Interoperability in Rail Systems

The Effect of Interoperability on the Performance of an Urban Rail System

Nicoline Dammers

2018.TEL.8270

Delft University of Technology

FACULTY MECHANICAL, MARITIME AND MATERIALS ENGINEERING
Department Marine and Transport Technology

Mekelweg 2
2628 CD Delft
the Netherlands
Phone +31 (0)15-2782889
Fax +31 (0)15-2781397
www.mtt.tudelft.nl

Specialization: Transport Engineering and Logistics

Report number: 2018.TEL.8270

Title: **Interoperability in Rail Systems, The effect of interoperability on the performance of an urban rail system.**

Author: Nicoline A.W. Dammers

Title (in Dutch): Interoperabiliteit bij Rail Systemen
De invloed van interoperabiliteit op de prestaties van een stedelijk railsysteem

Assignment: ~~literature / programming / experimental / design assignment~~ / Masters thesis

Confidential: no / ~~yes~~

Initiator (university): prof.dr. R.R. Negenborn

Initiator (company): ir. D.J. Koopman (Royal HaskoningDHV)

Supervisor: ir. M.B. Duinkerken

Date: October 04, 2018

Interoperability in Rail Systems

The Effect of Interoperability on the Performance of an Urban Rail System

by

Nicoline Dammers

to obtain the degree of Master of Science
at the Delft University of Technology, to be defended publicly on 04/10/2018

Student number:	4143035	
Project duration:	March 19, 2018 – October 4, 2018	
Thesis committee:	Ir. M. B. Duinkerken,	TU Delft, supervisor
	Prof. dr. R. R. Negenborn,	TU Delft
	ir. D.J. Koopman,	Royal HaskonigDHV

Cover Image (Dubbelman and Hollandse Hoogte, 2018)

An electronic version of this thesis is available at `http://repository.tudelft.nl/`.

Preface

Before you lies the master thesis “The Effect of Interoperability on the Performance of an Urban Rail System”, written to complete my master in Transport Engineering and Logistics at the faculty of Mechanical Engineering at the TU Delft. I was engaged in researching and writing this thesis from March to October 2018.

The project was initiated by Royal HaskoningDHV with the goal to better understand the effects of interoperability in rail systems. With no background or experience in the rail sector, I started this study with an open mind. In the course of my research I learned more about the railway sector than I could have ever imagined, and it is safe to say that my public transport trips will never be the same.

Acknowledgements

I would like to thank all of the colleagues from the network studies department at Royal HaskoningDHV for their endless patience in educating me on public rail transport systems. In particular I would like to thank David Koopman for his contribution to this research, endless checking of my thesis and daily supervision. For his help with the case study of Amsterdam I would like to thank Barth Donners, who taught me several lessons on how to best convey your message.

From the TU Delft, a special thanks goes out to Mark Duinkerken whose input and guidance helped with closing the gap between science and reality. Finally a thanks to Rudy Negenborn whose questions kept me alert and challenged me throughout the research.

Nicoline Dammers
Amsterdam, September 2018

Summary

Growing urbanization has caused the cities in the Netherlands to burst at their seams. This growth has resulted in an increasing demand for public transport with people use public transport more and are demanding ever better levels of service. This results in more pressure on transit lines and stations and a growing need for investments to increase the capacities. The population growth in the Amsterdam urban area will result in the biggest traffic bottleneck when it comes to passenger traffic in 2040 (Ministerie van Infrastructuur en Milieu, 2017). An innovative approach to public transit in the future could help with solutions to these bottlenecks.

The challenges and trends for the following years can be linked to this urbanization in the Netherlands. The goals of both the national governments as well as those of the metropolitan region of Amsterdam have a lot in common when it comes to public (rail) transport. Door-to-door travel combined with the integration and strengthening of public transport nodes are the common denominator of these goals. The main areas of interest are the economic centres and urban areas. Flexible, demand driving mobility is the aim because direct connections better meet the needs of commuters. Safety Reliability and sustainability are the boundary conditions to these goals. The municipality of Amsterdam explicitly expressed the use of the existing infrastructure to facilitate this door-to-door rush hour travel. Infrastructure managers and public transport authorities have shared a vision for a future in which trains continue their journey on metro infrastructure and metro systems can provide train connections. This track sharing is called interoperability. This rail interoperability is the main focus of this research, it will investigate the possibilities and benefits of track sharing over building new (expensive) infrastructure to cope with the increasing capacity demand.The situation sketched above led to the following research question:

How will interoperability between metro and train systems affect the performance of the urban rail network of the Amsterdam metropolitan area, given a public transport passenger demand?

Urban Rail Network Amsterdam Metropolitan Area

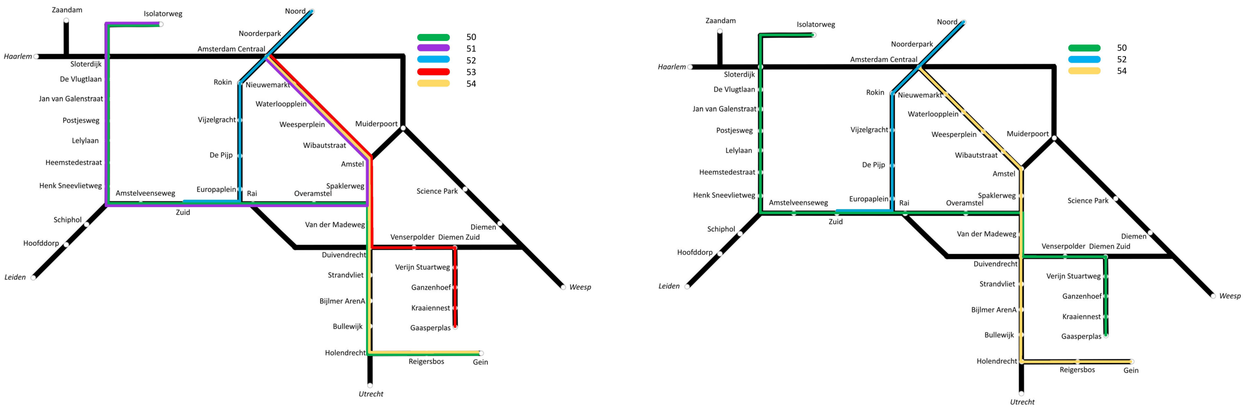
The research question discusses a change in the performance of a public transport system. In order to be able to asses this change, a base case scenario is sketched with corresponding performance indicators. The different goals, trends and planned improvements to the public transport network of both the Netherlands and the Amsterdam urban area were mapped. Based on this research, two base case scenarios where drafted, one that describes 2019 and one that sketches the situation for 2040. Both of the networks will be tested with the same passenger transport demand[1] after which they will be graded based on a set of Key Performance Indicators. These scenarios and the KPIs they are compared on are shown in the table at the bottom of this page.

The difference between these two scenarios is the configuration of the metro network, the underlying train network is kept the same and represent the most important regional train lines that serve people around the Amsterdam urban area.

Scenarios	**KPIs**
2019 Base Case 2019 Metro Configuration (Figure 1.a) Regular Train Configuration	Accessibility Passenger Satisfaction Costs Safety and Sustainability (as a boundary condition)
2040 Planned Case 2040 Planned Metro Configuration (Figure 1.b) Regular Train Configuration	

---

[1] Both scenarios will be tested with the 2040 High Scenario Passenger Demand(CPB/CBS, 2015)



(a) Metro Configuration 2019

(b) Metro Configuration 2040

Figure 1: Base Cases

Compatibility Issues

The main research question aims to investigate the interoperability between metro- and train systems. The feasibility of this interoperability and the compatibility issues that might occur between the systems were analysed and design alternatives with corresponding costs and actions to overcome these compatibility issues where drawn up.

The compatibility issues between metro- and train systems are multifaceted. They range from infrastructural and technical to operational and even political issues, the latter which has been left out of scope for this research. Table 1 shows what compatibility issues will arise when interoperability between a metro- and train system is the goal.The column Metro →Train tells if a compatibility issue will arise when running a metro on the train track and the column Train →Metro shows if a compatibility issue will arise when running a train on a metro track.

Table 1: Compatibility Issues

Characteristic	**Compatibility Issue? Metro →Train**	**Compatibility Issue? Train →Metro**
Track Gauge	No	No
Rail Profile	Yes	Yes
Axle Load	No	Yes
Load Gauge	No	Yes
Radius of Curvature	No (If correct speed)	No (If correct speed)
Power Supply	Yes	Yes
Stations and Nodes	Yes	Yes
Turnouts and Crossings	Yes for 1:9 Double Slip Switch No for all other switches	No
Saftey and Communication Systems	Yes	Yes
Stakeholders	No	No
Network	Yes	Yes

The compatibility issues that occur between Train →Metro are insurmountable without changing the NS fleet or the GVB infrastructure drastically. The NS rolling stock is for instance too heavy (Axle Load) and too high (Load Gauge) for the GVB infrastructure.

For the remainder of the research the choice was therefore made to focus on the interoperability between Metro →Train. Figure 2 shows this configuration for the chosen interoperability that will be researched and compared to the previous two scenarios in the remainder of this research. In this scenario the metro of the Noord/Zuidlijn continues its path on the train infrastructure to Schiphol and Hoofddorp.

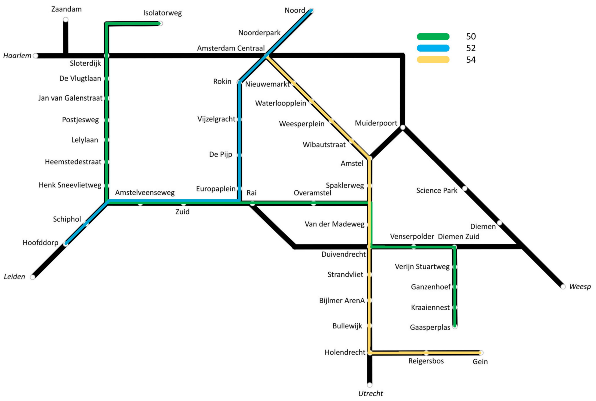


Figure 2: Metro Configuration 2040+

Design Directions (With Corresponding Costs and Actions)

Several industry examples where rail interoperability was achieved, combined with knowledge from industry experts were used to come up with design alternatives that would help with the creation of solutions to the compatibility issues that arise when Metro →Train interoperability is the goal.

It seems that all of the design directions for the technical incompatibilities are fairly straight forward. They can be achieved by alterations to the infrastructure and the rolling stock. The changes to the rolling stock can be done as refurbishments to the current fleet or they could be included in the program requirements drafted when new vehicles will have to be ordered. If the line will be extended to Schiphol and Hoofddorp, more metros will be necessary anyway to cope with the increased capacity.

If full interoperability and seamless rail networks are truly the goal of the stakeholders involved, more effort should be put into the composing of the necessary standards and laws that describe the interoperability between the rail systems. The issues in the safety and communication systems are significant and will take time and extra research to overcome. The design directions should be included in a standard that will describe the restrictions of rail interoperability between mainline and urban systems. This standard will have the goal to provide guidance on the technical and regulatory issues that need to be resolved before track sharing is permitted.

