facility is used to educate personnel of ProRail and of train operating companies. Multiple simulators are available to test new infrastructure designs on train drivers and maintenance personnel. A fully-functioning RBC is present to practice repairs for maintenance staff.

The main aim of the visit to the Railcenter in Amersfoort was to discuss operational transitions in railway infrastructure from a train driver point of view. Two train drivers of NS were present to discuss this topic. Both train drivers are occupied with the design of infrastructure since 2016. They both approach new infrastructure design from the train driver perspective. In this way, ProRail aims to prevent the creation of systems that are suboptimal from a train driver point of view. Before 2016, both drivers where full-time train drivers at NS Reizigers.

We started the conversation by discussing problems with operational transitions at the HSL-Zuid. According to the train drivers, three types of transition-related problems exist: technical problems, driver-related factors and operational causes. Combinations of these categories also exist.

Technical problems related to operational transitions

In some cases, no connection to the RBC can be made. Without this connection, the train received no new MA and has to come to a halt at the end of the ERTMS level 1 section at the entrance of the HSL. Connections can be lost in case the modem of the locomotive does not function properly. One of the train drivers mentioned that the reliability of the modem is influenced by the presence of corrosion on the roof of the locomotive. Connections can also be lost within the tunnels of the HSL-Zuid. These tunnels are equipped with antennas in order to transmit the GSM-R signals to and from the train. The calibration of these antennas is important for the reliability of this connection with the RBC. A small misalignment of an antenna due to wind or human action can cause connection losses.

Human factors in transition failures

The HSL-Zuid has combined transitions of train protection system and power supply system. The driver has to acknowledge the transition from ATB-EG to ERTMS level 1. If he does not acknowledge the transition, the train will apply a service brake until the driver has acknowledged the transition. Only a few seconds later, the driver has to switch of traction and lower the pantographs on both engines. If he does not do that, the system will do it automatically. The driver has to raise the pantograph again after the powerless section. If he raises the pantograph before the last locomotive has passed the neutral section, the system will be short-circuited and the train will come to a halt. There is no protection system that prevents raising the pantograph on the last locomotive too early. Between the 1500V and the 25kV section, there are three neutral sections. Raising the pantograph too early in each of these three neutral sections has different consequences.

Operational causes of transition failures

In some cases, trains cannot directly enter the HSL-Zuid, but have to wait for other traffic that is running late. When the operational transitions are approached with limited speed, the probability of train strandings significantly increases. This is especially the case at Hoofddorp and Zevenbergschen

Hoek, where the transitions are located on top of fly-overs. Especially when the train has to come to a complete stop, there's barely enough space to accelerate to a sufficiently high speed before the start of the neutral section. When acceleration of the train is limited because of low adhesion (slippery tracks) or when one of the locomotives does not function properly, the probability of stranding in the neutral section increases even further.

Combined causes of transition failures

The IC Direct trains consist of 2 Bombardier TRAXX 2MS locomotives and 6 to 9 ICR-carriages. These carriages, constructed in the 1980s, are equipped with electro-pneumatic brakes (EP-brakes). A pneumatic braking system is a relatively slow-acting system. It takes some time before all brakes are applied and when the brakes are released, it takes some time before all brakes are released. As applying and releasing the brakes is a slow process, the braking process cannot be stopped at all moments. Once the brake has been applied, the braking process has to be finished. A premature braking interruption can create a situation in which the rear end of the train is still braking, while the locomotive is accelerating again. The resulting forces on the train couplings can even break the train in multiple pieces, which happens a couple of times per year. Frequently applying and releasing the brake is known as 'milking the brake' or 'de rem melken' by train drivers. When drivers do not handle the EP-brake with care and constraint, the train speed decreases considerably more than the driver would have wanted. Experience is key to the sensible application of EP-brakes.

Experience also plays an important role in transitioning from the main line network to the HSL-Zuid tracks. When drivers have an uninterrupted path, there's little probability of stranding in one of the neutral sections of the power supply transition. When there's no path available on the HSL, some drivers choose to stop well before their End-of-Authority, even though the train is still blocking the main line tracks. This way, the driver is sure that he can attain enough speed to pass the neutral sections without stranding. This can lead to delayed trains on the main line network.

Solutions to transition failures

New intercity trains will enter service in 2020 (ICNG). These trains have several advantages over the current trains from a reliability point-of-view. Firstly, the ICNG will switch between power supply systems automatically, which means that the driver only should act when switching between automatic train protection systems. Furthermore, the new trains are equipped with two brake systems: electro-pneumatic (EP) brakes and electromagnetic (EM) brakes. EM-brakes use resistance in the electric motors of the train to brake. The strength of the EM-brake depends on the speed of the train. At low speeds, the EP-brakes function supplementary to the EM-brakes. EM-brakes apply and release instantly at the drivers wish, which means that the risk of 'overbraking' no longer exists.

The infrastructure will also be adapted. The length of the neutral sections between both power supply systems is reduced from approximately 600 meters to 50 meters. The probability of stranded trains in the neutral sections is therefore greatly reduced. The large 600-meter neutral section was originally designed to prevent a direct electric connection between the 1500V and 25kV areas via the train. In the new situation, it is no longer possible to raise the 'wrong' pantograph due to software restrictions in the train.

Other transition types

According to the train drivers, combinations of transitions should be avoided if possible. Furthermore, operational transitions should not be located near locations where drivers need to focus on something else. Level crossings are points that require driver attention. Road traffic may ignore closed level crossings and traverse the tracks anyway. When a level crossing is disrupted, i.e. the crossing remains closed although no train is approaching, the change of crossing traffic increases significantly. When a crossing remains closed for 5 minutes, the signal in front of the crossing automatically switches to red. The driver may pass this signal at reduced speed. The maximum speed at the disrupted level crossing is 10 km/h.

Appendix G. Interview with interviewee 7

25 march 2020 14:30 – 15:15

Skype call

Most disruptions at the Betuweroute occurred at the Botlek tunnel, which is located in the Rotterdam harbour area. This tunnel is characterised by long and steep slopes at either end of the tunnel. The Havenspoorlijn is equipped with ERTMS level 1 overlay. ERTMS components, such as balises and LEU's were built over the existing ATB-EG infrastructure. The old ATB-EG components were no longer in use as ERTMS had been implemented to replace this. The ERTMS overlay created a technological challenge at certain points in the tunnel with the underlying old systems, which contributed to trains stranding in the tunnel. This could also cause delay to other trains as well.

Another cause for disruptions and trains stranding in the Botlek tunnel was overspeed at the bottom of the tunnel. At both entrances of the tunnel, signs indicated advisory speed limits. When the driver adheres to this speed, the speed of the train at the bottom of the tunnel should not supersede the maximum line speed. In practice, however, many drivers entered the tunnel with a higher speed than advised. As a consequence, the train speed at the bottom of the tunnel supersedes the maximum line speed and the on-board ETCS equipment will apply the emergency brake, leading to a stranded train in the tunnel that cannot leave the tunnel unassisted.

The Sophia tunnel closely follows the Botlek tunnel in the amount of disruptions. The causes for disruptions are in part similar to disruption causes found at the Botlek tunnel. the Sophia tunnel has long and steep slopes at both tunnel ends. When a train comes to a complete stop in the tunnel, most trains cannot continue their journey without the assistance of another locomotive to help leave the tunnel. Jayne recalled that in practice, if the weight of a stranded train exceeded 1200 ton, they almost always required an extra locomotive to pull the train out of the tunnel. For the especially heavy coal and iron ore trains, two or three locomotives were sometimes required. The ProRail traffic control centre at Kijfhoek (VL-post Kijfhoek) has the authority to seize locomotives off any railway undertaking to assist. As experience with stranded trains in the Sophia tunnel grew, guidelines were developed to coordinate the process of retrieving stranded trains. These stated whether extra locomotives should be placed at the front or the back of the train and if the train would be retrieved in multiple pieces.

In the beginning stage, a transition from ATB-EG – ERTMS level 2 was present at the Kijfhoek side of the Sophia tunnel. Trains in the Sophia tunnel heading in the direction of Kijfhoek were sometimes faced with restrictive braking curves at the end of the ERTMS moving authority. When the first signal under ATB-EG indicated yellow-4, the braking curve would ensure that a train passed that signal at 40, leading to a very restrictive braking curve at the tunnel exit.

Yellow signals were common at the tunnel exit, as the Betuweroute section between Papendrecht and Kijfhoek and the shunting yard of Kijfhoek itself were part of different control area's (PPLGs) and therefore controlled by two different dispatchers in the dispatching centre of Kijfhoek. All train paths had to be set manually by these two dispatchers. When a continuous train path could not be provided in time, the ERTMS braking curve would force the train to decrease speed at the bottom of the tunnel.

The Zevenaar tunnel is the third tunnel that was a cause for disruptions, all be it far less that the Botlek tunnel and Sophia tunnel. Similar problems could be distinguished at the tunnel at Zevenaar. A transition between ERTMS level 2 and ATB-EG caused undesired effects of restrictive braking curves. The track section between Elst and Zevenaar is part of a different PPLG than the section between Zevenaar-oost and the German border, which meant that movement authorities were not always provided in time. The track section between Zevenaar and the German border, where freight trains leaving the Betuweroute and passenger trains between Germany and Arnhem use the same tracks, is controlled by two dispatching centres simultaneously (VL-post Arnhem and VL-post Kijfhoek).

After discussing operational problems at three tunnels, the discussion turned toward the connection between the Betuweroute and the main line network at Meteren. The lack of a continuous movement authority from the Betuweroute onto the main line Utrecht – Den Bosch v.v. is one of causes for disruptions, similar to the situations at the tunnels near Zevenaar-oost and Kijfhoek. As the number of daily freight trains on this route is not as frequent, the effects on other traffic are limited. Precautions are taken by railway undertakings in order to prevent unwanted stops on the connecting arches. DB Cargo, for instance, plans each trip over the connecting arc with a stop well in advance of the start of the connecting arch. The train departs when a continuous movement authority can be provided.

Appendix H. Interview with interviewee 8

9 March 2020 15:30 – 16:00

De Inktpot, Utrecht

The interaction between the HSL-Zuid and the conventional tracks do not generally lead to large problems. The high number of disruptions on the HSL-Zuid are not caused by the complexity of the infrastructure, as thought earlier, but rather technical malfunctions of one the subsystems used on the HSL. Subsequently, trains come to a stop at unfavourable locations, leading to long delays and to disruptions. Due to the complexity of the HSL, resolving issues takes longer than on other railway lines. Most difficulties with transitions are caused by the rolling stock and locomotives, which in turn are mainly caused by software problems. If the locomotive software was updated, new problems would arise. The three train types operating on the HSL-Zuid: Thalys, Eurostar and TRAXX locomotives all have their own unique software problems. Hardware problems also exist, for instance, the modems do not always function properly. Therefore, a connection with the RBC cannot be established. The train manufacturers do not built those modems themselves, but buy them from other manufacturers. When the modem do not function satisfactory, the operators will discuss it with the train manufacturer, who will discuss it with the manufacturer of modems. These chains of contractors and subcontractors make it difficult to actually change things. Bringing the people together who might be able to solve the problem is a difficult task.

It depends greatly on the level of experience of the train driver to what extent they consider the transitions of the HSL-Zuid challenging. Those who are more experienced are more confident about their abilities. This confidence may also lead to overconfidence and mistakes made by these experienced drivers. In order to help drivers when they are in trouble on the HSL, a helpdesk has been set up which can help drivers when a transition is failed or a malfunction has occurred. The helpdesk personnel consists of experienced train drivers, who have access to a large amount of real-time data on the status of each train on the HSL. Using this data, they can help the driver to resolve the issues of his or her train.

Acquiring more data on train malfunctions is one of the steps that has been undertaken to reduce the number of malfunctions on the HSL. Improving the overall performance of the HSL requires a lot of small steps to be made. Big steps could be made, but are too costly to implement.

Appendix I. Interview with interviewee 9 & 10

25-05-2020 10:30 – 11:00

Skype call

Interviewee 9 is Project Manager and is in charge of the SNG project for The Netherlands and Auckland Transport project for New Zealand among others. Interviewee 10 is Operations Manager, in charge of leading and coordinating the different projects for different customers all over the world. Both interviewees have experience with ATB-EG to ERTMS L2 transitions at the Amsterdam – Utrecht railway line and the Lelystad – Hattemerbroek railway line (Hanzelijn), where multiple tests have been conducted with ETCS-equipped SNG trains. Connection losses with the RBC are often caused by an unstable GSM-R signal. the GSM-R signal is not always able to create a stable connection between the on-board unit (Euroradio) and the RBC. These problems can occur at any location.

The GSM-R network operates close to other bands that are used for other commercial public GSM networks. Signals of the regular GSM network may therefore interfere with the GSM-R network. In practice, it is difficult to filter regular GSM signals from GSM-R signals, which can make it hard to create a stable connection with the RBC. The problem of signal interference between the GSM-R network and other public network is being recognized by the European Railway Agency (ERA) as well as by the UIC. New guidelines have been published by the European Integrated Railway Radio Enhanced Network (EIRENE) to improve radio frequency signal filters in modems. These modems with updated filters have been applied in NS SNG trains.

The relative strength of the GSM-R signal in relation to regular GSM signals also influences the reliability of the RBC connection. Regular GSM networks not only interfere with GSM-R signals, but also vice versa. Increasing the GSM-R signal strength may therefore cause issues for the regular GSM network. Therefore, increasing the GSM-R signal strength is not always an option to reduce RBC connection failures. The vulnerability of the GSM-R signal is also increased by ‘radioholes’, areas along the railway line where the coverage of GSM-R is not sufficient to create a reliable connection with the RBC or where signals are hindered by railway structures, such as tunnels.

In most cases, the transition from ATB-EG to ERTMS Level 2 is executed automatically. Trains with an on-board ETCS unit will automatically start connecting with the RBC when passing a balise group. Under normal circumstances, no manual tasks have to be performed by the train driver.

While driving under ATB-EG, the on-board ETCS unit operates under Level STM, which means that another ATP system is active. When transitioning to ETCS level 1 or level 2, no additional tasks or acknowledgements are required, as Level 1 and Level 2 are considered safer than level STM. However, the train driver has to acknowledge a transition to a lower level ETCS as it is deemed less safe. When the driver does not acknowledge the transition, the service brake will be applied until the driver acknowledges the transition.