The design directions with corresponding costs and actions involved can be found in Table 2. For some of the design directions found, the necessary costs cannot be seen as straightforward as others. Mainly because these costs involve regulatory changes which need to be initiated and executed by the state. The costs of creating these laws and standards are difficult to estimate as they are indirect costs that are not based on physical purchases but on knowledge gained.

Total Investment Costs

The total investment cost to achieve interoperability will be anywhere between **€56 252 000** and **€64 702 000**, depending on whether or not full CBTC/ERTMS interoperability will be achieved. It is interesting to see that the majority of the cost lay in connecting the two networks, more than preparing each individual system for interoperability.

If the above mentioned investment costs are calculated back to one hour of operation for the aspired start date in 2040 it results in an investment cost between **€558** and **€642** per hour of operation. The higher value was used for the remainder of the research.

Table 2: Costs and Actions

Compatibility Issue	Design Direction	Costs	Actions
Rail Profile	Change wheel dimensions	X	Alter wheel dimensions
Power Supply	Dual Traction System	€4.200.000	Equip metros with a transformer to bring 1500 V DC to 750 V DC
Stations and Nodes	Gauntlet Track	€6.192.000	- At the mainline stations, install a Gauntlet track - At the mainline stations, raise part of the platform
Turnouts and Crossings	Alterations to Turnouts	€60.000	Make turnouts slightly wider to better serve metros (trains can still use these turnouts
Safety and Communication Systems	CBTC/ERTMS Interoperability	€2.800.000	- Research into CBTC/ERTMS interoperability - Creation of laws and standards
	Metros with ERTMS	€11.250.000	Equip current fleet with ERTMS or have ERTMS as a standard installed in new metros
Network	Connect Metro Line to Mainline	€43.000.000	Connect Metro Line to Mainline

Amsterdam Case Study

To determine whether interoperability would contribute to the performance of the urban rail system of the Amsterdam Metropolitan Area, a series of experiments were drawn up. The model used for this case study is described in the research by (Van Beurden, 2017). This model allowed for further specifications of the KPIs as can be seen in Table 3.

Table 3: KPIs

Performance Category	KPI
Accessibility	Train Kilometres Provided [km]
	Unserved Demand [# Passengers]
	Stop Use [Access/Egress Passengers & Transfer Passengers]
Passenger Satisfaction	Walking Distance [€]
	In-Vehicle Travel Time [€]
	Waiting Time [€]
	Transfers [€]
Costs	Operator Cost [€]

The rail network around Amsterdam consists of three types (Train, Metro and Tram), of which two (Train and Metro) are of interest to this research. The experiments focussed on changes to the metro lines and the influence on the performance of the rail network. The train lines will remain unchanged, but their frequency and stopping patterns are also optimized in the optimization experiments. The goal is to investigate the performance of the network in these different scenarios.

For the optimization experiments (4 and 5) it was ensured that the same amount of runs (250 runs) would be used to best compare the results. These optimization runs were terminated when no (significant) new solution was found for a certain amount of time. It is important to note that an optimal solution is not guaranteed for this model, it is possible that the solution is a so called sub-optimal solution, meaning that more optimal solutions are present. A longer running time of the model does limit the chances of the final solution being a sub-optimal one.

Experiment 1: 2019 With Planned Timetable

The first experiment had the goal to find out how well the current situation is equipped to cope with the future. It calculated the current situation meaning that the infrastructure and timetable of 2019 was used combined with the passenger demand for 2040 (Figure 1.a). This experiment set a base case for 2019.

Experiment 2: 2040 With Planned Timetable

The second experiment investigated how well the plans released by the municipality of Amsterdam for 2040 (Figure 1.b) will cope with the 2040 passenger demand. It used the unbundled metro network with corresponding timetable and the original train timetable. It calculated how this network deals with the 2040 passenger demand. This experiment showed the effect the current plans have on the performance of the urban rail network. This experiment set the case for 2040.

Experiment 3: 2040+ With Planned Timetable

The third experiment first looked at interoperability in rail systems, it extended the plans of 2040 with interoperability (2040+) between station Zuid and Hoofddorp. The timetable of the planned situation for 2040 was be used with 2040 passenger demand (Figure 2). This experiment set the case for 2040+.

Experiment 4: 2040 Optimization

While experiment 2 was aimed at the infrastructure of 2040 with the *planned* timetable for 2040, this experiment is aimed at optimizing that scenario. The 2040 infrastructure with underlying train network (Figure 1.b) was used combined with 2040 passenger demand. The experiment optimized the frequency and stopping patterns based on a combination of costs. This experiment determined whether a more optimal frequency and stopping pattern is possible for the future case.

Experiment 5: 2040+ Optimization

This experiment optimized the frequency and stopping patterns for the 2040 infrastructure with interoperability (2040+). Where experiment 3 was aimed at the infrastructure of 2040+ with the *planned* timetable for 2040, this experiment is aimed at optimizing that scenario. The 2040+ infrastructure with underlying train network (Figure 2) was used combined with 2040 passenger demand. The experiment optimized the frequency and stopping patterns based on a combination of costs. This experiment showed if a more optimal frequency and stopping pattern is possible for the future case with interoperability.

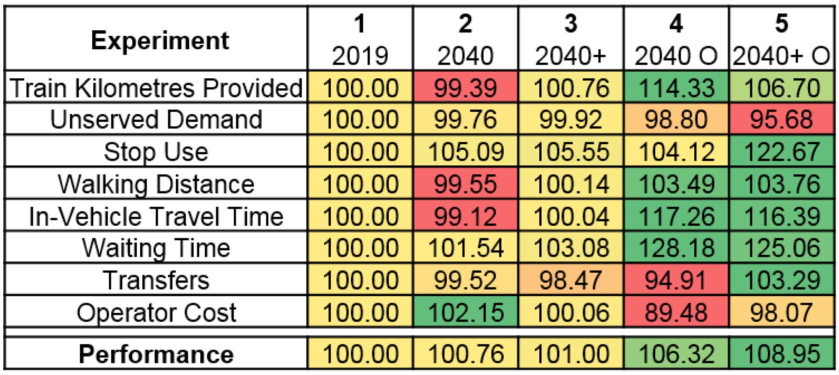
Conclusions

The effect of the different experiments on the performance of the rail network will be assessed by comparing them (percentage) to the base case scenario (experiment 1). A higher performance than the base case will result in a score higher than 100%, a lower performance in a lower score.

The performance of rail systems is complex to measure, so for the table below the choice was made to use equal count for each of the KPIs. The table already is a simplified representation of the true influence of the different scenarios on the performance and this type of representation was chosen to truly show the complexity and diversity of rail systems.

When all of the experiments are graded all of the performances are added up and the average is taken. The effect of the different experiments on the different KPIs can be seen in Table 4, the colours correspond with the level of performance.

Table 4: Performance Rating



Experiment	1 2019	2 2040	3 2040+	4 2040 O	5 2040+ O
Train Kilometres Provided	100.00	99.39	100.76	114.33	106.70
Unserved Demand	100.00	99.76	99.92	98.80	95.68
Stop Use	100.00	105.09	105.55	104.12	122.67
Walking Distance	100.00	99.55	100.14	103.49	103.76
In-Vehicle Travel Time	100.00	99.12	100.04	117.26	116.39
Waiting Time	100.00	101.54	103.08	128.18	125.06
Transfers	100.00	99.52	98.47	94.91	103.29
Operator Cost	100.00	102.15	100.06	89.48	98.07
Performance	100.00	100.76	101.00	106.32	108.95

To assess the effect of interoperability, experiments 3 and 5 are the ones to look at, as these are the experiments where the Noord/Zuidlijn continues its path to Schiphol and Hoofddorp. Here experiment 3 uses an original timetable and experiment 5 uses an optimized timetable.

When compared to the 2019 scenario, both of these experiments show an improved performance. It is however more fair to compare experiment 3 to experiment 1 and 2 (the experiments without a timetable optimization), and experiment 5 to experiment 4 (optimization experiments).

When graded from best performance to worst performance the experiments are rated in the following way [2]:

1. ***Experiment 5: 2040+ Optimized***
2. *Experiment 4: 2040 Optimized*
3. **Experiment 3: 2040+**
4. Experiment 2: 2040
5. Experiment 1: 2019

The base case (2019) is does not have optimal performance and improvements are feasible, the current plans released by the municipality of Amsterdam (2040) are an improvement to the base case performance but are still not optimal. When interoperability is added to these plans (2040+) an even better performance is achieved. And when interoperability is combined with an optimized timetable, the biggest improvement to the performance can be achieved.

A side note to this grading has to be made that this performance is based on a predefined set of KPIs. The goal was to sketch as complete an image as possible, but rail systems are very complex and many problems can not be seen as straightforward.

All of the optimization experiments score higher than the base case scenario, this means that part of the improvement in performance lies in the optimization of the timetable.

The interoperability has the biggest positive influence on stop use and the passenger waiting time. Overall, the interoperability has a positive effect on the performance of the urban rail network of the Amsterdam metropolitan area.

When the different configurations were tested with the public transport demand for 2040, it became evident that there are configurations possible in which the performance of the urban rail system can be improved when compared to the current configuration. The improvements in performance are achieved in twofold:

- An optimized timetable (frequencies and stopping patterns)
- Interoperability between metros and the train infrastructure

Overall interoperability between metro and train systems improves the performance of the urban rail network of the Amsterdam metropolitan area.

---

[2] Experiments with added **interoperability** are in bold, experiments with *optimized timetable* in italic.

Summary (in Dutch)

Verstedelijking in Nederland zorgt ervoor dat steden uit hun voegen barsten. Deze groei resulteert in een toenemende vraag naar openbaar vervoer. Reizigers maken meer gebruik van het openbaar vervoer en eisen hierbij steeds betere betere service. Dit resulteert in meer druk op OV-lijnen en stations en in een grotere behoefte aan investeringen om de capaciteit te vergroten. De bevolkingsgroei rondom Amsterdam zal het grootste personenvervoer knelpunt zijn in 2040. Een innovatieve benadering van openbaar vervoer in de toekomst zou kunnen bijdragen aan het oplossen van deze knelpunten.

De doelen van zowel de nationale overheden als die van de Metropoolregio Amsterdam hebben veel raakvlakken als het gaat over openbaar (rail)transport. Deur-tot-deur reizen in combinatie met de integratie en versterking van OV-knooppunten zijn gemene deler bij deze doelen. De belangrijkste aandachtsgebieden zijn de economische kernen en stedelijke gebieden. Flexibele, vraaggerichte mobiliteit is het doel omdat directe verbindingen beter aansluiten op de behoeften van forenzen. Veiligheid, betrouwbaarheid en duurzaamheid zijn randvoorwaardekijk aan deze doelen. De gemeente Amsterdam heeft expliciet het gebruik van de bestaande infrastructuur benoemd om dit deur-tot-deur spitsvervoer te faciliteren. Infrastructuurbeheerders en openbaar vervoer autoriteiten hebben een visie gedeeld voor een toekomst waarin treinen hun reis voortzetten op metro-infrastructuur en metrosystemen treinverbindingen kunnen verzorgen. Dit delen van infrastructuur wordt interoperabiliteit genoemd en is de kern van dit onderzoek. Het doel is te onderzoeken wat de mogelijkheden en voordelen van interoperabiliteit als alternatief voor het bouwen van nieuwe (dure) infrastructuur kunnen zijn. Dit alles om te kunnen omgaan met de toenemende capaciteitsvraag. De onderzoeksvraag is:

Wat is het effect van interoperabiliteit tussen metro- en treinsystemen op de prestaties van het stedelijk spoorwegnet van de Metropoolregio Amsterdam, gegeven een vervoersvraag voor openbaar vervoer?