In a double signalling regime, where ERTMS and ATB-EG are simultaneously present in the railway infrastructure, connection issues with the RBC can occur as well. In such cases, the OBU will use ATB-EG as a backup to ERTMS. When a connection to the RBC cannot be made, the train will remain driving under ATB-EG.

Connection issues with the RBC as a result of an unstable GSM-R connection or a malfunctioning modem are not unique issues to the Dutch railway system. These problems also occur on other railway networks with other national ATP systems. Transition failures are not therefore necessarily caused or reinforced by certain features of ATB-EG.

Appendix J. Interview with interviewee 5

26-05-2020 13:30 – 14:10

Phone call

Interviewee 5 is involved with the design of new railway infrastructure. He represents the perspective of train drivers on the design of new infrastructure. Interviewee 5 was also involved in the panel group discussion in Appendix F.

When transitioning from ATB to ERTMS L2, a connection with the RBC will be established. The RBC sends movement authorities to the on-board ETCS unit via GSM-R. Under some circumstances, no connection with the RBC can be established. For instance, no connection with the RBC is established when the train key is not registered to the RBC. One of the functions of balises is to verify the availability of a train key in the train and in the RBC. When this key is not available, no connection will be made between the train and the RBC.

When a key is present, the on-board ETCS equipment will automatically try to connect to the RBC, after passing a balise ordering the ETCS equipment to do so. In some cases, a connection with the RBC cannot be established successfully, for which multiple causes exist. First of all, the RBC itself can malfunction. In this case, all trains that are connected to the RBC will lose connection to the RBC simultaneously. Second, the on-board modem, responsible for receiving the GSM-R signals, malfunctions. A modem malfunction can be caused by either software or hardware related issues. When a train is not connected to the RBC or disconnects from the RBC at some point during its journey, an ERTMS Trip will occur, in which case the emergency or service brake is applied, depending on the ETCS configuration.

Acts of the train driver have no influence on connection failures or connection losses, but they do influence the time required to resolve connection issues. Train drivers have differing levels of experience with ETCS malfunctions and may not always be aware of the right procedures to regain connection with the RBC and continue the train journey. When a train driver is not certain how to resolve a malfunction, he or she can contact a dedicated NS helpdesk. This helpdesk, staffed with experienced train drivers, can advise train driver how to act in certain situation and what procedures to follow in order to solve ETCS malfunctions. While NS provides a helpdesk mainly for train drivers on the HSL-Zuid, most train drivers of other railway operations usually do not have access to such a helpdesk.

The transition from ATB to ERTMS and vice versa has to be acknowledged by the train driver within 5 seconds after receiving a signal. Acknowledgement is required when the level of safety differs between ETCS and the national ATP system, which is the case with ATB-EG. Transitions within ERTMS, from ETCS level 1 to ETCS level 2 and vice versa do not have to be acknowledged by the driver, as the level of safety does- not differ between level 1 and level 2. When a transition that is supposed to be acknowledged is not acknowledged, the train service brake will be applied and the train will come to a stop before the end of authority unless the transition is acknowledged by the train driver at a later moment. The effect of a late acknowledgement depends greatly on the train type and especially the braking system of the train. Trains that are equipped with an electro-pneumatic (EP) braking system will respond slowly to the application and release of the brake, as sufficient air pressure has to be built up in the braking system to release the brakes (5 bar is standard). Especially for long freight trains, this means that it can take 20 or 30 seconds before the brakes are fully released, leading to a large reduction in speed or even a train coming to a complete stop. Trains that are equipped with electro-magnetic (EM) brake instantly react to the application and release of the brake, leading to a much smaller reduction in speed than to train equipped with EP brakes.

At the Amsterdam – Utrecht railway line, ETCS level 2 is present as an overlay to ATB-EG. When a train is transitioning from ATB to ERTMS, but is unable to connect to the RBC or experiences another type of ETCS-related malfunction, an ERMTS trip will occur, forcing the train to stop. Only after the train has come to a complete stop is it possible to transition back to ATB-EG and continue the train journey under ATB-EG. This transition has to be carried out manually by the train driver.

Appendix K. Interview with interviewee 11

26-05-2020 15:00 – 16:00

Phone call

Interviewee 11 is, among other functions, an ERTMS specialist at DB Cargo Standards and Education. In this function, he is responsible for the (re)education of train drivers and rolling stock inspectors with respect to ERTMS.

ERTMS is developed as a European system, but in practice, the implementation of ETCS on the different national railway networks is conducted in varying ways. For an internationally operating railway undertaking, such as DB Cargo, this creates extra challenges when training staff. Not only can specifications differ per country, but the underlying infrastructure required for ERTMS is disconnected between countries.

An example given by the interviewee is the GSM-R network. GSM-R is used for radio communications of in the railway sector. When operating under ETCS level 2 or level 3, GSM-R is also used to transmit data between the Radio Block Centre (RBC) and the on-board ETCS equipment. Every country has its own GSM-R network, used for all sorts of radio communications. The transition between these networks has led to considerable problems in the past. Situations occurred, in which international trains, starting their journey somewhere in Germany would lose their GSM-R signal after crossing the Dutch border into the Netherlands. These trains automatically connected to the German GSM-R network at the start of their journey when the locomotive was made ready for that day. After crossing the Dutch border, for instance at Zevenaar, the German GSM-R signal would become less strong as the distance between the closest German GSM-R antenna and the train increased. After entering the Betuweroute at Zevenaar Oost, the train enters a tunnel. Antennas for the Dutch GSM-R network are installed in this tunnel in order to retain a reliable connection with the RBC of the Betuweroute. However, as the train is still connected to the German GSM-R network, the train would lose connection with the RBC, leading to the application of the service brake by the on-board ETCS equipment.

In order to transition from the German to the Dutch GSM-R network, network registration of the train ID on the Dutch GSM-R network is required. Initially, no balise group was present at the Dutch/German border at Zevenaar ordering an automatic registration of the train to the Dutch GSM-R network. As a workaround, train drivers would often reset the train radio. When it was reset, it would in most cases connected to the Dutch GSM-R network. This problem has since been addressed and trains coming from Germany are now automatically registered and connected to the Dutch GSM-R network.

Similar issues occur at Elst junction, where switchable balises are installed. Trains are reregistered to the correct network when a continuous train path onto the Betuweroute is available. However, when no continuous train path can be provided, for instance when a freight train is trailing a commuter train, no order to reregister to another GSM-R network was provided to the on-board ETCS equipment, which means that no connection to the RBC of the Betuweroute could be established when entering the Betuweroute. The switchable balises did not order a reregistration to another GSM-R network in this instance.

Apart from network registration issues when crossing a border, no major difficulties have been reported by train drivers when transitioning from ATB-EG to ETCS or vice versa. In cases where the driver is unsure how to resolve an ETCS-related issue, he or she can contact a DB Cargo helpdesk, where the driver is advised on resolving the issue at hand. Train drivers generally prefer driving under ETCS as the DMI (Driver Machine Interface) provides more information under ETCS than under ATB-EG. Driver are better able to anticipate on speed changes as they can see how long their movement authority is. This means that drivers can idle earlier in anticipation of the end of their movement authority or they can use the electro-dynamic (ED) brake of the locomotive, which feeds energy back into the catenary. Power consumption is therefore lower when driving under ETCS.

At Amsterdam – Utrecht, where an ETCS level 2 overlay is present, freight trains of which the locomotive is equipped with ETCS generally use ATB-EG. In order to use ETCS, communication between the On-board ETCS equipment and the RBC should be encoded. Each individual locomotive should be provided with a key to decrypt these signals. Likewise, a de/encryption key for each individual locomotive should be present in the RBC. At the time when ERTMS was first implemented on Amsterdam – Utrecht, a considerable price was charged by ProRail to register locomotive keys. As the added benefit of using ETCS on this track section, as well as on the Hanzelijn, did not outweigh the registration cost, it was decided not to register DB Cargo locomotives for these track sections. In a later stage, when DB Cargo started using BR193 Vectron locomotives to the Netherlands, these locomotives where automatically registered by ProRail. These locomotives are therefore able to use ETCS on Amsterdam – Utrecht and the Hanzelijn.

Appendix L. Interview with interviewee 12

04-06-2020 14:00 – 15:00

Skype call

The HSL-Zuid entrance at Zevenbergschen Hoek has proven prone to disruptions in the past few years, partly as the result of the combination of ATP transition, power supply system transition and fly-over. Often, trains have to wait in front of the SMB protecting the entrance to the HSL-Zuid. As this SMB is located in an ETCS level 1 area, a new movement authority can only be attained by passing the balise next to the SMB. The SMB is currently located at the foot of the fly-over. At the top of the fly-over, the neutral section separating the 1.5kV DC and 25kV areas is located. While the train driver can perform the transition him/herself by lowering the pantograph, the pantograph is automatically lowered by the on-board ETCS unit if the train driver does not lower the pantograph.

The pantograph is lowered automatically 17 seconds after passing the balise group announcing the power supply system transition. When passing this balise at regular speed, this means that the pantograph will be lowered just in advance of the neutral section. However, when the train has to start from a standstill, the pantograph is lowered 17 seconds after passing the relevant balise anyway, even though the start of the neutral section is still a couple of hundred meter away. As the train has not achieved sufficient speed to clear the fly-over, the train will come to a stop, even though the distance between the SMB and the start of the neutral section is theoretically sufficient to attain enough speed to clear the neutral section without coming to a standstill. This problem is being solved by placing the SMB further back. Another possible solution is to reprogram the on-board ETCS software so that the pantograph is not lowered after a certain amount of time, but based on the actual location of the train.

Transition problems between ATB and ETCS are mostly caused by technical problems of some sort. The role of the train driver is generally limited. Currently, drivers have to acknowledge a transition from ATB to ERTMS. For modern trains, this is no longer required. ERTMS has a higher safety level than ATB-EG, which is why no acknowledgement is required. When transitioning from ERMTS to ATB, an acknowledgement will be required, as ATB-EG is considered less safe than ERTMS. Furthermore, the train driver has to be aware that his attention should be shifted from the DMI to trackside signals for signalling information. The fact that a train driver has a DMI through which he or she receives all relevant information does not mean that he or she does not look out of the window of the train. As the driver can see where he or she has to act, more time is available for scanning the track.

Among the technical problems that occur during transitions from ATB to ERTMS, a lack of connection with the RBC is one of them. Currently, the transition from ATB to ERTMS is announced about 15 seconds before it will take place. The available time to contact the RBC is therefore limited. If a train cannot connect to the RBC, no movement authority can be supplied to the train and the train will come to a stop. There are multiple ways in which this problem can be solved. Firstly, the connection to the RBC can be established well ahead of the actual transition. If no connection can be achieved, the train can be stopped by a signal at danger under ATB-EG in front of the actual transition. Another option is to connect trains permanently to the RBC, even though the train is driving under ATB-EG. Either of these solution prevent that a connection has to be established in a short time period.

RBC connection failures can be caused by failing or malfunctioning modems in the train. Although the general reliability of these modems is relatively high (1 malfunction per 100 hours of service), solving these problems is often difficult for train drivers. A large variety of malfunctions can be the cause of a modem defect, some of which can be solved by the train driver and some cannot be solved by the train driver. Resetting the modem is the most common method to try to solve modem problems. A helpdesk is available for NS train drivers to assist train drivers in this kind of situations. In order to reduce the risk of a connection failure as a result of a failed modem, all trains are equipped with at least two modems. The Thalys trains are even equipped with three separate modems.

The GSM-R network is generally reliable with a very limited downtime. Furthermore, GSM-R cells overlap, so that a train is always in reach of one GSM-R cell if another cell malfunctions. In practice though, this redundancy does not always function properly. A way in which the redundancy of GSM-R can be increased is by connection both modems to two different networks simultaneously. If one of the networks or one of the modems does not function properly, a full replacement network is available to carry data and radio communication.

Modern trains and modern ATP systems such as ERTMS offer the possibility to use a large variety of data when analysing technical failures and malfunctions. It takes some time for organisations to discover the potential of these new data sources, but they are currently being used on an increasing scale. The same applies to train drivers, who have to get used to new operating principles of ETCS.

The braking curves of ETCS is one of the factors that requires some getting used to by train drivers. The way in which braking curves are calculated differ per country and depend on the level of risk that infrastructure managers (IM) are willing to take. Risk-averse IMs will choose for relatively flat braking curves, forcing the train speed down well in advance of the End of Authority (EoA). For passenger trains, ProRail uses a deceleration of 1 $m/_{s^2}$for calculating braking curves, which is the highest in Europe. Other countries, such as France and Belgium use a deceleration of 0.8 $m/_{s^2}$to calculate a braking curve. A ‘steeper’ braking curve has a slight, positive effect on overall track capacity of 2-3%.

Appendix M. Panel group discussion with interviewee 13 to 16

11-06-2020 10:00 – 11:00, 13:00 – 13:30

Skype call

What problems arise at ATB-ERTMS transitions?

From a human factors perspective, the transition from ATB-EG to ERTMS is relatively simple. Prior to the actual transition, a symbol appears in the DMI, indicating that a transition is imminent. Once the symbol starts blinking, the transition will follow shortly. The time between this announcement and the transition itself can differ. When the transition takes place, the driver has five seconds time to acknowledge the transition. If the driver acknowledges the transition within this time frame, everything is fine. If the driver does not acknowledge the transitions, the emergency train brake will be applied. Apart from acknowledging the transition by pressing a button, the driver should be aware to shift his attention from the driver DMI to the outside world in order to observe the trackside signals, in case of a ETCS to ATB-EG transition.

Most malfunctions occurring at transitions are caused by technical failures of some sort. For the train driver, the exact cause of malfunctions is often unknown. Even if the on-board ETCS equipment informs the driver on the causes of a malfunction, the amount of information provided by the system is often inadequate for the driver to identify the exact cause of a malfunction. The knowledge of train drivers on ETCS varies a lot. Drivers are well known on how to operate ETCS,but they lack the knowledge to fix any malfunctions arising from the system. Their education on ETCS is concentrated on the operation of the system. The principles on which ETCS is based on, are often little exposed. Because of this, train drivers do not see it as their task to know the technical specifications of ETCS to the fullest extent. Furthermore, they only consider it their responsibility to report malfunctioning ETCS units.