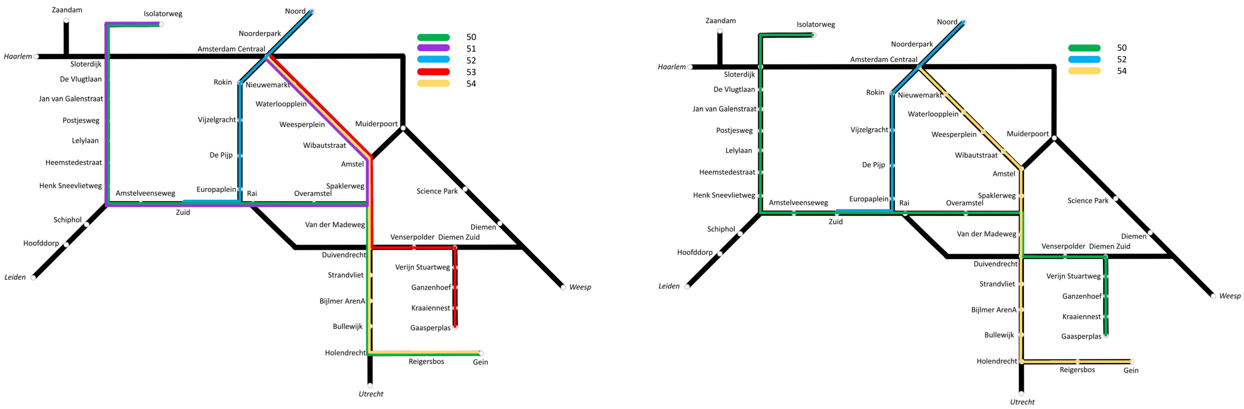
Stedelijk Rail Netwerk Metropoolregio Amsterdam

De onderzoeksvraag heeft betrekking op een verandering in de prestaties van een openbaar vervoersysteem. Om deze verandering te kunnen beoordelen, moest een basisscenario worden geschetst met bijbehorende kritieke prestatie indicatoren.De verschillende doelen, trends en geplande werkzaamheden aan het openbaar vervoersnetwerk in zowel Nederland als de regio Amsterdam zijn in kaart gebracht. Op basis van dit onderzoek zijn twee basisscenario's opgesteld, één scenario dat 2019 beschrijft en één scenario dat de situatie schetst voor 2040. Beide netwerken worden getest met dezelfde vervoersvraag[3], waarna ze worden beoordeeld op basis van een set kritieke prestatie indicatoren. Deze scenario's en de KPI's waarmee ze worden vergeleken, worden weergegeven in de tabel onderaan deze pagina. Het verschil in deze twee scenario's zit in de configuratie van het metronetwerk, het onderliggende treinnetwerk wordt hetzelfde gehouden en vertegenwoordigt de belangrijkste regionale treinlijnen die mensen rond het stedelijk gebied van Amsterdam bedienen.

Scenario's	**KPIs**
2019 Basisjaar 2019 Metro Configuratie (Figure 3.a) Reguliere Trein Configuratie	Toegankelijkheid Passagiers Tevredenheid Kosten Veiligheid en Duurzaamheid (als randvoorwaarden)
2040 Geplande Situatie 2040 Geplande Metro Configuratie (Figure 3.b) Reguliere Trein Configuratie	

---

[3] 2040 Hoog Scenario (CPB/CBS, 2015)



(a) Metro Configuratie 2019

(b) Metro Configuratie 2040

Figure 3: Basis Cases

Compatibiliteitsproblemen

De onderzoeksvraag heeft tot doel de interoperabiliteit tussen metro- en treinsystemen te onderzoeken. De haalbaarheid van deze interoperabiliteit en de compatibiliteitsproblemen die kunnen optreden tussen de systemen zijn geanalyseerd. Er zijn ontwerpalternatieven ontworpen met bijbehorende kosten en maatregelen om deze compatibiliteitsproblemen op te lossen.

Table 5: Compatibiliteitsproblemen

Kenmerk	**Compatibiliteitsprobleem? Metro →Trein**	**Compatibiliteitsprobleem? Trein →Metro**
Spoorbreedte	Nee	Nee
Railprofiel	Ja	Ja
Aslast	Nee	Ja
Omgrenzingsprofiel	Nee	Ja
Boogstraal	Nee (Bij juiste snelheid)	Nee (Bij juiste snelheid)
Tractiesysteem	Ja	Ja
Stations en Knopen	Ja	Ja
Wissels en Kruisingen	Ja voor 1:9 Engelse Wissel Nee voor alle andere wissels	Nee
Veiligheids- en Communicatiesystemen	Ja	Ja
Stakeholders	Nee	Nee
Netwerk	Ja	Ja

De compatibiliteitsproblemen tussen metro- en treinsystemen zijn veelzijdig. Ze variëren van infrastructurele en technische tot operationele en zelfs politieke kwesties, de laatste liggen buiten de strekking van dit onderzoek. Tabel 5 laat zien welke compatibiliteitsproblemen zullen optreden wanneer interoperabiliteit tussen een metro- en treinsysteem het doel is. De kolom Metro →Trein vertelt of een compatibiliteitsprobleem zich zal voordoen bij het rijden van een metro op het hoofdspoor en de kolom Trein →Metro toont of er zich een compatibiliteitsprobleem voordoet bij het rijden van een trein op het metrospoor.

De compatibiliteitsproblemen die zich voordoen bij Trein →Metro zijn onoverkomelijk zonder drastische veranderingen aan de NS-vloot of de GVB-infrastructuur. Het NS-rollend materieel is bijvoorbeeld te zwaar (Aslast) en te hoog (Omgrenzingsprofiel) voor de GVB-infrastructuur.

Voor de rest van het onderzoek werd daarom de keuze gemaakt om te concentreren op de interoperabiliteit tussen Metro →Trein. Figuur 4 toont de configuratie behorende bij de gekozen interoperabiliteit die in de rest van dit onderzoek zal worden onderzocht en vergeleken met de vorige twee scenario's. In dit scenario wordt de metro van de Noord/Zuidlijn doorgetrokken over het hoofdspoor richting Schiphol en Hoofddorp.

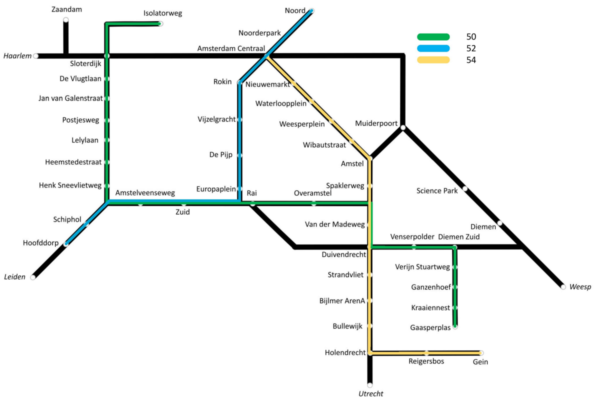


Figure 4: Metro Configuratie 2040+

Ontwerprichtingen (met Bijbehorende Kosten en Acties)

Verschillende voorbeelden waarbij interoperabiliteit op het spoor werd bereikt, gecombineerd met kennis van experts uit het vakgebied, werden gebruikt om ontwerpalternatieven te bedenken die de eerder genoemde compatibiliteitsproblemen zouden kunnen oplossen.

De ontwerprichtingen voor de technische onverenigbaarheden zijn redelijk rechttoe rechtaan. Ze kunnen worden bereikt door wijzigingen aan de infrastructuur en het rollend materieel. De wijzigingen aan het rollend materieel kunnen worden aangebracht als wijzigingen aan de huidige vloot of ze kunnen worden opgenomen in het programma van eisen dat wordt opgesteld wanneer nieuwe voertuigen moeten worden besteld. Bij verlenging van de lijn naar Hoofddorp zullen er hoe dan ook meer metro's nodig zijn om de capaciteit aan te kunnen.

Als volledige interoperabiliteit en naadloze spoorwegnetwerken echt het doel van de betrokken belanghebbenden is, moet er moeite worden gestoken in het opstellen van de noodzakelijke normen en wetten die de interoperabiliteit tussen de spoorwegsystemen beschrijven. De problemen tussen de veiligheids- en communicatiesystemen van de afzonderlijke systemen zijn aanzienlijk en er zal tijd nodig zijn om deze te overwinnen. De ontwerprichtingen moeten worden opgenomen in een norm die de beperkingen voor spoorweg interoperabiliteit tussen hoofdlijnen en stedelijke systemen beschrijft. Deze norm moet als doel hebben een advies te geven over de technische en regelgevingskwesties die moeten worden opgelost voordat het delen railinfrastructuur kan worden toegestaan.

De ontwerprichtingen met bijbehorende kosten en acties zijn te vinden in Tabel 6. Voor sommige van de gevonden ontwerprichtingen zijn de kosten lastiger te bepalen dan voor anderen. Dit komt vooral doordat deze kosten gepaard gaan met wijzigingen in de regelgeving, deze wijzigingen moeten door de staat worden geïnitieerd en uitgevoerd. De kosten voor het maken van deze wetten en normen zijn moeilijk in te schatten omdat het indirecte kosten zijn die niet gebaseerd zijn op fysieke aankopen, maar op verworven kennis.

Totale investeringskosten

De totale investeringskosten voor interoperabiliteit liggen ergens tussen **€56 252 000** en **€64 702 000**, afhankelijk van het al dan niet bereiken van volledige interoperabiliteit tussen CBTC en ERTMS. Het is interessant om te zien dat het merendeel van de kosten ligt in het verbinden van de twee netwerken, meer dan in het voorbereiden van elk afzonderlijk systeem op interoperabiliteit.

Als de bovengenoemde investeringskosten worden teruggerekend naar één uur operatie voor de beoogde startdatum in 2040, resulteert dit in investeringskosten tussen **€558** en **€642** per bedrijfs-uur. De hogere waarde werd gebruikt voor de rest van het onderzoek.

Table 6: Ontwerprichtingen met Kosten en Acties

Compatibiliteitsprobleem	Ontwerprichting	Kosten	Acties
Rail Profiel	Wielafmetingen Wijzigen	X	Wielafmetingen Wijzigen
Tractiesysteem	Duaal Tractie Systeem	€4.200.000	Rust metro's uit met een transformator om 1500 V DC naar 750 V DC om te zetten
Stations en knopen	Strengelspoor	€6.192.000	- Bij de NS stations wordt een strengelspoor geïnstalleerd - Bij de NS stations wordt een deel van het perron verhoogd
Wissels en Kruisingen	Aanpassingen aan wissels	€60.000	Wissels moeten wijder gemaakt worden zodat metro's het hoofdspoor kunnen gebruiken (treinen hebben geen last van deze aanpassingen)
Veiligheids- en Communicatie Systemen	CBTC/ERTMS Interoperabiliteit	€2.800.000	- Onderzoek naar CBTC/ERTMS interoperabiliteit - Opstellen van wetten en standaarden
	Metro's met ERTMS	€11.250.000	Rust de huidige vloot uit met ERTMS of laat ERTMS als een standaard gelden bij nieuwe metro's
Netwerk	Verbind Metro Spoor met Hoofdspoor	€43.000.000	Verbind Metro Spoor met Hoofdspoor

Amsterdam Case Study

Om te bepalen of interoperabiliteit bijdraagt aan een verbeterde prestatie van het stedelijke spoorwegsysteem van de Metropoolregio Amsterdam, werden een reeks experimenten opgesteld.