The probability of a failed transition differs greatly based on local circumstances. At some transition locations, technical failures occur more often than at other locations. The probability of a transition failure and the type of failure also differs per locomotive type. Some locomotive-specific malfunctions or difficulties in operation are described below:

- BR 193 (Siemens Vectron). The BR193 is the newest type of electric freight locomotives on the Dutch railway network. It is used by multiple freight railway companies. Some of these engines are owned by the operator and other engines are leased from leasing companies. 193s are equipped with a geo-positioning system. Based on the real-time location of the locomotive, certain transitions are allowed. For instance, when a 193-hauled train approaches the Betuweroute entrance at Kijfhoek, geo-positioning allows the train driver to transition from 1.5kV to 25kV, as the system is aware of the presence of this transition. In some cases, this system does not function. At the Venlo border crossing, the train is supposed to transition from PZB to ATB-EG. Geo-positioning does not recognise this transition location and therefore, the transition is not made. In order to work around this problem, all 193-hauled trains stop at Venlo to transition from PZB to ATB, even though they have a green signal in front of them.

- BR 193 (Siemens Vectron). A second point regarding the Siemens Vectron is the long time it takes to transition between two systems. For instance, it takes 2 minutes and 9 seconds before a full transition of power supply system is completed. This is not a malfunction, but a design choice. This can have serious consequences if the train driver suddenly has to apply power.
- BR 186 (Bombardier TRAXX F140 MS2). When transitioning from ETCS level 1 to level 2, a symbol in the DMI notifies the driver that the transition is imminent. The driver is, however, not informed whether or not a connection with the RBC has actually been established. Only when the transition is supposed to take place does the driver know if a connection with the RBC has been established.
- G2000 (Vossloh). G2000 engines in the Netherlands are equipped with separate units for ETCS and ATB-NG. A STM is used when driving under ATB-NG. Occasionally, when transitioning from ETCS to ATB-EG, no connection between the STM and the separate ATB unit can be established. As a result, ETCS will trip and the train will come to a stop. A workaround that has been successfully applied by train drivers is to apply the emergency brake before making the locomotive ready for service. Although the drivers do not know why this works, it works.

How are problems being solved?

As stated previously, the driver often is unaware of the precise cause of a failed transition. When a failure occurs, drivers reset the entire ETCS unit. This takes some time, but in most cases it will ensure that all malfunctions are removed at once. In order to minimise delays, the driver does not devote much attention to finding out what might have happened to the locomotive. In some cases, a side screen of the DMI might inform the driver of the actual cause of the failed transition and advise the driver how to resolve the issue at hand. Mostly, this is not the case and the driver remains uninformed. Another reason to immediately reset the locomotive is that fixing individual problems might create problems elsewhere. Completely resetting the system prevents this. If train drivers regularly drive on different locomotives with (slightly) different operating principles, the confusion on the cause of a failed transition only increases.

Smaller operators do not have dedicated personnel available to aide train drivers when a failed transition has occurred. Train drivers might contact other trains drivers in order to resolve an issue. A combined helpdesk for all railway operators is not considered an option due to fierce competition between railway operators. Furthermore, the margins on operating freight trains are too tight to finance a helpdesk, similar to NS Reizigers. When problems cannot be resolved by the train driver, the locomotive manufacturer or a maintenance facility might be contacted. These contacts are not free of charge. Therefore, most companies are reluctant to contact them.

Various remarks

Freight trains are fitted with pneumatic brakes. On long freight trains, the application and especially the release of train brakes can cost several minutes. The driver has to be well aware of this fact and anticipate on future conditions accordingly.

At the Dutch/German border crossing near Zevenaar, a transition between PZB and ERTMS Level 2 is made. For unclear reasons, no connection with the RBC can be established when the train operates at the normal line speed of 80 km/h. When the trains drive the same section with 60 km/h, a connection can be established and the train can enter the Betuweroute unhindered.

Operational differences exist between railway lines equipped with the same ETCS version. On the Betuweroute, for instance, the braking curve is calculated with a downward slope of 0.5‰ as standard, even though the vertical track alignment is level. This virtual downward slope is incorporated into the braking curve as an extra safety margin, on top of the standard safety margins that are used when calculating a braking curve. At Amsterdam – Utrecht, this extra precaution is not incorporated into the ETCS braking curve, leading to different braking curves on the Amsterdam – Utrecht railway line than on the Betuweroute. The difference in braking curves is also noticeable to train drivers.

The large number of failed transitions do not only lead to delays, but also lead to additional costs for the freight operators. First of all, the train might be damaged as a result of an emergency brake. The wheel tires might be damaged. Furthermore, a lot of extra fuel or electric energy is required to get the train up to speed again. Additional charges as a result of the train being delayed also add to the cost of failed transitions.

The degree to which ProRail is willing to actively participate in moving stranded trains depends largely on the disruption caused to the surrounding train traffic. If a lot of trains are hindered, ProRail is more inclined to act fast than if a train is stranded in a relatively harmless place.

When the emergency brake is applied for any reason, NS train drivers are able to momentarily interrupt the braking process. By doing so, the train driver can influence to location where the train is going to come to a stop. Locomotives used for freight operations generally are not equipped with such a system.

Train traffic on the Betuweroute and on Kijfhoek shunting yard is controlled by different interlocking systems. The Betuweroute interlocking (EBS or Electronische Beveiliging SIMIS) is constructed by Alstom, while the Kijfhoek interlocking system (VPI or Vital Processor Interlocking) is constructed by Siemens. At the Kijfhoek end of the Sophia tunnel, a transition between ETCS level 2 and level 1 is present. The EoA of Level 2 is only extended after the train passes an active balise group for level 1, providing the train with an extended movement authority. Furthermore, the Kijfhoek interlocking system VPI only allows a train path to be set if the first track section of that train path is actually occupied by a train. As a result, the train comes close to its EoA and has to slow down significantly, before the movement authority can be extended. In combination with the difficulty of braking a freight train fitted with pneumatic brakes, this often leads to strandings on the upward slope of the Sophia tunnel.

Appendix N. Braking systems

In this section, various train braking systems are described that are currently in use on locomotives and rolling stock operational in the Netherlands. Failed transitions, whatever the exact cause may be, can result in the application of the train brake. If no connection can be established with the RBC or a transitions is not acknowledged, the train brake will be applied until a connection has been established between train and RBC or until the transition has been acknowledged by the driver. The effects of a relatively short braking period depend largely on the braking system that is fitted to the train. Four braking systems are commonly used on Dutch trains: Pneumatic (P) braking system, Electro Pneumatic

(EP) braking system, Electro Magnetic (EM) braking system and the Electro Dynamic (ED) braking system. The main characteristics of each braking system will be described in more detail.

(electro) pneumatic brakes use air pressure to apply the train brakes. When the train brake is applied, the air pressure in the air pipe drops from the release pressure of (typically) 5 bar to a lower pressure. When the air pressure in the air pipe drops in each train car, the brake is applied by feeding air from the pressurised air reservoir to the braking cylinder of each wagon. By increasing the air pressure in the braking cylinder, the brake of each wagon is applied. When the brakes are released again, a compressor refills the air pipe to 5 bar and the air from the braking cylinder is released. Depending on the length of the train and the number of compressors distributed over the train, the time for the brakes to decrease and increase varies (Railway-technical.com, n.d.).

The principles of P- and EP-brakes are similar in the respect that they both rely on air pressure to apply the train brake. The main difference between P- and EP-brakes is the way in which the brakes are applied and released. With P-brakes, the brake is applied once the air pressure in the air-pipe starts to drop. EP brakes are applied by an electric signal, rather than by differences in air pressure. As a result, trains fitted with EP brakes can apply the brakes of each train carriage simultaneously (Railway-technical.com, n.d.).

Pneumatic brakes can be either fast-acting or slow-acting. Fast-acting pneumatic brakes fill the air pipe in 3 to 5 seconds and it can take 15 to 20 seconds before the brakes are fully released. For slow-acting brakes, the fill time of the air pipe is 18 to 30 seconds and the release time is 45 to 60 seconds (Cruceanu & Perpiniya, 2012). Slow-acting braking systems are used for (long) freight trains. Fast acting brakes are mostly used on passenger trains and slow-acting brakes are used for long freight trains. Slow-acting brakes are used on freight trains in order to reduce the force on the train couplings.

In contrast to EP brakes, EM can be applied and released in a matter of seconds. With EM brakes, braking force is created by friction between the (activated) electromagnets and the rails (Cruceanu & Perpiniya, 2012).

ED brakes transform kinetic energy into heat energy or electric energy. The train power generators are used to generate electric energy, which is converted into heat energy in resistors. Alternatively, the generated electricity can be fed back into the catenary. The latter process is also called regenerative braking (Sharma, Dhinkgra & Pathak, 2015). Similar to EM brakes, ED brakes can be applied and released instantly.

The type of train brake fitted to a train can have large effects on the train speed when a the brake is applied for a short period of time (Appendix J). While the effect of a short braking period is limited for trains equipped with EM or ED brakes, the effects can be very significant for trains fitted with (E)P brakes. Especially in the case of long freight trains, this can be problematic. With (E)P brakes, the brake may only be released when the brake pressure is level throughout the entire brake pipe of the train. If the pressure is unequal throughout the train brake pipe, forces on the couplings could become too large and the couplings could snap (Appendix F). So even if the (E)P brake is applied for a short amount of time, the train will lose a lot of speed or will even come to a complete stop.

Appendix O. Operational transitions in the Netherlands

In this appendix, the locations of all relevant operational transitions are identified. The exact location of each transition can be found in OBE-leaflets (Overzicht Baan en Emplacementen or Overview of tracks and yards). In Appendix O.1, an overview is given of all transitions in power supply systems, including phase separations. In appendix O.2, transitions in ATP systems are listed. Appendix O.3 the location of all moveable bridges is indicated. Finally, Appendix O.4 gives an overview of all significant gradients in the Dutch railway network.

O.1 Power supply systems and phase separations

The location of all power supply system transitions and of all phase separations are listed in Table 19. Most transitions are found on the HSL-Zuid, the Harbour railway line (Havenspoorlijn or Hsp) and the Betuweroute (BR). A limited amount of transitions is located on the main line network (Hoofrailnet or HRN). For each transition, the two power supply systems that are connected are listed. Transitions that are located very close to the border are not included in this table as they're out of the scope of this research. The approximate locations of all transitions have been found via ProRail (2019b). OBE-leaflets are used to define the exact location.

Table 19 Location of power supply system transitions and phase separations

	LOCATION	TYPE	OBE (SOURCE)
HSL	HSL Breda aansluiting Belgische grens --> Bd	1.5kV - 25kV	OBE 000885279
	HSL Breda aansluiting Bd --> Belgische grens	1.5kV - 25kV	OBE 000885280
	HSL Zevenbergschen Hoek aansluiting Bd --> Rtd	1.5kV - 25kV	OBE 000885277
	HSL Zevenbergschen Hoek aansluiting Rtd --> Bd	1.5kV - 25kV	OBE 000885277
	HSL Lage Zwaluwe Fasescheiding	25kV - 25kV	OBE 000885277
	HSL Barendrecht aansluiting	1.5kV - 25kV	OBE 000885274
	HSL Rotterdam Noord aansluiting	1.5kV - 25kV	OBE 000885676
	HSL Zoetermeer-Bleiswijk Fasescheiding	25kV - 25kV	OBE000885268
	HSL Hoofddorp aansluting Rtd --> Shl	1.5kV - 25kV	OBE 000885273
	HSL Hoofddorp aansluiting Shl --> Rtd	1.5kV - 25kV	OBE 000885274
HSP/BR	Hsp Barendrecht Vork	1.5kV - 25kV	OBE 000885257
	BR Kijfhoek aansluiting Kfh --> BRppd	1.5kV - 25kV	OBE 000885294
	BR Kijfhoek aansluiting BRppd --> Kfh	1.5kV - 25kV	OBE 000885295
	Br Lingewaal Fasescheiding	25kV - 25kV	OBE 000885301
	BR Meteren Noord aansluiting Gdm --> BRmet	1.5kV - 25kV	OBE 000885225
	BR Meteren Noord aansluiting BRmet --> Gdm	1.5kV - 25kV	OBE 000885226
	BR Meteren Zuid aansluiting	1.5kV - 25kV	OBE 000885227
	BR Tiel oost Fasescheiding	25kV - 25kV	OBE 000885305
	BR Valburg west Fasescheiding	25kV - 25kV	OBE 000885309
	BR Elst noord aansluiting	1.5kV - 25kV	OBE 000885313
	BR Elst zuid aansluiting	1.5kV - 25kV	OBE 000829212
	BR Duiven Fasescheiding	25kV - 25kV	OBE 000885317
HRN	Zevenaar oost	1.5kV - 25kV	OBE 000885287
	Maastricht Randwyck - Eijsden	1.5kV - 3kV	OBE 000200705
	Roosendaal - Essen	1.5kV - 3kV	OBE 000201968

O.2 transitions in train protection systems

In Table 20, the locations of all ATP system transitions are given. For each transition, the exact transition type is noted. Transitions at HSL-entrances are double transitions, as they incorporate a small ERTMS level 1 section between the ATB-EG and ERTMS level 2 sections. The approximate locations of all transitions have been found via ProRail (2019d). OBE-leaflets are used to define the exact location.