Table 7: KPIs

Prestatie Categorie	KPI
Toegankelijkheid	Aangeboden Trein Kilometers [km]
	Niet Voldane Vraag [# Passagiers]
	Stop Gebruik [In/Uitstappers & Overstappers]
Passagierstevredenheid	Loopafstand [€]
	Reistijd in Voertuig [€]
	Wachttijd [€]
	Overstappen [€]
Kosten	Kosten Vervoerder [€]

Het spoorwegnet rond Amsterdam bestaat uit drie typen (trein, metro en tram), waarvan er twee (trein en metro) interessant zijn voor dit onderzoek. De experimenten waren gericht op veranderingen in de metrolijnen en de invloed op de prestaties van het spoorwegnet. De treinlijnen blijven ongewijzigd, maar hun frequentie- en stoppatronen zijn ook geoptimaliseerd in de optimalisatie-experimenten. Het doel is om de prestaties van het netwerk in deze verschillende scenario's te onderzoeken.

Voor de optimalisatie-experimenten (4 en 5) was ervoor gezorgd dat dezelfde hoeveelheid runs (250 runs) zou worden gebruikt om de resultaten het best te vergelijken. Deze optimalisatie-runs werden beëindigd wanneer gedurende een bepaalde tijd geen (significante) nieuwe oplossing werd gevonden. Het is belangrijk op te merken dat een optimale oplossing niet is gegarandeerd voor dit model, het is mogelijk dat de oplossing een zogenaamde sub-optimale oplossing is, wat betekent dat er meer optimale oplossingen aanwezig zijn. Een langere doorlooptijd van het model beperkt de kans dat de uiteindelijke oplossing niet optimaal is.

Experiment 1: 2019 met gepland dienstregeling

Het eerste experiment heeft tot doel na te gaan hoe goed de huidige situatie is toegerust om met de toekomst om te gaan. Het zal de huidige situatie berekenen, wat betekent dat de infrastructuur en het dienstregeling van 2019 zullen worden gebruikt in combinatie met de passagiersvraag voor 2040 (Figuur 3.a). Dit experiment zal een basis case voor 2019 bepalen.

Experiment 2: 2040 met geplande dienstregeling

Het tweede experiment zal onderzoeken hoe goed de plannen van de gemeente Amsterdam voor 2040 (Figuur 3.b) de 2040 passagiersvraag aankunnen. Het maakt gebruik van het ontbundelde metronetwerk met bijbehorend dienstregeling en de oorspronkelijke dienstregeling van de trein. Het zal berekenen hoe dit netwerk omgaat met de 2040 passagiersvraag. Dit experiment toont de invloed van de huidige plannen op de prestaties van het stedelijke spoorwegnet. Dit experiment zal de situatie in 2040 schetsen.

Experiment 3: 2040+ met geplande dienstregeling

Het derde experiment gaat eerst in op interoperabiliteit in railsystemen, het zal de plannen van 2040 uitbreiden met interoperabiliteit (2040+) tussen station Zuid en Hoofddorp. Het dienstregeling van de geplande situatie voor 2040 zal worden gebruikt met 2040 passagiersvraag (Figuur 4). Dit experiment schetst de situatie in 2040+.

Experiment 4: 2040-optimalisatie

Terwijl experiment 2 gericht was op de infrastructuur van 2040 met het schema *gepland* voor 2040, is dit experiment gericht op het optimaliseren van dat scenario. De 2040-infrastructuur met onderliggend treinnetwerk (Figuur 3.b) zal worden gebruikt in combinatie met 2040 passagiersvraag. Het experiment optimaliseert de frequentie- en stoppatronen op basis van een combinatie van kosten. Dit experiment zal bepalen of een meer optimale frequentie en stoppatroon mogelijk is voor het toekomstige scenario.

Experiment 5: 2040+ optimalisatie

Dit experiment optimaliseert de frequentie en het stoppatroon voor de 2040-infrastructuur met interoperabiliteit (2040+). Waar experiment 3 was gericht op de infrastructuur van 2040+ met het schema *gepland* voor 2040, is dit experiment gericht op het optimaliseren van dat scenario. De 2040+ infrastructuur met onderliggend treinnetwerk (Figuur 4) zal worden gebruikt in combinatie met 2040 passagiersvraag. Het experiment optimaliseert de frequentie- en stoppatronen op basis van een combinatie van kosten. Dit experiment zal laten zien of een meer optimale frequentie en stoppatroon mogelijk is voor de toekomstigscenario met interoperabiliteit.

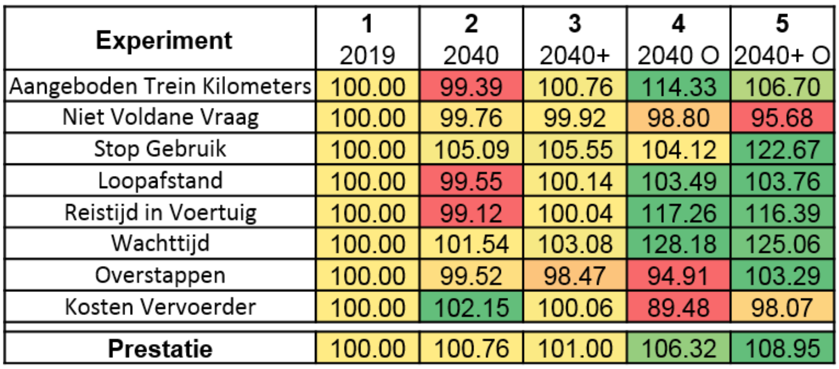
Conclusies

Het effect van de verschillende experimenten op de prestaties van het spoorwegnet zal worden beoordeeld door ze te vergelijken met het basisscenario (experiment 1). Een hogere prestatie dan het basisscenario resulteert in een score hoger dan 100, een lagere prestatie in een lagere score.

De prestaties van railsystemen zijn complex om te meten, dus voor de onderstaande tabel is ervoor gekozen om voor elk van de KPI's een gelijke weegfactor te gebruiken. De tabel is al een vereenvoudigde weergave van de werkelijke invloed van de verschillende scenario's op de prestaties en onderstaande weergave is gekozen om de complexiteit en diversiteit van spoorwegsystemen te laten zien.

Wanneer alle experimenten worden beoordeeld, worden alle scores opgeteld en het gemiddelde genomen. Het effect van de verschillende experimenten op de verschillende KPI's is te zien in Tabel 8. De kleuren komen overeen met het prestatieniveau.

Table 8: Performance Rating



Experiment	**1** 2019	**2** 2040	**3** 2040+	**4** 2040 O	**5** 2040+ O
Aangeboden Trein Kilometers	100.00	99.39	100.76	114.33	106.70
Niet Voldane Vraag	100.00	99.76	99.92	98.80	95.68
Stop Gebruik	100.00	105.09	105.55	104.12	122.67
Loopafstand	100.00	99.55	100.14	103.49	103.76
Reistijd in Voertuig	100.00	99.12	100.04	117.26	116.39
Wachttijd	100.00	101.54	103.08	128.18	125.06
Overstappen	100.00	99.52	98.47	94.91	103.29
Kosten Vervoerder	100.00	102.15	100.06	89.48	98.07
Prestatie	100.00	100.76	101.00	106.32	108.95

Om het effect van interoperabiliteit te beoordelen, zijn experimenten 3 en 5 belangrijk, omdat dit de experimenten zijn waarbij de Noord/Zuidlijn zijn weg vervolgt naar Schiphol en Hoofddorp. Hier gebruikt experiment 3 de originele dienstregeling en experiment 5 gebruikt een geoptimaliseerd tijdschema.

In vergelijking met het 2019 scenario laten beide experimenten een verbeterde prestatie zien. Het is echter beter om experiment 3 te vergelijken met experiment 1 en 2 (de experimenten zonder een tijdlijn-optimalisatie) en experiment 5 met experiment 4 (optimalisatie-experimenten).

Bij beoordeling van de beste prestaties tot de slechtste prestatie worden de experimenten als volgt beoordeeld: [4]:

1. ***Experiment 5: 2040+ geoptimaliseerd***
2. *Experiment 4: 2040 geoptimaliseerd*
3. **Experiment 3: 2040+**
4. Experiment 2: 2040
5. Experiment 1: 2019

De basissituatie (2019) heeft geen optimale prestaties en verbeteringen zijn mogelijk, de huidige plannen die zijn vrijgegeven door de gemeente Amsterdam (2040) zijn een verbetering op de prestatie maar nog steeds niet optimaal. Wanneer interoperabiliteit aan deze plannen (2040+) wordt toegevoegd, wordt een nog betere prestatie bereikt. En wanneer interoperabiliteit wordt gecombineerd met een geoptimaliseerd tijdschema, kan de grootste verbetering van de prestaties worden bereikt.

Een kanttekening bij deze beoordeling is gebaseerd op een vooraf gedefinieerde reeks KPI's. Het doel was om een zo compleet mogelijk beeld te schetsen, maar railsystemen zijn erg complex en veel problemen kunnen niet als eenvoudig worden gezien.

Alle optimalisatie-experimenten scoren hoger dan het basisscenario, dit betekent dat een deel van de verbetering van de prestaties ligt in de optimalisatie van het tijdschema.

De interoperabiliteit heeft de grootste positieve invloed op het stopgebruik en de wachttijd van de passagier. Over het algemeen heeft de interoperabiliteit een positief effect op het stedelijk spoorwegnet van het metropolitane gebied van Amsterdam.

Toen de verschillende configuraties werden getest met de vraag naar openbaar vervoer in 2040, werd het duidelijk dat er configuraties zijn waarin de prestaties van het stedelijke railsysteem kunnen worden verbeterd in vergelijking met de huidige configuratie. De verbeteringen in prestaties zijn tweeledig:

- Een geoptimaliseerd tijdschema (frequenties en stoppatronen)
- Interoperabiliteit tussen metro's en de treininfrastructuur

Interoperabiliteit tussen metro- en treinsystemen verbetert de prestaties van het stedelijk spoorwegnet van de Metropoolregio Amsterdam.

---

[4] Experimenten met toegevoegde **interoperabiliteit** zijn vetgedrukt, experimenten met *geoptimaliseerde dienstregeling* cursief.

List of Figures

List of Tables

List of Abbreviations

ATC – Automatic Train Control

ATO – Automatic Train Operation

ATP – Automatic Train Protection

ATS – Automatic Train Supervision

CBTC – Communication Based Train Control

ECTS – European Train Control System

ERTMS – European Rail Traffic Management System

KPI - Key Performance Indicator

MCA - Multi Criteria Analysis

MRA – Metropool Regio Amsterdam

RBC – Radio Block Centre

RHDHV – Royal HaskoningDHV

TNDP - Transit Network Design Problem

TPH – Trains Per Hour

UTO – Unattended Train Operation

Contents

1

Introduction

This MSc thesis is commissioned by Royal HaskoningDHV (RHDHV) with the goal to gain more insight in the consequences that interoperability of metros and trains on the same rail-network could have. Royal HaskoningDHV is an independent international engineering and project management consultancy agency. This research was performed within the rail and network optimization department located in Utrecht.

This chapter will give an introduction to the motivations for this research. The problem statement and projects to be evaluated are defined and the research questions and scope are discussed. A plan of action is presented and finally the structure of the report will be introduced.

1.1. Motivations for the Research

Growing urbanization has caused the cities in the Netherlands to burst at their seams. This growth has caused an increasing demand for public transport, with more people choosing to travel by train, tram and metro and demanding ever better levels of service. The result is busier rail networks and stations, pressure on train schedules and the need for greater investment to increase capacity. The infrastructure required to meet these challenges is also changing. An innovative approach is required to provide a truly integrated railway design. Clear insight from the outset about the impact of such a design on the networks is necessary.

The current rail infrastructure is used intensively in and around large cities, several functional network levels can be defined within the rail infrastructure. Metro connections have a local focus, Sprinters have a regional focus and Intercity trains have an (inter)national focus. The combination of different network levels puts pressure on the available infrastructure capacity. The definition between different networks is fading and will become less important in the future and can be classified in a different way. Infrastructure managers and public transport authorities meanwhile have shared a vision for a future in which trains continue their journey on metro infrastructure and metro systems will provide train connections in the future, this infrastructure sharing is called interoperability (Ministerie van Infrastructuur en Waterstaat, 2016).

According to IEC 62290-1:2006, interoperability refers to: “The ability of a transport network to operate trains and infrastructures to provide, accept and use services so exchanged without any substantial change in functionality or performance. This ability rests on all the regulatory, technical and operational conditions which must be met in order to satisfy all the defined requirements applicable to the given grade of automation taking into account grade of line, irrespective of which supplier provides which components or systems”(Nederlands Normalisatie Instituut, 2016).

Interoperability on rail networks by combining two transport modes seems to have great potential. The separation of infrastructure and operators that is currently present in the rail industry is being challenged more and more. In new long term studies the potential of letting those boundaries go is taken seriously by all stakeholders. This research aims to investigate the current issues obstructing interoperability on rail networks and predict the possibilities that could be achieved with this interoperability. During the course of this research explicit interest was shown by the metro operators of different cities, the GVB (Amsterdam) and RET (Rotterdam) which could both benefit from the outcomes.

This research will focus on rail network of the metropolitan area of Amsterdam and the possibilities to continue the services of the different metro lines (e.g. the Noord/Zuidlijn) on the national train network (e.g. to Schiphol and Hoofddorp). This service continuation has been the topic of discussion since the start of the build of the Noord/Zuidlijn. Recently, the CEO of ProRail, Pier Eringa, expressed that the double track between Amsterdam-Zuid and Schiphol Airport stations must be used not only by trains but also by metros or other forms of light rail (van Lieshout, 2016). The case of the Noord/Zuidlijn is very relevant as the start date for the operation of this line (22nd of July 2018) occurred during this research making it a current research topic, which is highly in the public eye.

The case of interoperability between the national railway network and an urban metro network could present many advantages. The costs of a metro network, both infrastructural costs as well as operational costs are lower than heavy rail costs (Tirachini et al., 2010). If two networks could be linked, thus minimizing the initial infrastructural costs, an increase in transport capacity could be reached which might provide many advantages for the city under investigation. This research could be an incentive to take interoperability in rail networks as a serious alternative for building (expensive) new rail infrastructure.

All over the globe, integrated transport systems are becoming more popular as stakeholders are starting to realize the many advantages they can provide. This joint operation of railways can provide many advantages as summarized by the Transit Cooperative Research Program (TCRP)(Phraner et al., 1999):

- Cost can be avoided if the construction, maintenance, and operations of separate parallel tracks and infrastructure is avoided.
- Joint operation enables the expansion of rail transit services and capacity without creating additional facilities, public takings, or environmental/social disruption.
- By service integration it will provide extended routes and/or two-way running, reducing passenger transfers.
- It will increase the probabilities for new starts in metropolitan areas where rail transit is currently absent, but desirable.
- It will increase the spectrum for incremental financing of rail transit on rail infrastructure that is underused or disused.

All of the above leads to the following problem statement: Will interoperability of rail systems contribute to an increased level of quality of the public rail network in Dutch cities?

1.2. Goals of the Research

This research aims to investigate the influence of interoperability on the quality of the urban rail network. The feasibility of this interoperability is a research goal on its own, as the type of interoperability discussed in this report is currently not yet present in the Netherlands. The aim is to identify what compatibility issues will arise when interoperability between train and metro systems is the goal. The next area of interest is how these compatibility issues can be overcome to achieve interoperability of the metro network of Amsterdam and the national railway network in and around the city.

The plan is to find out what the infrastructure of the Amsterdam metropolitan rail network would look like if interoperability is achieved. How is this new network different from the old, and is it an improved infrastructure that better meets the demands of both the operators and the passengers? Key aspects for this research are the characteristics of the different network levels and infrastructure, network developments as well as network capacity. For the rolling stock, the characteristics such as the stopping patterns and security systems of the different modalities will be taken into account.

This research will contribute to the public transportation network in the Netherlands and the way that the different public transport modalities work together. For the city of Amsterdam a higher level of accessibility can be achieved, combined with the strengthening of the position of Schiphol as a multimodal hub. The research aims to show how actions of the individual components directly affect the performance of the overall transport system.

1.3. Research Questions

Now that the problem analysis, problem statement and research goals are clear, the research questions will be introduced. The research questions will provide the structure to answer the problem statement at hand.

Main Research Question

How will interoperability between metro and train systems affect the performance of the urban rail network of the Amsterdam metropolitan area, given a public transport passenger demand?

Sub Research Questions

- *What is the base case scenario for the urban rail network of the Amsterdam metropolitan area and how can the performance of this network be assessed?*
- *What compatibility issues are there between metro and train systems?*
- *What design alternatives with corresponding costs and actions are there to overcome these compatibility issues?*
- *How can the effect of interoperability on the performance of the urban rail network be modelled?*
- *What is the effect of interoperability on the performance of the urban rail network of the Amsterdam metropolitan area?*

1.4. Plan of Action

In this section the plan of action for answering the research questions will be described.

What is the base case scenario for the urban rail network of the Amsterdam metropolitan area and how can the performance of this network be assessed?

Before any comparisons or ideas for improvements can be made, the current state must be clear, that is the goal of this research question. To answer it, a summary of the trends and planned improvements for the Amsterdam urban area and the Netherlands will be given. This will sketch an image for the base case. This base case is necessary to asses the influence of infrastructural and network changes caused by interoperability on the performance of a network. This base case reflects the current state of the urban rail network, which can later be compared to a possible future state of the urban rail network.

The base case will reflect the plans and visions shared by the different operators, government agencies and infrastructural managers for the year 2040. This year was chosen because infrastructural rail projects take a lot of time and planning. Many projects planned to start operation before 2040 have already been determined today.

To quantify the performance of the public rail system, the key performance indicators (KPIs) need to be determined. A KPI is a variable used to analyse the performance of a system. A literature research will be performed to identify how the performance and quality of a rail network can be graded. This will be used for the comparison between the base case scenario and a possible future state scenario later on to determine if the future state is in improvement to the base case.

What compatibility issues are there between metro and train systems?

To identify what compatibility issues will arise when interoperability between rail systems is to be achieved, the rail systems under investigation must be analysed and compared.

The different characteristics of both the national rail system and the urban rail system will be investigated by means of a literature research. When the systems have been mapped based on their infrastructure, safety and communication systems, rolling stock and network characteristics, an assessment of the compatibility issues that the systems have can be made.

After this a choice has to be made on the type of interoperability that will be used for the research. Will it be metros using the train infrastructure, trains using the metro infrastructure, or both?

What design alternatives with corresponding costs and actions are there to overcome these compatibility issues?

The aim is to investigate the effects of overcoming the compatibility issues connected to rail interoperability. To do this, the design solutions with corresponding costs and actions necessary to achieve this interoperability need to be known.

A study will be performed to identify possible design solutions that can be used to overcome these issues. This study will use industry examples of cases where (partial) interoperability between rail systems is achieved.

After the different design solutions are identified, the corresponding costs and actions needed to implement these solutions will be examined and listed. The expert knowledge of the specialists at RHDHV and from the industry will be used combined with industry examples to achieve the best possible estimates for these costs and actions.

How can the effect of interoperability on the performance of the urban rail network be modelled?
In order to assess the effect of interoperability, a tool to model the interoperability is necessary. This model can be used to simulate different situations that will help assess the performance of the urban rail network of the Amsterdam metropolitan area. With this model, both the base case scenario as well as possible future scenarios can be modelled.

A literature research into possible models that can be used for this research question will be performed. After a model has been chosen, the necessary adjustments necessary must be inventoried and implemented to equip the model to answer the final research question. The KPIs found in Chapter 2 can also be further specified depending on the output of the model.

What is the effect of interoperability on the performance urban rail network of the Amsterdam metropolitan area?
The goal of this question is to find out how the infrastructure of the Amsterdam metropolitan area will change when interoperability is an option. Will these changes be an improvement to the current infrastructure based on the performance indicators established earlier?

Experiments have to be set up that can be simulated, the output of these experiments will have to be translated to the Key Performance Indicators to answer the main research question.

1.5. Structure of the Report

The chapters in this research will follow the research questions, meaning that at the end of each chapter, a research question will be answered.

The report will start with a summary of the vision key stakeholders shared for public transport in 2040. The challenges, trends, goals and planned improvements will be discussed to best sketch an image for the future. The chapter has the goal to give the reader an idea of what the urban rail network of the Amsterdam metropolitan area will look like in the future. The chapter will finish with a description of the Key Performance Indicators base on which the performance of a public rail transport is assessed.

In Chapter 3 the two systems of interest to this research will be analysed. The national railway network of the Netherlands and the Noord/Zuidlijn will be analysed based on the infrastructure, safety and communication systems, rolling stock, stakeholders and network characteristics. After the networks have been thoroughly analysed, the compatibility issues between the two systems can be assessed. When this is done a choice is made on the type of interoperability that will be used for the research. Will it be metros using the train infrastructure, trains using the metro infrastructure, or both?

Chapter 4 will start with a literature research into cases where interoperability or integration between railway systems was executed successfully. This literature research will look at trams, trains and metros. After this, design directions to solve the compatibility issues found in Chapter 3 will be drafted. An indication of the necessary actions and costs involved with achieving these design alternatives will be made. Chapter 4 will end with a multi criteria analysis to determine what set of design alternatives will be used to achieve interoperability.

Now that the way to achieve the desired interoperability has been mapped, it is time to assess its influence on the performance of the urban rail network of the Amsterdam metropolitan area. Chapter 5 describes the model, first the process and reasoning behind the choice of model are described followed by a description of the chosen model.