Table 20 Locations of train protection system transition

	LOCATION	TRANSITION TYPE	OBE (SOURCE)
HSL	HSL Breda aansluiting Belgische grens - Bd	ATB-EG - ERTMS l1 - ERTMS l2	OBE 000885265
	HSL Zevenbergschen Hoek aansluiting Bd --> Rtd	ATB-EG - ERTMS l1 - ERTMS l2	OBE 000885277/63
	HSL Zevenbergschen Hoek aansluiting Rtd --> Bd	ATB-EG - ERTMS l1 - ERTMS l2	OBE 000885277/64
	HSL Barendrecht aansluiting Bd --> Rtd	ATB-EG - ERTMS l1 - ERTMS l2	OBE 000885274
	HSL Barendrecht aansluiting Rtd --> Bd	ATB-EG - ERTMS l1 - ERTMS l2	OBE 000885274
	HSL Rotterdam Noord aansluiting	ATB-EG - ERTMS l1 - ERTMS l2	BVS 001365247
	HSL Hoofddorp aansluting Rtd --> Shl	ATB-EG - ERTMS l1 - ERTMS l2	OBE 000885553
	HSL Hoofddorp aansluiting Shl --> Rtd	ATB-EG - ERTMS l1 - ERTMS l2	OBE 000885553
BR/	Barendrecht Vork Hsp --> Rtd	ATB-EG - ERTMS l1	OBE 000885257
HSP	Barendrecht Vork Rtd --> Hsp	ATB-EG - ERTMS l1	OBE 000201860
	Barendrecht Vork Kfh --> Hsp	ATB-EG - ERTMS l1	OBE 000210158
	Kijfhoek emplacement (oost)	ATB-EG - ERTMS l1	OBE 000826417
	Kijfhoek emplacement (midden)	ATB-EG - ERTMS l1	OBE 000865691
	Kijfhoek emplacement (west)	ATB-EG - ERTMS l1	OBE 000865692
	Kijfhoek – Rotterdam Ijselmonde	ATB-EG - ERTMS l2	
	Kijfhoek Sophiatunnel	ERTMS l1 - ERTMS l2	OBE 000885293
	Gdm --> Brmet	ATB-EG - ERTMS l2	OBE 000885225
	Brmet --> Gdm	ATB-EG - ERTMS l2	OBE 000885225
	Zbm --> Brmet	ATB-EG - ERTMS l2	OBE 000885225
	Brmet --> Zbm	ATB-EG - ERTMS l2	OBE 000885225
	BR elst – Nijmegen	ATB-EG - ERTMS l2	OBE 000829212
	BR elst - Arnhem	ATB-EG - ERTMS l2	OBE 000829212
	Zevenaar oost	ATB-EG - ERTMS l2	OBE 000885286
	Diemen Zuid	ATB-EG - ERTMS l2	OBE 000885543
	Amsterdam Muiderpoort - Bijlmer	ATB-EG - ERTMS l2	OBE 000200772
	Duivendrecht aansluiting	ATB-EG - ERTMS l2	OBE 000885503
	Utrecht Noord	ATB-EG - ERTMS l2	OBE 000885431
	Swifterband aansluiting	ATB-EG - ERTMS l2	OBE 000885447
	Hattemerbroek aansluiting	ATB-EG - ERTMS l2	OBE 000885428
HRN	Zevenaar oost	ATB-EG - ATB-NG	OBE 000885286
	Elst - Zetten-Andelst	ATB-EG - ATB-NG	OBE 000829214

Tiel	ATB-EG - ATB-NG	OBE 000200128
Nijmegen - Mook Molenhoek	ATB-EG - ATB-NG	OBE 000885603
Blerick - Lottum	ATB-EG - ATB-NG	OBE 000885605
Venlo - Tegelen	ATB-EG - ATB-NG	OBE 000200754
Roermond - Swalmen	ATB-EG - ATB-NG	OBE 000200702
Landgraaf	ATB-EG - ATB-NG	OBE 000200728
Zutphen - Vorden	ATB-EG - ATB-NG	OBE 000210178
Zutphen - Laren-Almen	ATB-EG - ATB-NG	OBE 000210178
Zutphen - Klarenbeek	ATB-EG - ATB-NG	OBE 000210178
Apeldoorn - Klarenbeek	ATB-EG - ATB-NG	OBE 000885327
Hengelo - Delden	ATB-EG - ATB-NG	OBE 000200264
Almelo - Vroomshoop	ATB-EG - ATB-NG	OBE 000200261
Wierden - Nijverdal	ATB-EG - ATB-NG	OBE 000885675
Zwolle - Heinlo	ATB-EG - ATB-NG	OBE 000885323
Zwolle - Kampen	ATB-EG - ATB-NG	OBE 000885323
Vroomshoop - Marienberg	ATB-EG - ATB-NG	OBE 000200342
Haren - Waterhuizen aansl.	ATB-EG - ATB-NG	OBE 000200393
Gr. Europapark - Waterhuizen aansl.	ATB-EG - ATB-NG	OBE 000200391
Groningen - Leeuwarden/Sauwerd	ATB-EG - ATB-NG	OBE 000885325
Leeuwarden - Harlingen/Stavoren	ATB-EG - ATB-NG	OBE 000200176
Coevorden - BE Zuid	ATB-EG – No ATP	OBE 000885563
Coevorden - BE Noord	ATB-EG – No ATP	OBE 000885563
Weert - Budel	ATB-EG – No ATP	OBE 000200698
Sloe - Goes	ATB-EG – No ATP	OBE 000885338
Venlo - Kaldenkirchen	ATB-EG - PZB	OBE 000200754
Maastricht Randwyck - Eijsden	ATB-EG - Krokodile	OBE 000200705
Roosendaal - Essen	ATB-EG - Krokodile	OBE 000201968

O.3 moveable bridges

The location of all moveable bridges is provided by ProRail (2019d). Only moveable bridges on electrified railway lines have been included in Table 21. With the additional information from the OBE-leaflets, extra information has been acquired on the bridge type, the presence of catenary on the bridge and the exact catenary construction on the bridge.

Table 21 Location of moveable bridges on electrified railway lines

LOCATION	BRIDGE TYPE	CATENARY ON BRIDGE?	MOVEABLE CATENARY?	OBE (SOURCE)
LEEUWARDEN HARINXMAKANAAL	turning bridge	yes	yes	OBE 000885714
GROU PRINSES MARGRIETKANAAL	turning bridge	no	n/a	OBE 000885711
ALKMAAR DE BOARN	turning bridge	no	n/a	OBE 000885710
ALKMAAR MONNIKERAK	draw bridge	no	n/a	OBE 000885709
MEPPEL DRENTHSCHE HOOFDVAART	turning bridge	no	n/a	OBE 000885698
NIEUW AMSTERDAM VERL. HOOGEVEENSEVAART	Lift bridge	yes	no	OBE 000200351
COEVORDEN COEVORDERSTADSGRACHT	Lift bridge	yes	no	OBE 000885563
ZUTPHEN IJSSELBRUG	Lift bridge	yes	yes	OBE 000210178
DEN HELDER ZUID NOORD-HOLLANDS KANAAL	draw bridge	no	n/a	OBE 000201874
ALKMAAR NOORD KANAAL ALKMAAR OMVAL-KOLHORN	Lift bridge	yes	no	OBE 000200440
ALKMAAR NOORD-HOLLANDS KANAAL	draw bridge	no	n/a	OBE 000200459
WORMERVEER NAUERNASCHE VAART	draw bridge	no	n/a	OBE 000200467
PURMEREND WHEREBRUG	draw bridge	no	n/a	OBE 000200455
PURMEREND NOORDHOLLANDS KANAAL	turning bridge	no	n/a	OBE 000200456
ZAANDAM ZAANBRUG	turning bridge	no	n/a	OBE 000200470
AMSTERDAM SINGELGRACHT	draw bridge	yes	yes	OBE 000885491
AMSTERDAM RIEKPOLDER NIEUWE MEER	draw bridge	yes	yes	OBE 000885505
WEESP VECHTBRUG	draw bridge	yes	yes	OBE 000885684
HAARLEM NOORDER BUITEN SPAARNE	draw bridge	yes/no	yes/ n/a	OBE 000885696
SASSENHEIM RINGVAART	draw bridge	no	n/a	OBE 000885557
LEIDEN OUDE RIJN	draw bridge	yes	yes	OBE 000200529

LEIDEN – LEIDEN LAMMERSCHANS RIJN	draw bridge	yes	yes	OBE 000201871
LEIDEN LAMMERSCHAN RIJN - SCHIEKANAAL	draw bridge	no	n/a	OBE 000200794
ALPHEN DE GOUWE	turning bridge	no	n/a	OBE 000200800
GOUDA – ALPHEN DE GOUWE	turning bridge	yes	yes	OBE 000155349
GOUDA - MOORDRECHT DE GOUWE	lift bridge	yes	yes	OBE 000155350
WOERDEN - BODEGRAVEN DUBBELE WIERICKE	lift bridge	yes	no	OBE 000200804
ROTTERDAM - SCHIEDAM DELFSHAVENSE SCHIE	draw bridge	yes	yes	OBE 000200551
DORDRECHT DORDSE KIL	Lift bridge	yes	yes	OBE 000201886
DORDRECHT STADSPOLDERS WANTIJ	Lift bridge	no	n/a	OBE 000200609
SLIEDRECHT BAANHOEK BENEDEN MERWEDE	bascule bridge	no	n/a	OBE 000200610
ARKEL MERWEDEKANAAL	turning bridge	yes	no	OBE 000200618
PERNIS OUDE MAAS	lift bridge	no	n/a	OBE 000210115
BOTLEK - EUROPOORT CALLANDKANAAL	lift bridge	yes	yes	OBE 000200595
ZEVENBERGEN MARK	lift bridge	yes	no	OBE 000200638
KRUININGEN-YERSEKE KANAAL DOOR ZUID BEVERLAND	bascule bridge	no	n/a	OBE 000200655
MIDDELBURG ARNEKANAAL	turning bridge	no	n/a	OBE 000200660

O.4 Vertical track alignment

In Table 22, the gradients at all tunnels and at major bridges are listed. For each location, the presence of operational limitations in the form of extra signals, the presence of entry speeds in tunnels and the maximum gradient at structures is listed. The location of tunnels is based on ProRail (2019d). Due to the large amount of bridges in the Netherlands, only a small section of bridges has been examined. Only bridges crossing a river or canal that are classified as CEMT Va or higher are included in this overview (Ministry of Infrastructure and Water Management, 2017).

Table 22 Location of gradients at tunnels and bridges

TUNNELS	LOCATION	SIGNALS	MAX. SPEED FREIGHT TRAINS (KM/H)	GRADIENT (‰)	OBE (SOURCE)
	Botlek	L/H	60	26.8	OBE000201848
	Drontermeer	L/H	50	25	OBE000885451
	Velsen	L/H	30	16.5	OBE000885380
	Nijverdal	-	50	25	OBE000210059
	Schiphol	-	-	5 to 25	OBE000885551
	Sophia	L/H	60	22.2/25	OBE000885293/94
	Best	-	-	~6	OBE000200083
	Hem	X/G	40 and 30	25	OBE000200471
	Delft	X/G	80	25/12.5	OBE000885461
	Blaak	X/G	40	5 tot 25	OBE000201848/158430
	Almelo	L/H	60	22.5/25	OBE000210070
	BR Barendrecht aansl.	L/H	-	0	OBE000829431
	BR Giessen	-	80	25/12.5	OBE000885298
	BR Pannerdens Kanaal	-	60	25	OBE000885315
	BR Zevenaar	-	80	25/12.5	OBE000885317
	HSL Dordtse Kil	-	-	25	OBE000885276
	HSL Oude Maas	-	-	5 to 25	OBE000885675
	HSL Rtd Noord	-	-	25	OBE000885676
	HSL Groene hart	-	-	5 to 25	OBE000885270
RIVERS AND CANALS (CEMT VA OR HIGHER)	Location	Signals	Max. speed freight trains	Gradient (‰)	OBE (source)
IJSSEL	Westervoort	-	-	4	OBE000885572
	Zutphen	-	-	0	OBE000210178
	Deventer	L/H	-	7 en 8	OBE000200251
	Zwolle	L/H	-	15/25	OBE000885428/324
LEK	Arnhem	-	-	4	OBE000200116

	Culemborg	L/H	-	~9	OBE000885361
MAAS	Maastricht (Laanaken)	-	-	9	OBE000885409
	Roermond	-	-	6	OBE000885601
	Venlo	-	-	6,6	OBE000885605
	Mook	-	-	0	OBE000885607
	Ravestein	L/H	-	7	OBE000200095
	Hedel	-	-	5	OBE000200083
OUDE MAAS	Dordrecht	L/H	-	?	OBE000201949
	Botlek	L/H	-	17 en 12	OBE000210115
WAAL	Nijmegen	-	-	5	OBE000885603
	Zaltbommel	L/H	-	8	OBE000885226/200082
	Sliedrecht	-	-	~5	OBE000200610
HOLLANDS DIEP	Moerdijk (HRN)	-	-	~5	OBE000885241
	Moerdijk (HSL)	-	-	25	OBE000885276
VAN STARKENBORG	Groningen	L/H	-	25	OBE000885227
	Zuidhoorn	-	-	5 to 25	OBE000210033
ZAAN	Zaandam	-	-	5 to 25	OBE000200470
ZWARTE WATER/MEER	Herfte	-	-	5 to 25	OBE000200357
SCHELDE-RIJNKANAAL	Rilland-Bath	L/H	-	5 to 25	OBE000200650
KANAAL VAN Z.B.	Kruiningen-Yerseke	L/H	-	5 to 25	OBE000200655
PRINSES MARGRIET	Grou	L/H	-	5 to 25	OBE000885711
IJSSELKANAAL ZWOLLE	Zwolle Stadhagen	-	-	5 to 25	OBE000200319
AMSTERDAM-RIJNKANAAL	Weesp	L/H	-	7	OBE000885683/84
	Maarssen	-	-	5	OBE0008854300
	Vleuten	-	-	?	OBE000200783
	Houten	L/H	-	8	OBE000885360
	Tiel BR	-	-	10	OBE000885305
	Tiel HRN	-	-	5 to 25	OBE000200127
TWENTEKANAAL	Zutphen noord	L/H	-	5 to 25	OBE000210178
WAAL-MAASKANAAL	Nijmegen Goffert	L/H	-	8	OBE000885500/01
IJMEER	Almere Poort	-	-	17	OBE000200206

The locations of all fly-overs (FO), dive-unders (DU) and connecting arches (verbindingsbogen or VB) are listed in Table 23. In column two, the number between brackets indicates the number of fly-overs, dive-unders and connecting arches at that location. Column three indicates if any special signals are present. The fourth column indicates the gradient in per mille. For some gradients, no information on the precise angle could be found.