In Chapter 6 the case study for the metropolitan area of Amsterdam is discussed. The experiments used to answer the final research question are introduced. The chapter continues with the results of the experiments and the discussion of these results. Finally a conclusion can be made to answer the final research question.

Chapter 7 will contain all of the conclusions that can be made after this research. The chapter will present a final recap and answer all of the research questions. Chapter 7 will also include all of the recommendation for further research.

2

Public Transport in the Netherlands

The public transport network in the Netherlands is always changing, to best serve the changing demands of the passengers. Urbanization is one of the main reasons which requires the public transport network to change. There are many government institutions who are involved with the management and research into changes to the network.

The goal of this chapter is to answer the research question: *What is the base case scenario for the urban rail network of the Amsterdam metropolitan area and how can the performance of this network be assessed?* This base case is necessary in order to make a comparison later on to assess the influence of metro-train interoperability on the performance of the network.

The chapter will start with an introduction to the predicted public transport demand for 2040. After that a study into the trends and planned improvements for public transport and rail networks in the Netherlands to cope with this prediction will be performed. This study will sketch an image of what the future of public transport in the Netherlands will look like if it were up to the different agencies involved. Based on this information a base case scenario will be set. Finally the Key Performance Indicators (KPIs) that are used to rate the performance of the public urban rail system will be discussed.

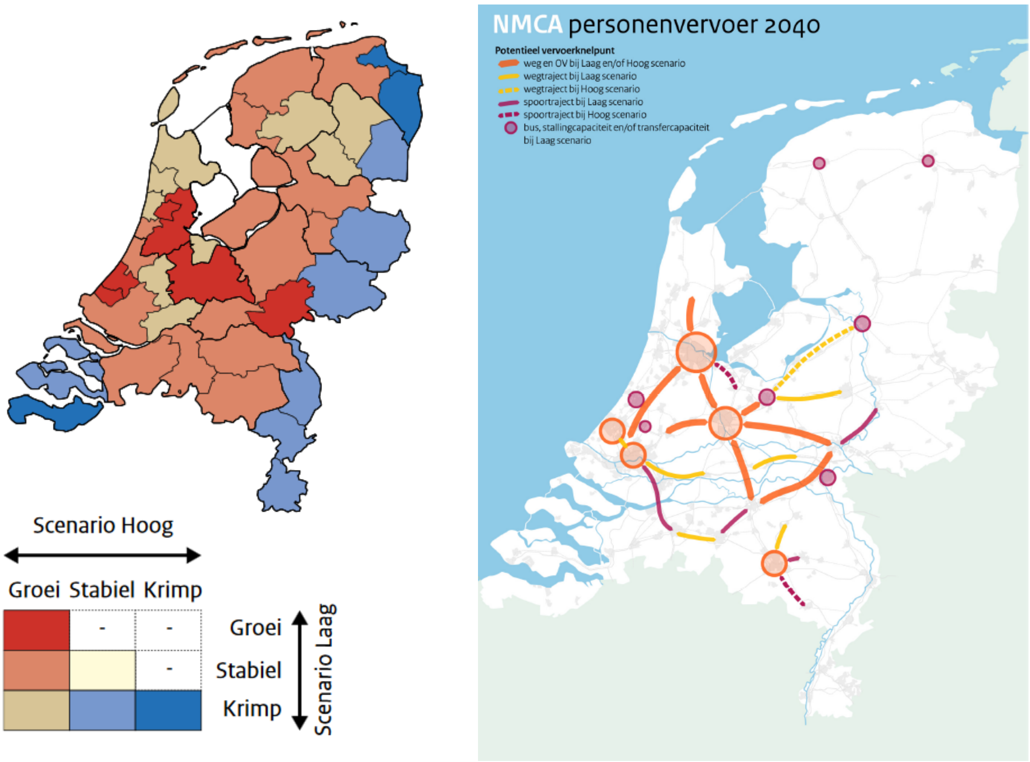
2.1. Public Transport 2040

Public transport is always changing, and its role in the Dutch infrastructure is becoming more and more important. This section describes the challenges, opportunities, trends, goals and planned improvements for the Dutch public transport system towards the year 2040.

2.1.1. Challenges

The population in the Netherlands is ever growing, the Dutch Environmental Assessment Agency (PBL) and the Dutch Bureau for Economic Policy Analysis (CPB) performed a study into the future population sizes in the Netherlands (CPB/CBS, 2015). The results of this research were a high and a low scenario, as seen in Figure2.1.a. Scenario High combines relatively high population growth with high economic growth; scenario Low has a more moderate demographic development and a more modest economic growth.

Based on the data of this research, the Ministry of Infrastructure and the Environment carries out a National Market and Capacity Analysis (NMCA) once every four years to gain insight into the long-term bottlenecks on roads, waterways, railways and regional public transport (ProRail, 2017). The NMCA is one of the most used researches for identifying national and regional accessibility issues. Figure 2.1.b. show the results of this research for people transport in 2040. The research takes investments up to 2030 into account, but nothing has been planned for the period until 2040. Figure2.1.b. illustrates that up until 2030 it will become increasingly busier on the Dutch infrastructure. In the ten years that will follow, the infrastructure in the the Netherlands will clog up completely. As a result, more serious challenges in passenger transport will arise. The accessibility tasks on the road and in the public transport network are stacking on busy connections, around and between the major cities (Amsterdam, The Hague, Rotterdam, Utrecht and Eindhoven)(Ministerie van Infrastructuur en Milieu, 2017).



(a) Population Size WLO Scenario (CPB/CBS, 2015)

(b) Potential Traffic Bottlenecks Passenger Transport (Ministerie van Infrastructuur en Milieu, 2017)

Figure 2.1: The Netherlands in 2040

For this research, the high scenario for 2040 (Figure 2.1a.) will be used. This scenario was based on fast economic growth and an accompanying large growth in mobility. The high scenario was chosen because this scenario results in the biggest transport bottleneck that needs solving and illustrates the "worst case scenario".

2.1.2. Trends

As a result of the two researches discussed in the previous section, the ministry of Infrastructure and Water Management shared a vision for public transport in 2040 based on a number of trends.(Ministerie van Infrastructuur en Waterstaat, 2016):

- **Population Growth:** In metropolitan areas, population growth and demand for mobility will increase in the coming years. In other areas the population will stabilize or decline, partly as a result of ageing.
- **Metropolitan Areas:** Public transport is particularly strong in and between metropolitan areas and for long distances. Outside the big cities, the car offers a strong competitive alternative.
- **Individualisation:** Changing lifestyles cause travellers to have different requirements for mobility. Effects of trends such as individualisation and the sharing economy on the use of public transport are unclear.
- **Technological Developments:** Technological developments such as digitization and new transport concepts change the role of public transport and fade the boundaries between modalities.
- **Sustainability:** Making the mobility sector more sustainable requires considerable effort. Public transport plays a leading role in this.

2.1.3. Goals for Public Transport

Different government institutions shared publications about their vision for public transport in the future. This section highlights the goals that were expressed by national institutions as well as the vision of the metropolitan area of Amsterdam.

National

The Ministry of Infrastructure and Water Management shared their vision for public transportation in 2040. Their vision consists of eight key points (Ministerie van Infrastructuur en Waterstaat, 2016):

1. **From public transport to mobility** Integrate public transport into the mobility chains of travellers.
2. **Offer new mobility at lower demand** Where the demand for and the supply of traditional public transport falls short, ensure that flexible, demand-oriented transport becomes available.
3. **Faster connection of economic core areas** To strengthen the competitiveness of the Dutch economy, ensure fast connections between the most important economic areas throughout the country and across the border.
4. **Strengthen and integrate public transport in urban regions** To guarantee accessibility and liveability in and around crowded cities and large-scale urban regions collective transport has to be strengthened.
5. **Continue to link regional centres and medium-sized cities** In 2040 there has to be a mobility network that will also covers and connects all regions.
6. **Continue sustainability** Continue on making mobility more sustainable. In the coming decade, a stronger collective transport will be needed to improve the climate- and air quality targets.
7. **Driving innovation** Encourage innovations aimed at accessibility in large cities, flexible demand-driven mobility and cost reduction in infrastructure, equipment and operation.
8. **Smarter collaboration and financing** To enable good and affordable door-to-door journeys, strengthen the cooperation across the boundaries of modalities and policy fields.

For the case of interoperability between metro- and train systems and the ProRail network, especially point 4 is of interest. The point is elaborated on as followed : “Direct connections better meet the needs of commuters: they prefer higher frequencies and accept the greater distance to the stops. In the four major cities opportunities lie in combining light rails and buses together with the sprinter, metro and RandstadRail to create a high functioning, coherent network that serves travellers better. For example by track sharing of metros and light rail with the heavy rail”(Ministerie van Infrastructuur en Waterstaat, 2016).

The same ministry also published their long term rail agenda , the focus of this document is on the developments on the national railway sector. The main goal of this agenda is: **Improving the quality of the railways as a transport product, so that the passenger and carrier increasingly see and use the train as an attractive transport option** (Ministerie van Infrastructuur en Milieu, 2012). This rail agenda has the goal to improve door-to-door travel time and the ease of travel whilst ensuring the travellers in charge of their own journey. Safety and reliability are key quality aspects and space must be provided to enable growth for rail traffic.

Amsterdam Metropolitan Area

The Metropolitan Amsterdam Region (MRA) has shared their development agenda for rail transportation for the coming years (Metropoolregio Amsterdam, 2015). The main vision shared is to maximize the facilitation of the door-to-door travel for the (rush-hour) traveller by making better use of the existing infrastructure. Examples of concrete measures are improving the infrastructure, the construction of extra tracks and providing better transfers. In addition, smart use can be made of the existing track by changing the timetables.

The additional goals for the region for the coming years are the following:

- Maintain and improve a robust and reliable rail network
- Optimizing regional and interregional connections
- Promote chain mobility (P+R, bus rapid transit, bicycle, stations) to provide an attractive door-to-door journey
- Sustainable freight transport
- Providing suitable access for existing and new living and working areas

Mainport Schiphol

Strengthening the position of Schiphol as a mainport is the ambition of both the national and regional government. This will not only mean improvement of the air-side capacity, but the land-side accessibility of the airport will also need to evolve. The focus is on maintaining the competitive position of the airport, preferably by means of direct and reliable connections via the rail network. The node Schiphol has to become more robust and functional, the continuous growth in the number of train, bus and airline passengers leads to the necessity of a renewal of the station building and the improvement of the transfer function. The function of the station is closely related to the land side infrastructure - the Schiphol rail-tunnel.

The MRA also published their vision for the future of public transport in the region where the most interesting development for the rail network is the development of the node by introducing high-frequency driving on the rail corridors Zaan and Schiphol-Amsterdam-Almere-Lelystad (SAAL)(Metropoolregio Amsterdam, 2016).

For the railway station area, it is the joint ambition of Amsterdam Airport Schiphol together with ProRail, NS, Metropolitan region of Amsterdam and the ministry of Infrastructure and Environment, to improve the public transport access to Schiphol and to implement a large-scale redesign of the public transport hub at Schiphol Plaza and the Jan Dellaertplein (the bus station)(Rijksoverheid, 2017).

Finally, the municipality of Amsterdam carried out research in 2015 (with an addition in 2017(Garritsen et al., 2017)) into the possible expansion of the metro network, including the extension of the Noord/Zuidlijn to Schiphol and a new East/West line that also connects Schiphol with Amsterdam. More about this research in Section 2.1.4.

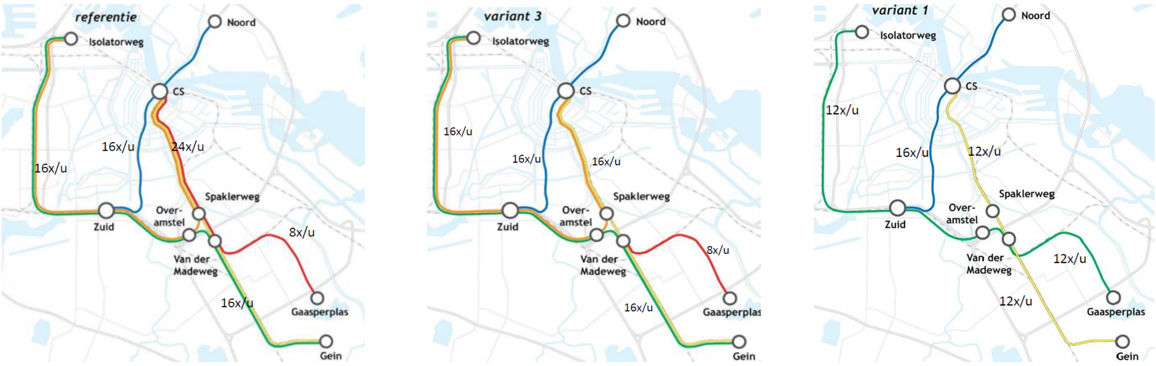
2.1.4. Planned Improvements

The Amsterdam Urban Region has shared several projects and researches into the possible future of the urban rail network around the city. This section will highlight two of the researches most interesting for this research.

Unbundling Metro Network Amsterdam

The metro network in the Amsterdam is changing, with the start of the Noord/Zuidlijn in the summer of 2018 and the change in the Amstelveense Lijn (Line 51, see 4.1.3) combined with a new rolling stock order for the so-called M7 metro series planned to start operation in 2021-2024. All of these changes were an incentive for the City Council and GVB to do a joint study on the desired metro-lines and rolling stock for 2019 for the Amsterdam metro network. This section describes the outcomes of that study (GVB and Stadsregio Amsterdam, 2016).

Three possible alternatives to the current situation were created of which the two best are discussed in this section shown in Figure 2.2. The possible alternatives were scored on five different criteria: a social cost-benefit analysis(SCBA), capacity, quality, robustness and safety. From this study, the variant 3 appeared to be the most suitable for the projected transport demand in 2030. This variant also provides the most benefits, also financially. In 2030 (or earlier if necessary) the switch to an unbundled line (variant 1) will be made. Variant 1 is the most robust (future-proof) and has the largest growth capacity.



(a) Reference Network Metro 2019 (b) Variation 3 (c) Variation 1

Figure 2.2: Possible Unbundling Metro Network Amsterdam (GVB and Stadsregio Amsterdam, 2016)

Extensions to the Amsterdam Metro Network

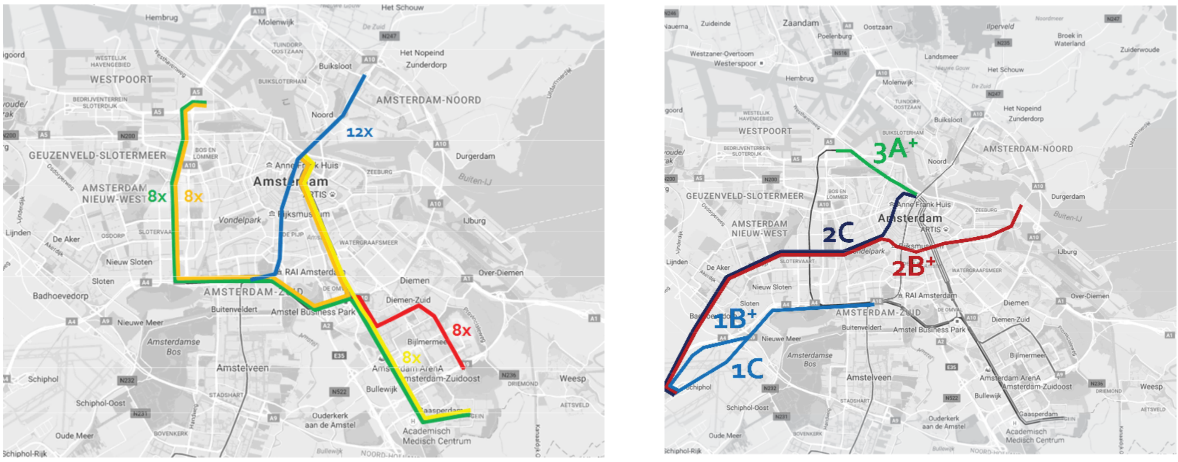
This section will go more in-depth on the research conducted by the municipality of Amsterdam about possible extensions to the Amsterdam metro network (Garritsen et al., 2017). As reference network for 2030 variation 3 of the previous section was used (but with different frequencies). Figure2.3 shows what the future of the Amsterdam metro network could look like, combined with the routes that were explored in this research. The environment around the metro line is also taken into account. For the three variants with a plus sign (+), it has been calculated how many extra inhabitants and jobs could theoretically still be realized in a radius of 800 meters around the metro stations (the most important operating area of a metro). No concrete plans have been made to implement any of the route extensions explored in this research. The route explorations of interest to this research are 1B+ and 1C (Figure 2.4.a and 2.4.b), the metro lines that would continue the Noord/Zuidlijn to Schiphol Airport as a metro network on newly built infrastructure. Table 2.1 shows a comparison between the two scenario's.

Variant 1 C consists of the most direct connection possible between Amsterdam Zuid and Schiphol. The line will be mainly above ground, with a tunnel between Schiphol Noord and Schiphol Centrum. It will consist of 6 extra stations over 9 kilometres and the travel time from Schiphol to Station Zuid will be 11 minutes (versus 6 minutes by train). The busiest part of the new route is Amstelveenseweg-Zuid with 39.000 travellers/day. The advantage of this variant is that, if desired, it can also be extended in the direction of Hoofddorp. What stands out is that the stations Schiphol Centrum and Amstelveenseweg are doing great, but the intermediate stations have little entrants.

For version 1B, the route generally follows the A4 and deviates from variant 1C as can be seen in Figure 2.4.b. The entire route and all new metro stations are above ground. The route consist of 6 stations over 11 kilometres and the travel time is 13 minutes from Schiphol to Station Zuid (versus 6 minutes by train). The busiest part of the route is Amstelveenseweg-Zuid with 37.000 travellers daily. This variant can not be extended or will be very difficult to continue towards Hoofddorp. Just like with variant 1C it is noticeable that the stations Schiphol Centrum and Amstelveenseweg do well again, but that stations Anderlechtlaan and Riekerpolder do better than variation 1C, due to the extra spatial program that has been added here.

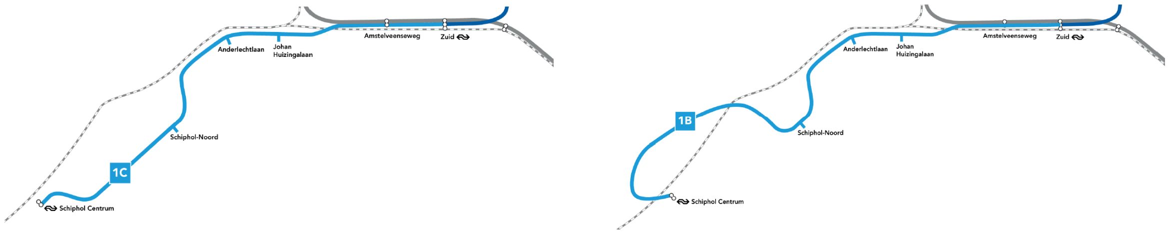
Table 2.1: Comparison Scenario's 1C and 1B+

Scenario	Investment costs	Extra entries new stations /24hrs	Extra entries existing stations Noord/Zuidlijn /24hrs	Less Entries Station Zuid /24hrs	Travellers Extended Route /24hrs	Average Occupation /24hrs
1C	€3,4 Billion	30.000	6.000	3.000	51.000	34.000
1B+	€2,4 Billion	40.000	6.000	3.000	62.000	37.000



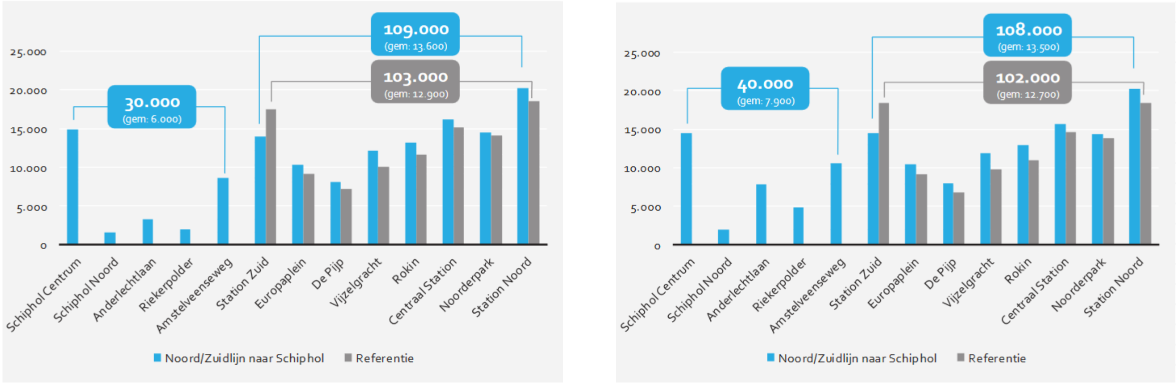
(a) Reference Network Metro 2030 (b) Route Explorations

Figure 2.3: Future of Amsterdam Metro Network(Garritsen et al., 2017)



(a) Variation 1C (b) Variation 1B+

Figure 2.4: Route Variations(Garritsen et al., 2017)



(a) Access passengers metro 1C per station per 24 hours (b) Access passengers metro 1B+ per station per 24 hours

Figure 2.5: Access Passengers(Garritsen et al., 2017)

OV-SAAL

The number of people travelling by train between Schiphol and Lelystad is growing strongly. In 2030, approximately 80.000 people will commute between Almere and Amsterdam every day. This growth can be explained by the the growth of the Zuidas, which is developing into the most important international business centre in the Netherlands. Also, the city of Almere will receive a total of 60.000 new homes(Ministerie van Infrastructuur en Waterstaat).

The current track cannot cope with the growth of train passengers, thus OV SAAL was created. OV-SAAL (Public Transport Schiphol - Amsterdam - Almere - Lelystad) is an infrastructure improvement project that ProRail carries out to expand the capacity of the network around Amsterdam and the Flevolijn. OV-SAAL consists of three parts: the short term, medium term and the long term. The short term project is finished and consisted, among others, of the doubling of the track from two to four tracks between Schiphol and Amsterdam Zuid. The medium term project will contain the implementation of ERTMS Level 2 on the route section, more about this in Section 3.3. The projects for the long term are not decided upon yet.