Table 23 Locations of gradients at fly-overs, dive-unders and Connecting track

LOCATION	FO/DU/VB	SPECIAL SIGNALS	INCLINES (‰)	OBE (SOURCE)
ZWOLLE AANSL. (HANZEBRUG)	DU	L/H	25	OBE000885428
KEVERDIJK AANSL.	DU (2)	-	5 to 25	OBE000885685
DIEMEN	FO (2)	L/H	12	OBE000885681
BIJLMER	FO (2)/DU (1)	L/H	25	OBE000200773
DUIVENDRECHT	FO (2)	L/H	25	OBE000885506
ZAANSTRAAT	DU (3)	L/H	5 to 25	OBE000885491
SLOTERDIJK BOOG	FO (2)	L/H	5 to 25	OBE000865619
RIEKPOLDER	FO (2)	-	5 to 25	OBE000885507
ZAANDAM (NOORD)	FO (1)	-	5 to 25	OBE000200470
HOOFDDORP HSL	FO (1)	-	8	OBE000885553
WARMOND	FO (1)	L/H	15	OBE000885559
DEN HAAG MARIAHOEVE	DU (1)	-	5 to 25	OBE000200532
MOORDRECHT	FO (1)	-	5 to 25	OBE000829494
WOERDEN	FO (1)	-	16.7	OBE000200786
HARMELEN	FO (1)	L/H	25	OBE000200784
UTRECHT (NOORD)	FO (4)	-	25	OBE000885431
LUNETTEN	DU (2)	L/H	25	OBE000885519
BLAUWKAPEL	FO (2)	-	25	OBE000200226
AMERSFOORT (WEST)	DU (1)	-	5 to 25	OBE000885666
AMERSFOORT SCHOTHORST	FO (1)	L/H	5 to 25	OBE000885670
ELST AANSL. ZUID	VB (1)	L/H	4.5	OBE000829212
METEREN ZUID	VB (1)	-	10	OBE000885225
METEREN NOORD	FO (1)	-	8.6	OBE000885225
METEREN NOORD	VB (1)	-	5 to 25	OBE000885225
ROTTERDAM WEST	FO (2)	-	25/22	OBE000201850
BARENDRECHT	FO (2)	-	18	OBE000201860
BARENDRECHT HSP	FO (1)	L/H	10	OBE000885257
WAALHAVEN ZUID	FO (1)	L/H	10	OBE000885258
KIJFHOEK WEST	FO (1)	L/H	5 to 25	OBE000865691
KIJFHOEK MIDDEN	FO (2)	-	25	OBE000865692
LAGE ZWALUWE	FO (1)	-	25	OBE000200634
ZEVENBERGSCHE HOEK AANSL.	FO (1)	-	25	OBE000885277
BREDA WEST	FO (1)	-	5 to 25	OBE000885465
BREDA HSL	FO (1)	-	25	OBE000885279
BOXTEL ZUID	FO (1)	L/H	5 to 25	OBE000201936
DEN BOSCH NOORD	FO (1)	-	24.4	OBE000201978
ARNHEM	DU (1)	-	25	OBE000885566

Appendix P. Disruption data Meteren junction

Appendix P contains the data that is used for the analysis of disruptions at Meteren junction. This data is retrieved from raw data provided by Sherlock software. Disruption data per (sub)section is based on (ProRail, 2020d). P.1 contains disruption data on TROTS section level. P.2 contains data on TROTS subsection level. Section P.3 contains the data for validation that is used to validate findings in subsection 6.2.3. Finally, section P.4 contains the data on delay causes at Meteren junction

P.1 TROTS section data

Sherlock has provided a list of all disruptions at TROTS rail sections at Meteren junction. For each disruption, the time, date, TROTS-section and the length of the disruption have been noted, among other things. When possible, a reason for the disruption is automatically assigned to each disruption. In Table 24, the frequency of disruptions is shown. These disruptions have been subdivided into four groups with different disruption durations: <5 minutes, 5 to 15 minutes, 15 to 30 minutes and larger than 30 minutes

Table 24 disruption frequency per TROTS section at Meteren junction

TROTS SECTION	<5 MIN	5 - 15 MIN	15 - 30 MIN	>30 MIN	TOTAL DISRUPTIONS
ZE2	31	8	3	4	**46**
ZE1	12	3	1	1	**17**
ZD6	34	12	6	0	**52**
ZD5	9	3	2	4	**18**
KE2	12	6	1	3	**22**
KE1	19	6	2	3	**30**
KD6	8	29	2	1	**40**
KD5	73	16	1	0	**90**
FF2	32	12	12	6	**62**
EE2	89	34	7	3	**133**
DD2	28	6	3	5	**42**
CC2	173	74	8	3	**258**
523	30	7	6	9	**52**
522	48	32	9	6	**95**
521	40	26	6	7	**79**

In Table 25, the total delay time per TROTS rail section and per time category is shown for 2019. In TROTS section ZE2, 31 trains had a delay smaller than 5 minutes. These 31 delays account for 1:04:43 hours in delays over the entire year. Similarly, 4 trains had a delay larger than 30 minutes. The cumulative delay of these four trains was 4:25:24 hours.

Table 25 disruption time per TROTS section and per time category at Meteren junction

TROTS SECTION	<5 MIN	5 - 15 MIN	15 - 30 MIN	>30 MIN	TOTAL TIME
ZE2	01:04:43	01:00:11	01:09:27	04:25:24	**7:39:45**
ZE1	00:23:11	00:32:22	00:18:47	00:40:29	**1:54:49**
ZD6	01:26:38	01:26:38	01:50:58	00:00:00	**4:44:14**
ZD5	00:18:32	00:22:29	00:47:01	03:12:03	**4:40:05**
KE2	00:33:03	00:37:08	00:23:28	03:48:08	**5:21:47**
KE1	00:45:56	00:45:55	00:33:34	02:29:33	**4:34:58**
KD6	00:22:46	04:29:08	00:42:27	00:44:27	**6:18:48**
KD5	02:50:30	01:58:31	00:15:13	00:00:00	**5:04:14**
FF2	01:24:38	01:57:59	04:09:30	07:14:26	**14:46:33**
EE2	03:43:51	04:27:44	02:16:32	02:22:46	**12:50:53**
DD2	01:07:30	00:40:12	00:56:38	20:48:17	**23:32:37**
CC2	07:47:37	09:31:10	02:31:10	02:39:35	**22:29:32**
523	01:11:36	00:49:19	02:26:35	14:00:51	**18:28:21**
522	02:03:54	04:28:24	03:05:25	04:38:56	**14:16:39**
521	01:43:17	03:34:50	01:52:34	06:17:16	**13:27:57**

In Table 26, the train intensities per track section have been noted. With this information, the average delay time per train and the delay probability per train have been calculated, using data from Table 24 and Table 25. The number of trains per year that use each section is based on ProRail (2020e).

Table 26 Disruption data per train at Meteren junction

TROTS SECTION	TRAINS PER YEAR	TOTAL DELAY TIME	NUMBER OF DISRUPTIONS	AVERAGE DELAY PER TRAIN (HOUR)	DELAY PROBABILITY PER TRAIN
ZE2	11212	07:39:45	46	**00:00:02**	**0,41%**
ZE1	11212	01:54:49	17	**00:00:01**	**0,15%**
ZD6	10040	04:44:14	52	**00:00:02**	**0,52%**
ZD5	10040	04:40:05	18	**00:00:02**	**0,18%**
KE2	11005	05:21:47	22	**00:00:02**	**0,20%**
KE1	11005	04:34:58	30	**00:00:01**	**0,27%**
KD6	9641	06:18:48	40	**00:00:02**	**0,41%**
KD5	9641	05:04:14	90	**00:00:02**	**0,93%**
FF2	452	14:46:33	62	**00:01:58**	**13,72%**
EE2	656	12:50:53	133	**00:01:11**	**20,27%**
DD2	720	23:32:37	42	**00:01:58**	**5,83%**
CC2	708	22:29:32	258	**00:01:54**	**36,44%**
523	10040	18:28:21	52	**00:00:07**	**0,52%**
522	1364	14:16:39	95	**00:00:38**	**6,96%**
521	10093	13:27:57	79	**00:00:05**	**0,78%**

P.2 TROTS subsection data

For a selected number of TROTS sections, a further analysis is conducted, using data on subsection level. The typical length of such a section is 100 to 500 meter. Table 27 contains an overview of all subsections that make up an entire TROTS section. The distribution of delays in multiple time ranges over the subsections is also shown in Table 27. Table 28 shows the total delay time per TROTS subsection

Table 27 delay frequency per TROTS subsection at Meteren junction

TROTS SECTION	SUBSECTION	FREQUENCY	<5 MIN	5 - 15 MIN	15 - 30 MIN	>30 MIN
CC2	**4190AT**	247	165	72	6	**3**
	4190BT	1	1	0	0	**0**
	4190CT	2	1	0	1	**0**
	4190DT	6	4	2	0	**0**
	4227T	1	1	0	0	**0**
	4231T	1	1	0	0	**0**
DD2	**4192AT**	10	6	1	1	**2**
	4192BT	3	3	0	0	**0**
	4192CT	7	4	0	0	**3**
	4192DT	21	14	5	2	**0**
	4223T	1	1	0	0	**0**
EE2	**4201T**	5	3	2	0	**0**
	4204T	3	2	1	0	**0**
	4205T	2	0	0	1	**1**
	4204AT	35	30	3	1	**1**
	4204BT	88	54	28	5	**1**
FF2	**4206T**	2	1	1	0	**0**
	4206AT	31	20	3	3	**5**
	4206BT	6	3	2	1	**0**
	4206CT	23	8	6	8	**1**

Table 28 total delay time per TROTS subsection at Meteren junction

TROTS SECTION	TROTS SUBSECTION	<5 MIN	5 - 15 MIN	15 - 30 MIN	>30 MIN	TOTAL DELAY TIME
CC2	**4190AT**	07:27:06	09:10:23	01:54:30	02:39:35	**21:11:34**
	4190BT	00:01:40	00:00:00	00:00:00	00:00:00	**00:01:40**
	4190CT	00:01:06	00:00:00	00:21:18	00:00:00	**00:22:24**
	4190DT	00:12:23	00:20:47	00:00:00	00:00:00	**00:33:10**
	4227T	00:04:15	00:00:00	00:00:00	00:00:00	**00:04:15**
	4231T	00:01:07	00:00:00	00:00:00	00:00:00	**00:01:07**
DD2	**4192AT**	00:16:35	00:07:51	00:15:37	05:03:43	**05:43:46**
	4192BT	00:09:12	00:00:00	00:00:00	00:00:00	**00:09:12**
	4192CT	00:09:04	00:00:00	00:00:00	15:44:34	**15:53:38**
	4192DT	00:31:23	00:32:21	00:41:01	00:00:00	**01:44:45**
	4223T	00:01:16	00:00:00	00:00:00	00:00:00	**00:01:16**
EE2	**4201T**	00:09:11	00:14:27	00:00:00	00:00:00	**00:23:38**
	4204T	00:05:50	00:11:33	00:00:00	00:00:00	**00:17:23**
	4205T	00:00:00	00:00:00	00:20:36	00:37:24	**00:58:00**
	4204AT	00:54:16	00:28:12	00:19:17	01:04:13	**02:45:58**
	4204BT	02:34:34	03:33:32	01:36:39	00:41:09	**08:25:54**
FF2	**4206T**	00:01:54	00:06:04	00:00:00	00:00:00	**00:07:58**
	4206AT	00:54:30	00:23:14	01:05:40	05:07:50	**07:31:14**
	4206BT	00:07:00	00:12:56	00:18:18	00:00:00	**00:38:14**
	4206CT	00:21:14	01:15:45	02:45:32	02:06:36	**06:29:07**

P.3 Data for validation

Table 29 contains the data used for validation. This data is based on ProRail (2020f) and ProRail (2020g).

Table 29 Average delay time and delay probability (21-03-2020 – 18-04-2020) at Meteren junction

DATE	TROTS SECTION	TRAINS PER YEAR	DELAY (HOURS)	DELAY (HOURS)	NUMBER OF DELAYS (FREQ.)	DELAY PROBABILITY (%)
2019 (NORMAL TIMETABLE)	**EE2**	656	12:50:53	00:01:11	133	20,27
	CC2	708	22:29:32	00:01:54	258	36,44
2020 (REDUCED TIMETABLE)	**EE2**	58	00:49:59	00:00:52	7	12,07
	CC2	41	00:41:13	00:01:00	5	12,20

P.4 Causes for delay at Meteren junction

This section contains data on the number of delays per TROTS subsection per delay cause. For each TROTS subsection, the number of delays in each delay type category (Table 30) and the total delay time as a result of these delays, per delay type (Table 31) are shown.

Table 30 Number of delays per delay cause and per TROTS subsection at Meteren junction

TROTS (SUB)SECTIONS

	CC2	**DD2**			**EE2**		**FF2**		
DELAY CAUSES	4190AT	4192AT	4192CT	4192DT	4204AT	4204BT	4206AT	4206CT	total
WORKPROCESS TRAIN DRIVER	0	1	0	0	3	2	3	3	12
WORKPROCESS DISPATCHER	9	1	0	1	4	5	2	6	28
ROUTE SETTING	10	0	0	0	1	15	2	0	28
NO CONNECTION WITH RBC	0	2	4	0	2	2	4	3	17
ERTMS TRIP	1	1	0	1	2	3	0	0	8
ROLLING STOCK DEFECT	1	0	0	0	0	1	0	3	5
INFRASTRUCTURE DEFECT	6	0	1	1	0	4	0	0	12
DELAYED BY OTHER TRAIN	182	1	2	3	9	29	8	4	238
EARLY ARRIVAL	15	0	0	1	3	11	1	1	32
MINOR DELAYS	5	1	0	8	9	6	5	1	35
OTHER CAUSES	5	1	0	0	0	1	1	1	9
CAUSE UNKNOWN	13	2	0	6	2	9	5	1	38
TOTAL DELAYS PER SUBSECTION	**247**	**10**	**7**	**21**	**35**	**88**	**31**	**23**	**462**

Table 31 delay time per delay cause and per TROTS subsection at Meteren junction

TROTS (SUB)SECTIONS

	CC2	**DD2**			**EE2**		**FF2**		
DELAY CAUSES	4190AT	4192AT	4192CT	4192DT	4204AT	4204BT	4206AT	4206CT	total
WORKPROCESS TRAIN DRIVER	00:00:00	00:03:05	00:00:00	00:00:00	00:17:44	00:10:16	00:31:12	00:48:59	1:51:16
WORKPROCESS DISPATCHER	01:18:33	00:07:51	00:00:00	00:05:51	00:18:28	00:37:05	00:28:58	01:08:10	4:04:56
ROUTE SETTING	00:30:36	00:00:00	00:00:00	00:00:00	00:01:18	01:32:04	00:36:24	00:00:00	2:40:22
NO CONNECTION WITH RBC	00:00:00	05:03:43	15:47:52	00:00:00	01:08:31	00:18:11	03:36:04	00:55:04	26:49:25
ERTMS TRIP	00:01:03	00:03:28	00:00:00	00:03:28	00:20:18	01:03:41	00:00:00	00:00:00	1:31:58
ROLLING STOCK DEFECT	00:02:04	00:00:00	00:00:00	00:00:00	00:00:00	00:03:34	00:00:00	02:36:08	2:41:46
INFRASTRUCTURE DEFECT	00:15:07	00:00:00	00:02:18	00:08:00	00:00:00	00:21:36	00:00:00	00:00:00	0:47:01
DELAYED BY OTHER TRAIN	13:56:54	00:02:33	00:03:28	00:24:23	00:14:56	01:50:36	00:21:38	00:25:24	17:19:52
EARLY ARRIVAL	00:52:04	00:00:00	00:00:00	00:01:46	00:04:31	01:11:41	00:02:02	00:16:23	2:28:27
MINOR DELAYS	00:07:34	00:01:37	00:00:00	00:13:16	00:13:06	00:11:09	00:10:08	00:02:56	0:59:46
OTHER CAUSES	01:02:28	00:02:50	00:00:00	00:00:00	00:00:00	00:03:49	00:24:23	00:01:41	1:35:11
CAUSE UNKNOWN	03:20:33	00:18:39	00:00:00	00:48:01	00:07:06	01:02:12	01:20:23	00:14:22	7:11:16
	21:26:56	**5:43:46**	**15:53:38**	**1:44:45**	**2:45:58**	**8:25:54**	**7:31:12**	**6:29:07**	**70:01:16**

Appendix Q. Disruption data Zaandam

Appendix Q contains the data that is used for the analysis of disruptions at Zaandam. This data is retrieved from raw data provided by Sherlock software. Disruption data per (sub)section is based on (ProRail, 2020f). Section Q.1 contains data on train frequencies per TROTS section at Zaandam. Q.2 contains disruption data on TROTS section level. Q.3 contains data on TROTS subsection level. Finally, section Q.4 contains the data on delay causes at Zaandam.

Q.1 train frequencies

In this section, the number of trains per year that use each TROTS section at Zaandam is determined. In contrast to Meteren junction, it is not possible to assume a typical sequence of TROTS sections for certain train services, as there are many possible route deviations that can be used by the dispatcher. Procesleiding Rijwegen (PRL) data is therefore used to determine the route of each train through Zaandam. PRL records the position of switches and signals and gathers data on route setting. In Table 32, the number of trains per TROTS section at Zaandam is shown (ProRail, 2020g). Due to the large size of data files, only data for the first four months of 2019 could be acquired (column 2 of Table 32). Multiplying these train frequencies by three is a good approximation of the actual number of trains per TROTS section in 2019 (column 3 of Table 32).

Table 32 Train frequencies per TROTS section at Zaandam

TROTS SECTION	TRAIN FREQUENCY (4 MONTH PERIOD)	TRAIN FREQUENCY (FULL YEAR)
401	14.114	42.342
402	10.368	31.104
403	528	1.584
404	13.304	39.912
405	11.230	33.690
406	744	2.232
407	355	1.065
421	14.416	43.248
422	9.538	28.614
423	5.631	16.893
PB	9.430	28.290
PC	9.430	28.290
PO	9.539	28.617
PP	9.539	28.617
TJ	21.966	65.898
TK	12.209	36.627
TL	14.289	42.867
WB	14.668	44.004
WO	14.832	44.496

Q.2 TROTS section data

TRain Observation and Tracking System (TROTS) registers all alleged unplanned stops of trains. Using this data, a list of delays at Zaandam has been compiled. Based on this list, the number of delays per TROTS section as well as the (average) duration of delays can be determined. In Table 33, the number of delays per TROTS section and per delay duration category is shown. In Table 34, the total delay time per TROTS section is shown.

Table 33 Total number of delays per TROTS section at Zaandam

TROTS SECTION	<5 MIN	5 - 15 MIN	15 - 30 MIN	> 30 MIN	TOTAL
401	42	4	10	4	60
402	19	9	11	1	40
403	15	8	0	1	24
404	60	12	7	4	83
405	43	15	4	5	67
406	5	1	1	1	8
407	46	7	0	1	54
421	18	1	1	0	20
422	69	6	0	0	75
423	120	5	0	0	125
PB	16	9	1	0	26
PC	150	11	4	5	170
PO	1	1	0	0	2
PP	64	14	3	5	86
TJ	104	6	0	0	110
TK	52	5	1	0	58
TL	3	1	0	0	4
WB	109	8	1	2	120
WO	10	1	1	0	12

Table 34 Total delay time per TROTS section at Zaandam

TROTS SECTION	<5 MIN	5 - 15 MIN	15 - 30 MIN	> 30 MIN	TOTAL
401	01:25:57	00:43:23	03:19:51	04:25:16	9:54:27
402	00:36:13	01:27:35	03:51:36	00:39:03	6:34:27
403	00:32:41	00:53:35	00:00:00	01:49:38	3:15:54
404	01:44:59	01:59:54	02:36:47	04:11:32	10:33:12
405	01:51:57	01:56:18	01:15:57	03:46:27	8:50:39
406	00:12:15	00:09:10	00:15:06	00:33:45	1:10:16
407	01:38:07	00:53:22	00:00:00	00:47:51	3:19:20
421	00:37:16	00:05:22	00:27:53	00:00:00	1:10:31
422	02:32:11	00:38:42	00:00:00	00:00:00	3:10:53
423	04:44:43	00:35:52	00:00:00	00:00:00	5:20:35
PB	00:35:06	01:21:26	00:27:38	00:00:00	2:24:10
PC	05:34:28	01:19:01	01:09:45	03:27:42	11:30:56
PO	00:01:47	00:12:20	00:00:00	00:00:00	0:14:07
PP	02:03:34	01:56:26	01:04:02	06:31:51	11:35:53
TJ	04:13:44	00:57:37	00:00:00	00:00:00	5:11:21
TK	01:57:19	00:32:29	00:23:15	00:00:00	2:53:03
TL	00:07:25	00:06:52	00:00:00	00:00:00	0:14:17
WB	03:46:10	00:51:37	00:16:02	01:56:50	6:50:39
WO	00:19:09	00:10:53	0:28:58	00:00:00	0:59:00

Based on the train frequencies (Q.1), delay frequency (Table 33) and average delay time (Table 34), the average delay time per train can be calculated for each TROTS section, as well as the probability of a train delay (Table 35).

Table 35 Disruption data per train at Zaandam

TROTS SECTION	TRAINS PER YEAR	TOTAL DELAY TIME	NUMBER OF DISRUPTIONS	AVERAGE DELAY PER TRAIN	DELAY PROBABILITY PER TRAIN
401	42.342	9:54:27	60	**00:00:01**	**0,142%**
402	31.104	6:34:27	40	**00:00:01**	**0,129%**
403	1.584	3:15:54	24	**00:00:07**	**1,515%**
404	39.912	10:33:12	83	**00:00:01**	**0,208%**
405	33.690	8:50:39	67	**00:00:01**	**0,199%**
406	2.232	1:10:16	8	**00:00:02**	**0,358%**
407	1.065	3:19:20	54	**00:00:11**	**5,070%**
421	43.248	1:10:31	20	**00:00:00**	**0,046%**
422	28.614	3:10:53	75	**00:00:00**	**0,262%**
423	16.893	5:20:35	125	**00:00:01**	**0,740%**
PB	28.290	2:24:10	26	**00:00:00**	**0,092%**
PC	28.290	11:30:56	170	**00:00:01**	**0,601%**
PO	28.617	0:14:07	2	**00:00:00**	**0,007%**
PP	28.617	11:35:53	86	**00:00:01**	**0,301%**
TJ	65.898	5:11:21	110	**00:00:00**	**0,167%**
TK	36.627	2:53:03	58	**00:00:00**	**0,158%**
TL	42.867	0:14:17	4	**00:00:00**	**0,009%**
WB	44.004	6:50:39	120	**00:00:01**	**0,273%**
WO	44.496	0:59:00	12	**00:00:00**	**0,027%**

Q.3 TROTS subsection data

In this section, delay event statistics for all TROTS subsections of TROTS section 405, 407, PP and TL are presented. Table 36 shows the number of delay events per TROTS subsection and per time category. In Table 37, the total delay time of these delay events are presented per time category.

Table 36 distribution of delay frequency per time category for Zaandam TROTS subsections

TROTS (SUB)SECTION		<5 MIN	5 - 15 MIN	15 - 30 MIN	>30 MIN	TOTAL
405	260A/BT	49	17	6	5	77
	295BT	2	0	0	0	2
407	A264/281T	40	10	0	1	51
	285AT	1	1	0	0	2
PP	278A-ET	50	7	1	1	59
	194A-CT	0	0	0	1	1
	194D/ET	14	7	2	3	26
TL	705C/DT	1	1	0	0	2
	715BT	27	0	1	1	29
	296BT	3	0	0	0	3
	705A/BT	0	1	0	0	1

Table 37 distribution of average delay time per time category for Zaandam TROTS subsections

TROTS (SUB)SECTION		<5 MIN	5 - 15 MIN	15 - 30 MIN	>30 MIN	TOTAL DELAY TIME
405	260A/BT	02:03:24	02:08:22	00:00:00	03:46:27	07:58:13
	295BT	00:05:25	00:00:00	00:00:00	00:00:00	00:05:25
407	A264/281T	01:51:33	01:11:02	00:00:00	00:47:51	03:50:26
	285AT	00:01:02	00:11:27	00:00:00	00:00:00	00:12:29
PP	278A-ET	01:29:53	00:55:09	00:26:27	01:28:02	04:19:31
	194A-CT	00:00:00	00:00:00	00:00:00	02:37:32	02:37:32
	194D/ET	00:33:41	01:01:17	00:37:35	02:26:17	04:38:50
TL	705C/DT	00:04:24	00:20:27	00:00:00	00:00:00	00:24:51
	715BT	01:02:44	00:00:00	00:18:46	01:17:37	02:39:07
	296BT	00:07:25	00:00:00	00:00:00	00:00:00	00:07:25
	705A/BT	00:00:00	00:06:52	00:00:00	00:00:00	00:06:52

Q.4 Causes for delay at Zaandam

This section contains data on the number of delays per TROTS subsection per delay cause at Zaandam. For each TROTS subsection, the number of delays in each delay type category (Table 38) and the total delay time as a result of these delays, per delay type (Table 39) are shown.

Table 38 Number of delays per delay cause and per TROTS subsection

	TROTS (SUB)SECTIONS						
	405	**407**	**TL**	**PP**			
DELAY CAUSES	260A/BT	A264/281T	715BT	278A-ET	194A-CT	194D/ET	Total
WORK PROCESS TRAIN DRIVER	0	0	2	0	0	0	2
WORK PROCESS CONDUCTOR	1	0	0	0	0	0	1
ROUTE SETTING (DISPATCHER)	14	4	8	1	0	1	28
DISPATCHER MANDATE	0	0	0	1	0	6	7
ROLLING STOCK DEFECT	2	0	0	2	0	6	10
INFRASTRUCTURE DEFECT	1	1	0	2	0	0	4
DELAYED BY OTHER TRAIN	28	15	10	5	0	3	61
EARLY ARRIVAL	1	11	3	1	0	1	17
CONSTRUCTION WORKS	1	0	0	1	0	4	6
PASSENGER-CAUSED DELAYS	2	0	1	0	0	0	3
MINOR DELAYS	9	11	3	42	0	3	68
VARIOUS CAUSES	0	0	2	1	0	1	4
CAUSE UNKNOWN	6	1	0	3	1	1	12
TOTAL DELAY EVENTS PER SUBSECTION	**65**	**43**	**29**	**59**	**1**	**26**	**223**

Table 39 delay time per delay cause and per TROTS subsection

	TROTS (SUB)SECTIONS						
	405	**407**	**TL**	**PP**			
	260A/BT	**A264/281T**	**715BT**	**278A-ET**	**194A-CT**	**194D/ET**	**Total**
WORK PROCESS TRAIN DRIVER	0	0	0:03:58	0	0	0	**0:03:58**
WORK PROCESS CONDUCTOR	0:15:21	0	0	0	0	0	**0:15:21**
ROUTE SETTING (DISPATCHER)	0:49:12	0:11:39	0:17:17	0:01:18	0	0:02:54	**1:22:20**
DISPATCHER MANDATE	0:00:00	0	0	0	0	0:11:10	**0:12:58**
ROLLING STOCK DEFECT	1:20:55	0	0	1:37:30	0	1:38:02	**4:36:27**
INFRASTRUCTURE DEFECT	0:43:28	0:47:51	0	0:37:53	0	0	**2:09:12**
DELAYED BY OTHER TRAIN	2:48:16	1:03:13	0:26:10	0:25:02	0	0:26:10	**4:57:50**
EARLY ARRIVAL	0:02:15	0:51:11	0:10:04	0:01:33	0	0:03:34	**1:08:37**
CONSTRUCTION WORKS	0:07:04	0	0	0:08:21	0	2:08:03	**2:23:28**
PASSENGER-CAUSED DELAYS	1:07:16	0	0:01:27	0	0	0:01:27	**1:08:43**
MINOR DELAYS	0:17:28	0:21:20	0:03:48	1:08:01	0	0:05:11	**1:55:48**
VARIOUS CAUSES	0	0	1:36:23	0:08:42	0	0:11:33	**1:56:38**
CAUSE UNKNOWN	1:13:59	0:03:04	0	0:09:23	2:37:32	0:03:14	**4:07:12**
TOTAL DELAY EVENTS PER SUBSECTION	8:45:14	3:18:18	2:39:07	4:19:31	2:37:32	4:38:50	**26:18:32**

Exploring the role Human factors in ATP system transition failures

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Abstract: Transitions between the Dutch ATP system ATB-EG and ERTMS in practice are vulnerable to disruptions in train operations. At Meteren junction, approximately 1% of all trains transitioning between ATB-EG and ERTMS experienced transition failures. Transition failures are mostly caused by a failure to create a connection between the on-board unit (OBU) and the Radio Block Centre (RBC). While the technical causes of these failures have been investigated, the contribution of human factors to transition failures is unclear. This paper aims to explore the contribution of human factors in ATP system transition failures. Grounded theory approach is used as research method and interviews and panel group discussions are used as data. During the ATP system transitions, the role of the driver is limited to acknowledging the transition. Prior to the transition, the driver can use several workarounds and measures to prevent failures from occurring. After a transition failure has occurred, drivers often lack knowledge and information to initiate a speedy recovery. Time pressure and stress play an important role as well, when recovering from a failed transition.

Keywords: Automatic Train Protection, ERTMS, human factors, transitions, disruptions, train operations

1 Introduction

The number of train journeys on the Dutch railway network is increasing year on year. NS expects an increase in passenger-kilometres of 27% to 45% between 2018 and 2040 (NS, 2019). In order to meet passenger demand, train services are expanding to accommodate the growth in passenger-kilometres. Due to the increasing number of trains on the Dutch railway network, many railway lines will meet their maximum capacity if significant changes to the rail infrastructure are not made. One of the ways in which capacity gains can be made, is by introducing a new railway signalling system, ERTMS. In comparison to the current ATP system (ATB-EG) and block signalling system (NS'54), ERTMS allows for smaller headways between trains, depending on the ERTMS level. Apart from increases in capacity, ERTMS offers an increased level of safety and it allows higher speeds to be achieved on the Dutch railway network.

Replacing the currently used ATP system with ERTMS is a long-term project. ERTMS is planned to be operational on the entire rail network in 2050 (Ministry of Infrastructure and Water Management (I&W), 2018). As a result, there is a long time frame in which the old and the new system operate simultaneously on different parts of the network. A number of locations already exist where trains have to transition between ATB-EG and ERTMS/ETCS,

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for instance at the entrances of the Betuweroute and of the HSL-Zuid.

In practice, the already existing ATB-EG – ERTMS transition points cause delays and disruptions in train operations. When transitioning from ATB-EG to ERTMS, occasionally no connection can be established between the on-board ETCS unit (OBU) and the Radio Block Centre (RBC). At Meteren junction, the Betuweroute freight railway has multiple connecting arches to the main line network. On these connecting arches, which are almost exclusively used by freight trains, approximately 1% of all trains experience connection issues with the RBC while transitioning from ATB-EG to ERTMS (De Hek, 2020). Badly functioning on-board modems, low-quality GSM-R signals and the interference of other signals are among the causes for connection failures with the RBC (Ministry of I&W, 2014a; Ministry of I&W 2015; Ministry of I&W, 2016). ATP transition failures can have large impacts on train operations. First of all, ATP transition failures often result in trains coming to a stop. Only when a connection with the RBC is established (in the case of ATB-EG to ERTMS transitions) can a train continue. Often, this results in delays and the propagation of delays. Second, if an ATP transition fails and trains are forced to a stop due to a lack of Movement Authority (MA), the location where these trains come to a stop greatly influences the length of the delay. At Meteren junction, ATP transitions are combined with transitions in power supply system (1.5kV DC to 25kV AC). These power supply system transitions contain a neutral, powerless section of approximately 30 meter. Furthermore, these transitions are located in some cases located on top of a fly-over, which means that there are significant inclines of 10‰ at either side of the neutral section (ProRail & NS, 2016; ProRail & NS, 2018). When a freight train comes to a stop on the upward slope of the fly-over or in the neutral section of the power supply system transition, the train is stranded, leading to a disrupted track for one or several hours.

The number of ATB-EG – ERTMS transitions is currently limited to connections between the HSL-Zuid or Betuweroute and the main line network. However, as ERTMS is being applied on more railway lines, the number of operational transitions is expected to increase. Six main lines will be equipped with ERTMS between 2026 and 2030 (see Figure 56). Large stations on those railway lines, like Amsterdam, Rotterdam and Utrecht, will not be equipped with ERTMS yet, as experience is lacking with converting large station areas to ERTMS. In daily operations, the number of ATP transitions will therefore grow considerably from 2026 onwards.

While, technical causes of ATP system transition failures are largely known and

Figure 56 ERTMS transition strategy until 2030 (Ministry of I&W, 2018)

documented, the contribution of the train driver to transition failures is largely unknown. The literature on human factors in the railway sector mainly focusses on long-term factors influencing the performance of drivers. Short-term factors or even transitions of some sort are not mentioned. Literature on aviation and autonomous driving have provided useful insights that can be applied to ATP system transitions. The aim of this paper is to investigate the contribution of human factors to these transitions. From a scientific point of view, this paper will add to scientific knowledge on ATP system transitions. From a societal point of view, this research can contribute to solving some of the problems surrounding ATP system transitions. The research question is: *'What is the contribution of human factors to ATP system transition failures?'*.

In section 2, an overview is given of the literature on human factors. In section 3, the various ATP systems used in the Netherlands are described. In section 4, methods and data are described. The results are shown in section 5. In section 6, conclusions are drawn and the results are discussed.

2 Literature study

A lot of research has been conducted on factors influencing the overall performance of train drivers. In this section, three of those factors will be discussed: personal characteristics of train drivers, system automation and external factors. Furthermore, literature on transitions outside the railway sector is discussed

Personal characteristics of train drivers is one of the factors influencing train driver performance. Investigating beneficial skills for train drivers, Branton (1993) found that anticipation, internal representation of the system and constant testing of the drivers internal representation are important skills for train driving. Furthermore, Rajabalinejad, Maartinetti & Van Dongen (2016) argue that driver experience plays an important role in driver performance. While inexperienced drivers make mistakes relatively often, drivers with more experience are less inclined to make mistakes. Experienced driver might, however, become complacent and let their concentration slip more easily, thereby increasing the number of mistakes. As Kyriakidis et al. (2012), Madigan, Golighly & Madders (2016) and Baysari, McIntosh & Wilson (2008) found, human errors are often caused by a lack of concentration and distraction. Driver inattention can lead to missed information, such as restrictive signal aspects (Philips & Sagberg, 2010).

Another factor that influences driver performance is system automation. Automation can influence driver workload, which indirectly influences the performance and wellbeing of a train driver (Pickup et al. (2005). Brandenburger et al. (2018) and Brandenburger & Naumann (2019) argue that increased levels of automation lead to driver underload. Due to underload, drivers and signallers are more easily distracted and therefore make more mistakes. Hely et al. (2015) on the other hand found that increased levels of automation slightly increased the driver workload. During operations under ETCS, the driver focussed on the DMI for signalling information and simultaneously has to keep scanning the track for trackside hazards that are not displayed by the DMI. This distribution of attention led to an increased workload. Similar to Hely et al. (2015), Large, Golightly & Taylor (2014) found increases in driver workload as a result of the application of Driver Advisory Systems (DAS). DASs inform the driver on the optimal driving strategy with respect to energy usage and arrival time. Sometimes, DASs would give advice to the driver that was conflicting to the driver's intentions, leading to confusion and an increased workload. The differences in findings with respect to automation and workload might be explained by the fact that ETCS and DAS do not take away tasks from the driver. Under ETCS, the driver remains responsible for observing signals and speed limits, although this information is now communicated via in-cab instruments rather than by trackside signals. Similarly, DAS do not take away any driving tasks. Driving tasks, such as speed supervision, were taken away in the studies of Brandenburger et al. (2018) and Brandenburger & Naumann (2019), leading to a reduction in the number of tasks the driver had to perform.

External conditions and characteristics of the railway infrastructure also influence driver performance. Zoer, Sluiter & Frings-Dresen (2014) investigated driver vigilance in varying conditions. They found that driver vigilance dropped faster if the route requires a lot of multitasking by the driver. Large fluctuations in driver effort will ‘wear out’ the driver faster, leading to a reduction of vigilance (Rhaman et al., 2013). During a driver workday, Zoer, Sluiter & Frings-Dresen (2014) found that vigilance dropped with 20 points on a 100 point scale, pointing toward a reduction in driver attention toward the end of the shift. Rhaman et al. (2013) also found that adverse weather conditions, such as heavy rainfall and night-time driving negatively influenced driver vigilance. More driver effort was required to concentrate on the driving tasks.

The literature on human factors in the railway sector is mainly focussed on long-term factors that lead to changes in driver performance. ATP-transitions, however, are short term in nature. The literature on human factors in the railway sector does not seem to account for that. In other sectors, more attention is being paid to short-term or near-instant transitions.

Automation in driving is one of the fields in which transitions play an important role. Lu & De Winter (2015) define transitions as a change from one static state to another static state. Transitions in the level of automation in driving can be initiated by the driver or initiated by the auto-pilot (Lu et al., 2016). In the latter case, the driver can be surprised by the transition. These situations, in which the system initiates a transition, are known as ‘automation surprises’ in the autonomous car research field. Merat et al. (2014) found that sudden system-initiated transitions would unsettle the driver greatly. In experiments, it took up to 40 seconds after the auto-pilot switched of before the driver had regained full control of the car and was fully focussed again.

Another sector where automation surprises occur and are recognized as such is the aviation sector. Under normal circumstances, most flying tasks are automated and tasks executed by the auto-pilot. During degraded-mode flying, the auto-pilot hands over certain tasks to the pilot and co-pilot. During manual flight, all tasks are handed over to the pilot and co-pilot. When transitions between one of these three automation states occur, this may not always lead to the desired change of mind set to the pilot and co-pilot (Stoop & Van Kleef, 2015). When the mental mode of operators are not in sync with the system state, this situation is known as cognitive dissonance (Harmon-Jones & Mills, 2019). Similar to Merat et al. (2014), system-initiated transitions can surprise pilots and co-pilots. Sarter, Wood & Billings (1997) found that aircraft crew sometimes were not aware of system transitions that had taken place for quite some time. Although pilots and co-pilots are occasionally surprised by unexpected changes in automation state, they generally trusted the auto-pilot systems (De Boer & Dekker, 2017). Automation surprises generally occurred as a consequence of malfunctions. However, as aviation systems have a high level of reliability, these situations don’t occur frequently.

The concept of automation surprises can prove to be useful when investigating the contribution of human factors to ATP system transition failures. Although the location of the ATP system transitions can be known by the driver in advance of the driver, the train driver may not always know how to accomplish the transition in all situations. When running in degraded mode, this might require other tasks to be performed by the driver than in normal running mode. Kecklund et al. (2001) note that the available information to the train driver is very limited in when driving in degraded mode comparison to the normal operating mode.

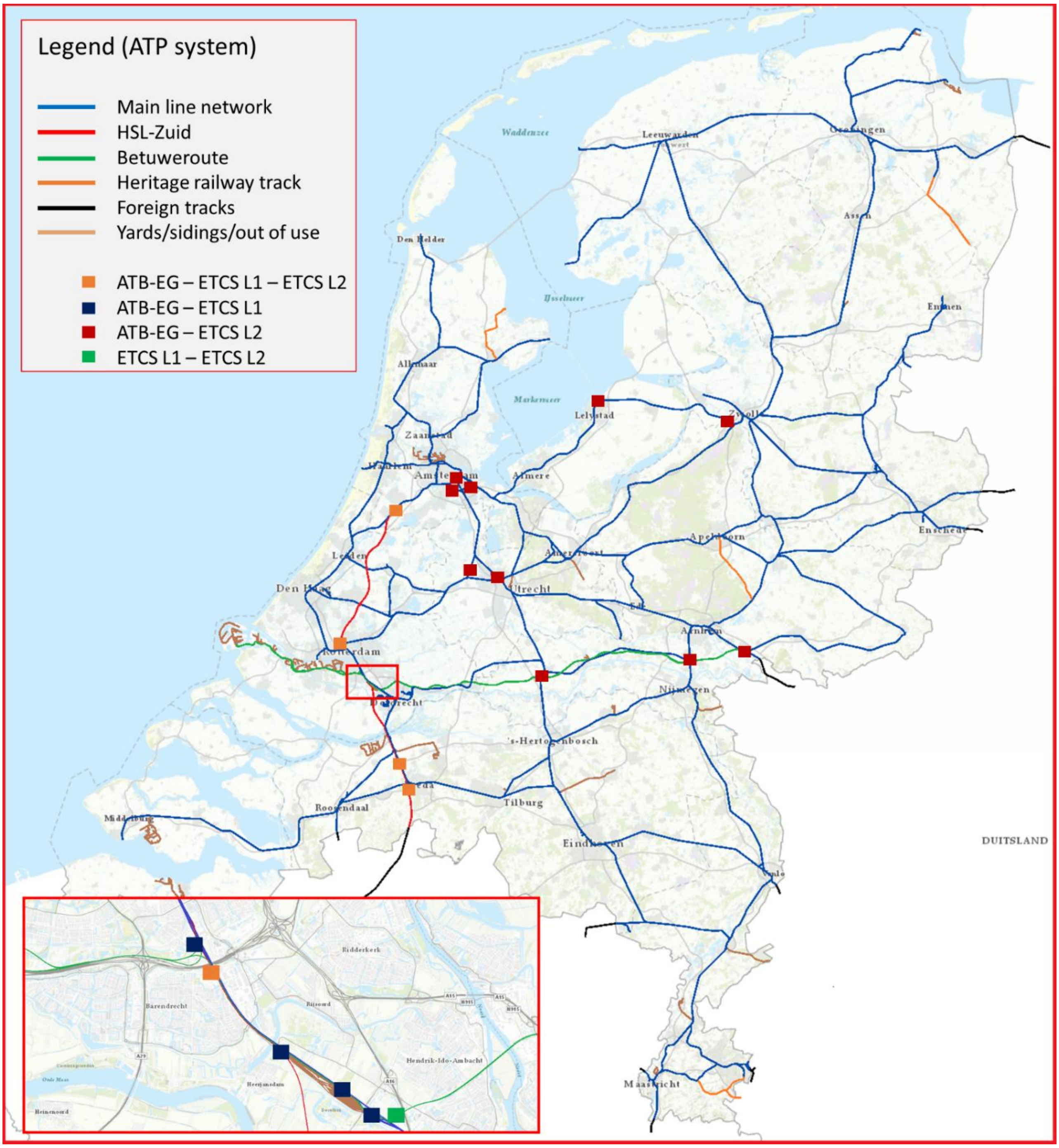

Figure 57 ATP system transitions in the Dutch railway network (ProRail, 2019)

3 Railway signalling in the Netherlands

Currently, two types of ATP system are being used on the Dutch main line network, ATB-EG and ERTMS/ETCS. The main technical principles of each system will be described in more detail.

ATB-EG

On the main line network, railway lines are equipped with ATB-EG (Automatische TreinBeïnvloeding – Eerste Generatie). This continuous ATP system, introduced on the Dutch railway network in the 1960s, was primarily introduced to prevent signal passages at danger (SPADs), although it is possible to pass signals at danger unhindered if the train speed is below 40 km/h (ProRail, 2017).

Furthermore, a limited number of speed limits is supervised. The maximum speed limit is communicated to the ATB on-board unit (ATB OBU) using coded track circuits (ProRail, 2019b). When a speed reduction is announced by a yellow signal, the ATB OBU checks that the driver applies a minimum level of braking pressure, although this fixed minimum braking pressure level does not guarantee that the train reaches the desired speed before the next signal (ProRail, 2017).

ERTMS/ETCS

ERTMS (European Rail Traffic Management System) is a signalling system that has been implemented in the Netherlands on the high-speed line (HSL-Zuid) and the Betuweroute and Havenspoorlijn freight railway lines. These ERTMS consists of two main elements (UIC, n.d.)

- European Train Control System (ETCS). ETCS is a cab-signalling system
- GSM-Railway (GSM-R). Data communication is transmitted via GSM-R between the train modem and the Radio Block Centre (RBC)

Apart from three dedicated ETCS railway lines, ETCS L2 is also used as an overlay on two main lines. Under ETCS Level 2, Movement authorities (MAs) are transmitted to the ETCS OBU via GSM-R, rather than through balises. MAs are generated by the RBC based on interaction with the interlocking. Radio communication (GSM-R) is used to transmit these MAs from the Radio Block Centre (RBC) to the ETCS OBU (Ministry of I&W, 2014b; ERA, 2016). An overview of the locations where transitions currently take place between two ATP systems is shown in Figure 57.

4 Methodology and data

As stated in section 1, little is known on the role of human factors in ATP system transitions. An explorative research methodology, Grounded theory approach (GTA), is therefore used. The GTA was conceived by Gläser & Strauss (1967), who used it as a method for initial conceptualisation and theorizing of topics that are not well explored (Khan, 2014). In GTA, data gathering, data analysis and theory formulation are a continuous process, making it an inductive approach (Backman, 1999). Due to this (lack of) research structure, defining an ending point to research conducted with GTA is not straight-forward, as there is no predefined logical ending point of research. On the other hand, this gives a lot of flexibility to the researcher (Bryant & Charmaz, 2007). The level of flexibility in research led Gläser and Strauss to diverge in different directions. Gläser's approach allowed for a high level of flexibility in research, while Strauss aimed to formalise GTA (Beckman, 1999). While Gläser approved of nearly all research methods and data sources (Kelle, 2007), Strauss and Corbin stressed systematic data gathering and a stricter application of coding schemes (Strauss & Corbin, 1990). Gläser's approach to the GTA will be used for this paper.

In this research, data has been gathered through Semi-structured interviews with researchers and managers of the Dutch infrastructure manager ProRail, who are familiar with ATP transitions on the Dutch railway network. They are able to provide a high-level impression of the problems surrounding these transitions. Panel group discussions were conducted with train drivers who experience ATP transitions on a regular basis. They provide detailed information on their role in these transitions. Although conducting semi-structured interviews is labour-intensive which limits the number of interviews that can realistically be conducted, they are very suitable for an in-depth reconnaissance of a topic. Furthermore, they allow follow-up question to be asked and to delve deeper into topics that were not expected at the start of the interview (Newcomer, Hatry & Wholey, 2015).

5 Results and analysis

Five interviews have been conducted with researchers and managers closely connected to ATP systems and ATP transitions. Furthermore, two panel group discussions have been conducted with 6 train drivers in total. Train drivers of both passenger and freight railway companies were interviewed. The findings of these interviews and panel group discussions have been used as source for this analysis. Most data has been acquired on ATB-EG – ERTMS transitions, while other ATP transitions will also be discussed.

Primary causes of transition failures

The interviewees named several reasons for failing ATB-EG to ERTMS Level 2 transitions: technical defects to components of the OBU, GSM-R malfunctions and a failure to acknowledge transitions. These three primary causes for transition failures will be discussed each.

Several technical failures can cause ATB-EG – ETCS Level 2 transitions to fail. The most common technical failure is a defect on-board modem. When GSM-R signals are not received by the modem, the OBU does not receive new MAs. Modem malfunctions usually can't be fixed by train drivers. In some cases, modem malfunctions are caused by loose or dusty adapters, in which case the driver can fix the problem. In many cases, technical defects remain unidentified by the train driver. The DMI often only informs the driver that a technical failure has occurred, but it does not inform the driver of the type of failure. In those circumstances, it is impossible for the train driver to identify the type of malfunction.

Apart from technical failures, connections between the OBU and the RBC cannot always be made via GSM-R. GSM-R signals cannot be received when antennas on either side of the connection are malfunctioning. Signal interference of other GSM-networks also hinders a robust connection between the RBC and the OBU. The radio frequency bandwidths that are used for GSM-R signals are close to radio frequencies bandwidths of other networks (Figure 58). To combat this problem, improved radio frequency (RF) filters are being applied to the OBU modems (EIRENE, 2015).

The role of the train driver during the actual transition is limited. Depending on the train type, the driver must acknowledge the transition from ATB-EG to ERTMS. Not all train types require an acknowledgement of an ATB-EG to ERTMS transition, as the safety level offered by ERTMS is higher than that by ATB-EG. When transitioning from ERTMS to ATB-EG, an acknowledgement is always required, due to the lower safety level offered by ATB-EG. If the driver does not acknowledge the transition within 5 seconds after receiving the signal for acknowledgement, the ETCS OBU will apply the train brake. After acknowledgement, the brake will automatically be released. Apart from acknowledging the transition, the driver must be aware to shift attention from the DMI to the outside world or vice versa for receiving speed and signalling information.

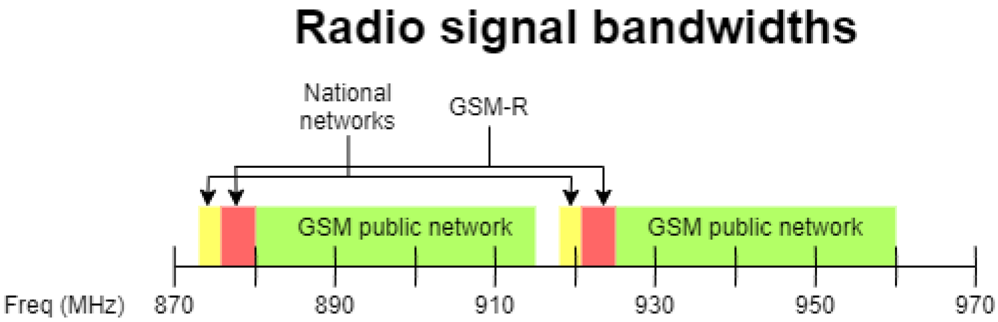

Figure 58 Radio signal bandwidth of GSM-R, public GSM and national networks in the EU

Resolving malfunctions

When a failure has occurred, the driver will have to resolve the malfunction. In general, train drivers do not know the exact cause of the malfunction. In most cases, the DMI does not inform the driver what type of failure has occurred. There is a large variety of possible defects and malfunctions, either caused by hardware or by software failures. While train drivers are fully able to operate the ETCS OBU, they lack the technical knowledge to fix most failures. The simplest way in which to resolve ETCS-related issues, whatever the cause may be, is to reset the entire ETCS OBU. In most cases, this resolves any ETCS-related problems. Although a full system reset is a time-consuming process, often lasting 10-15 minutes, this is therefore usually the first step that train drivers undertake when a failure or malfunction has occurred. In some cases, the DMI provides the driver with information on the exact nature of a failure and provides ways in which to resolve the malfunction. When such information is available, the driver will first follow this information before attempting to reset the ETCS OBU.

NS (Dutch Railways) train drivers have the possibility of contacting a dedicated helpdesk, staffed with experienced train drivers, when ETCS-related issues occur. The helpdesk staff have access to real-time data of each ETCS OBU and are therefore able to identify specific failures. Using this information, they can support the train driver in resolving failures. Drivers of other (smaller) railway undertakings lack this kind of formalised support. When they experience a failure, they must rely on their own knowledge or, when possible, on the knowledge of colleagues who happen to be on shift as well. Due to the fact that no formalised means of backup are available to these drivers, in-door education of these railway undertakings focuses more on technical knowledge than the education of NS train drivers.

The means by which train drivers resolve malfunctions is not only influenced by their own knowledge and the available information, but also by external factors pressuring the train driver. A failed transition almost always leads to delays. When a train is sufficiently delayed, the train loses its right to its planned train path, leading to additional delays. Drivers, of both passenger and freight trains, will always try to minimize delays. This means that they do not have time to investigate the causes of failed transitions. For freight operators, delays caused by failed transitions can easily lead to delays lasting more than an hour. On most rail corridors, the number of available train paths for freight trains is limited to a few paths per hour, which may be allocated to other freight trains. Only when a free path is available can the freight train continue its journey.

The pressure to prevent delays may also lead to drivers taking suboptimal decisions in how to recover from transition failures. Resetting the ETCS OBU or other components takes a lot of time. The time pressure that some drivers experience sometimes leads to drivers trying to depart while the system has not been fully reset. As a result of the incomplete reset, the train cannot move or will apply the brakes shortly after departure. High levels of workload can therefore lead to poor decisions being made by the driver. Pickup et al. (2005) make a distinction in workload types. Workload is made up of imposed load by internal load and by the perceived load. Imposed load is the load that the driver imposes on him- or herself because of the internal goals the driver has. Drivers who are relatively indifferent to delays suffer less from a high internal load than drivers who value punctuality a lot.

Anticipating on transition failures

When specific transition failures are known to train drivers, it is possible to anticipate on these likely failures. One way in which transition failures can be prevented is by ensuring that the conditions under which transition failures occur are not met. For instance, train drivers noted a situation in which no connection with the RBC could be established at a specific point. When the drivers reduced their speed from 80 km/h to 60 km/h when passing this point, the connection failures stopped occurring. By altering one condition, the train speed, the connection issues at that location were resolved.

Another way in which transition failures can be prevented is by coming up with a workaround long before the actual transition takes place. A malfunction was found to be occurring to a specific locomotive type when transitioning from ETCS to ATB-EG. During the transition, the ETCS OBU does not recognise the on-board ATB unit, which is connected to the ETCS OBU via a Specific Transmission Module (STM). As a result, the train would come to a stop when entering the ATB-EG area. It was found that the specific failure did not occur if the emergency brake was applied at the start of the locomotive trip. Therefore, before starting to prepare the locomotive for service, the driver would apply the emergency brake. After that, the locomotive is prepared for service according to normal procedures.

These two examples indicate that there are several measures that drivers can take, just before the actual ATP transition or a long time in advance of the transition, that reduce or eliminate the possibility of a specific failure during a transition. In both examples, the drivers do not know why the measures work out the way they do and prevent transition failures from occurring. Often, there is no logical connection between the transition failure and the measure or workaround used to resolve the transition failure.

6 Conclusion and discussion

In this paper, the contribution of human factors to ATP transitions has been examined. As little prior research is available on this topic, an explorative approach was used by using grounded theory approach. Several conclusions can be drawn on the contribution of human factors in ATP transition failures.

First, during the actual transition, the role of the train driver in causing or preventing a transition failure is limited. Apart from acknowledging the transition, the driver should shift focus from the DMI to the trackside signals and vice versa during a transition. Most failures are caused by technical failures rather than by human mishandling of the system.

Second, when a transition failure has occurred, train drivers often lack the knowledge to solve malfunctions or technical failures. Most train drivers are not educated in identifying and resolving technical failures. Furthermore, the DMI often does not provide information on the failure causes or the means by which to resolve the failures, which cause additional delays. Internal pressure and stress can also cause transition failures to be resolved slower than necessary.

Third and final, there are several measures that train drivers can take prior to the transition that prevent certain failures from occurring. Train drivers use precautions and workarounds to prevent that circumstances under which transition failures can take place are met. There is often no logical link between the workaround and the non-occurrence of the failure. Drivers often do not know why the workaround they apply in daily traffic works the way it does.

Though this paper addresses a new topic in railway operations, it has been possible to connect the results to concepts found in literature. Automation surprises, a concept derived from autonomous vehicles (Merat et al., 2014) and automation in the aviation sector (Stoop & Van Kleef, 2015; De Boer & Dekker, 2017) can to a certain extent be applied on unexpected transition acknowledgements during a transition. Furthermore, anticipation on upcoming transitions can help to reduce the probability of a transition failure form occurring (Branton, 1993). Driver experience also influences the ability to handle transition failures (Rajabalinejad, Maartinetti & Van Dongen, 2016). Finally, internal workload, a concept derived from Pickup et al. (2005) is applicable to the time-pressure experienced by some train drivers.

Due to the limited number of interviewees, evidence supporting the hypotheses posed in this paper is somewhat anecdotal in nature, limiting the generalizability of the findings of this study. Though the number of interviewees is limited, the selection of interviewees does cover a wide range of actors in the railway sector.

This study has contributed to scientific knowledge by providing initial findings on the role of human factors in ATP system transitions. The concept of transitions itself is also new to the railway sector in this context. The concept of transitions in the railway sector is currently applied to changes in track support, for instance a change from ballasted track to track laid on concrete slaps and structures (Paixão, Fortunato & Calçada, 2015).

From a societal point of view, this study can help to find means by which the number of transition failures can be reduced, leading to an increase in train service punctuality.

It is recommended to conduct more research on the topic of human factors in ATP system transitions. It is also recommended to study the role of human factors in the context of other operational transition types. Finally, it is recommended to investigate to what extent transition failures occur regularly between national train control systems and ETCS in other countries than the Netherlands.

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Cover picture: Freight train at Lorch am Rhein, Maurits de Hek

Back pictures: Freight train at Haaften, Betuweroute, Frank Heins. Benelux train near Delft, Frank Heins.