Station Amsterdam Zuid

In 2018, Station Amsterdam Zuid processes more than 80 000 passengers a day. With the arrival of the Noord/Zuidlijn and the growth of train traffic on the Schiphol-Amsterdam-Almere-Lelystad route, that number will increase to 250.000 passengers a day by 2030. Amsterdam Zuid will be the hub of the improved transport network around Zuidas and Amsterdam. For these reasons renovations are planned for the station, the station will become a public transport terminal where all forms of transport come together. The current passage under the station will become twice as wide and will be accompanied by a second passage. The train and metro platforms will become wider and there will be entrances to the platforms from both passages. This way the passenger flows will become better distributed over the station (ProRail, 2018a).

2.2. Key Performance Indicators

Throughout this research, the performance of the urban rail system is often mentioned, but the performance of a system depends on many factors. This section will describe how the performance of rail infrastructures can be measured and defined. Key performance indicators (KPIs) can help railway companies to become more attractive for their customers and more efficient in their operations. A distinction will be made between KPIs and boundary conditions. The boundary conditions represent the matters that need to be safeguarded at all costs. The KPIs defined in this section will be used later on to compare different scenario’s.

2.2.1. Accessibility

The indicator accessibility has a number of different aspects, on the passenger side it entails the percentage of areas having public transport accessible within a reasonable time period, by a reasonable path (unobstructed infrastructure) and presence of information systems to access public transport. This can than be translated to revenue passengers per service area population. Accessibility also deals with the service coverage, so the provided train paths and connections (two way) to different junctions for travellers. A train path is a capacity reservation on the track that is necessary to be able to drive a train from A to B.

2.2.2. Reliability

This KPI deals with trains delayed due to the infrastructure. For the operator and for the passenger, the train punctuality is of interest. Passenger punctuality gives an indication of the percentage of journeys that have been delayed by less than a certain amount of minutes. Train punctuality is the percentage of train arrivals where the difference between the originally scheduled time and the established realization time is less than a certain amount of time. Failed passenger trains, the percentage of train arrivals that have not been realized.

2.2.3. Robustness

The robustness of a system is closely related to its network distribution. A robust system deals well with defaults. It should be able to provide new routes between two different stations if one of the routes is blocked. It refers to how many lines are available to go from a point of origin to destination without requiring to leave the system.

The GVB defines robustness as the ability of a network configuration to accommodate passenger growth by means of higher frequencies and the use of extra equipment. Here the infrastructural bottlenecks are taken into account. Robustness also applies to the flexibility of the rolling stock; the capacity of the fleet must be relatively simple increase.

There are many different ways one can look at robustness, many of which deal with disruptions and defaults to the network.

2.2.4. Infrastructure Defects

Failures on the infrastructure with significant impact must be minimized, a fault arises due to a problem with the infrastructure and has an impact on the timetable of the operators and therefore on the passengers. The average recovery time to solve these failures is also important and must be as short as possible so that service can continue swiftly.

2.2.5. Safety and Sustainability

Safety is expressed in the number of times that an undesirable [1] event occurs. There are various external effects that have an impact on the performance of rail transport when it comes to sustainability, these various components include: external noise, air pollution, climate change, nature and landscapes. What is the level and savings of energy and emissions as a result of increased usage of public transport Emissions per km, fuel efficiency, share of fleets run on clean fuels.

Safety and sustainability will be a boundary condition to the system, meaning that in any situation, safety must be guaranteed and sustainability must be achieved.

2.2.6. Passenger Satisfaction

The passenger satisfaction is an important part of the operators performance, this is measured by the general customer rating, and is based on the following:

- Ease of travel, how crowded is the vehicle, seating opportunity in rush hour
- Passenger is in charge of their own journey
- Traveller information
- Door-to-door trip
- Travel time, composed of: walking time from/to origin/destination, in-vehicle travel time and waiting time
- Amount of transfers
- Supply of transport (denied boarding or unsatisfied demand)

2.2.7. Costs

Finally, costs are a very quantitative way to measure the performance of a system, operator costs depend on the number of vehicles that is needed and the length of the routes those vehicles have to travel. The latter can be expressed in either time, distance, or both. Operator costs can be categorized in operating expenses per total passenger, per revenue passenger or per passenger kilometre. The costs for this research will depend on: the number of vehicles needed, (depending on frequency and cycle time of a line), personnel costs, vehicle costs and maintenance costs.

---

[1] Collision train-train, stop showing signal passage (danger point reached), stop showing signal passage (danger point not reached), derailment, accident with level crossing-user, collision of personnel or environmental violations

2.3. Conclusions

The challenges and trends for the following years coincide with the urbanization in the Netherlands. The population and thus the demand for public transport in the Netherlands is set to keep increasing in the following years. For this research, picture painted by the Dutch Environmental Assessment Agency (PBL) and the Dutch Bureau for Economic Policy Analysis (CPB) will be used as the passenger demand to test the network with. The data that describes the *2040 High* scenario will be used as it will best prepare the public transport towards 2040.

The goals of both the national government as well as those of the metropolitan region of Amsterdam have a lot in common when it concerns public (rail) transport. This section will outline these combined goals.

Door-to-door travel, combined with the integration and strengthening of public transport nodes are the common denominator when looking at the goals of the different government agencies. The main areas of interest are the economic cores and urban areas. Flexible, demand driven mobility is the aim because direct connections better meet the needs of commuters. Safety, Reliability and sustainability are conditional to these goals. The Municipality of Amsterdam explicitly expressed the use of the existing infrastructure to facilitate this door-to-door rush hour travel.

Trends in public transport are driven by the population growth in urban areas combined with a higher demand for mobility. The mobility system in the future must be flexible and adaptive to cope with this population growth.

Explorations about extensions of the metro network of Amsterdam to Schiphol have been performed and show interesting conclusions. If an extension (by building new infrastructure) would be created, the increase in passengers on the route would be significant, especially at the stations Schiphol and Amstelveenseweg the numbers would go up, at Station Zuid, they would go down a little bit, relieving the station.

Schiphol is an area of high interest to the metropolitan region of Amsterdam. The strengthening of the position of Schiphol as a mainport in the Netherlands must be facilitated by, among other things, continuous improvement of the land-side accessibility of the airport.

Both for Schiphol as well as station Amsterdam Zuid, there are issues with transfer passengers. The capacity for these stations is reached. The transport hub at Schiphol Plaza will likely have to undergo a large-scale redesign to better cope with transfer passengers. For station Zuid there are also plans to redistribute passengers.

The goal of this chapter was to set the stage for public rail transport in 2040 and sketch a base case scenario. The proposed scenarios to be investigated and compared based on their performance in this research are:

- 2019 Base Case (Reference Network Metro Amsterdam)
  - 2019 Metro Configuration with Regular Train Configuration(See Figure 2.6)
- 2040 Planned State
  - 2040 Planned Metro Configuration with Regular Train Configuration (See Figure 2.7)

The second part of the first research question was about how to measure the performance of an urban rail system. The **K**ey **P**erformance **I**ndicators found for public rail transport are: Accessibility, Reliability, Robustness, Infrastructure Defects, Safety and Sustainability, Passenger Satisfaction and Costs. However, some of these KPI's are indifferent to this research as they deal with disruptions to the network, this research will focus on a network during normal operation. The KPIs that will be used to assess the performance of the network are: Accessibility, Customer Satisfaction and Costs, Sustainability and Safety will be a boundary condition.

Figure 2.6: Reference Network Metro Amsterdam 2019

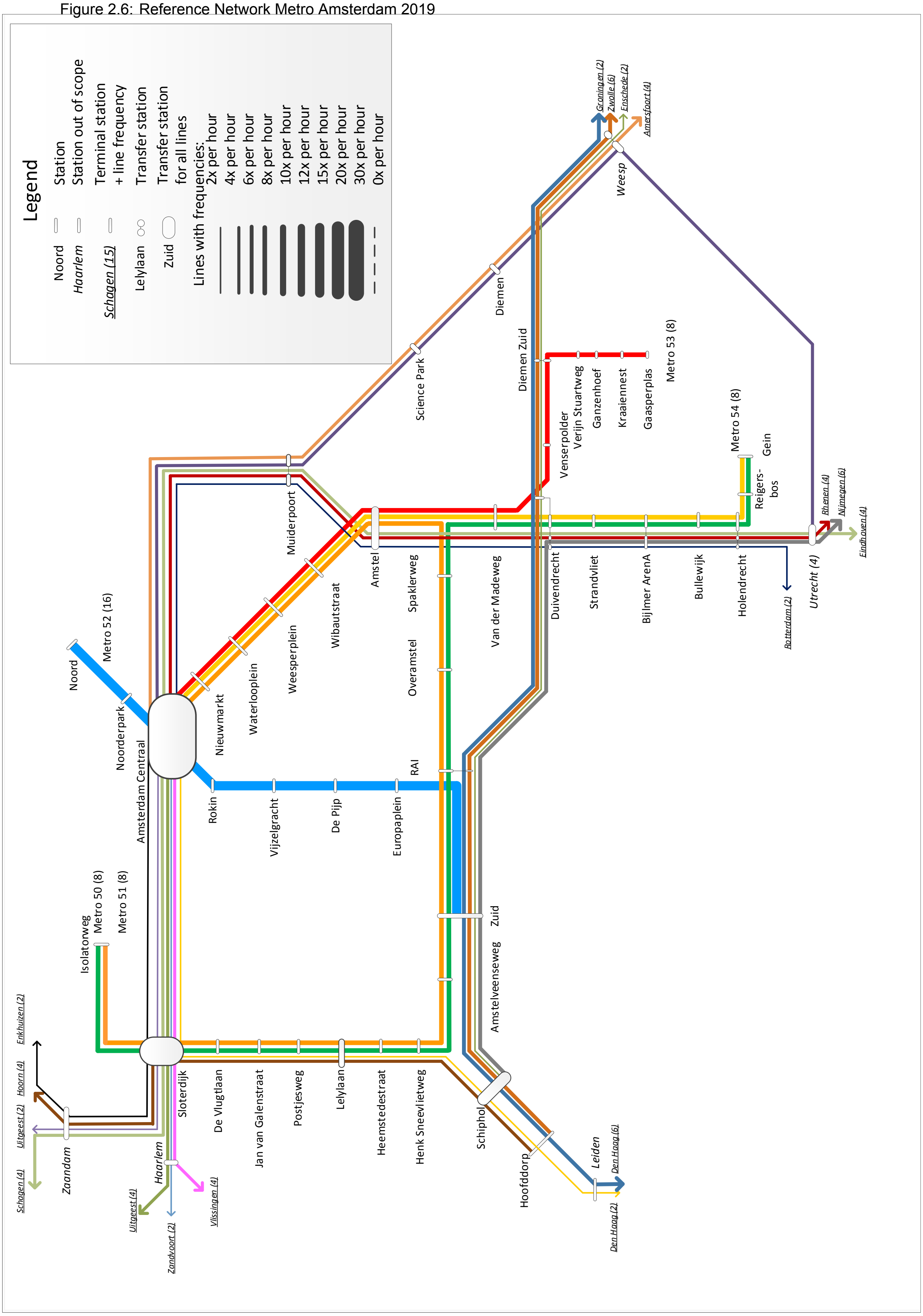
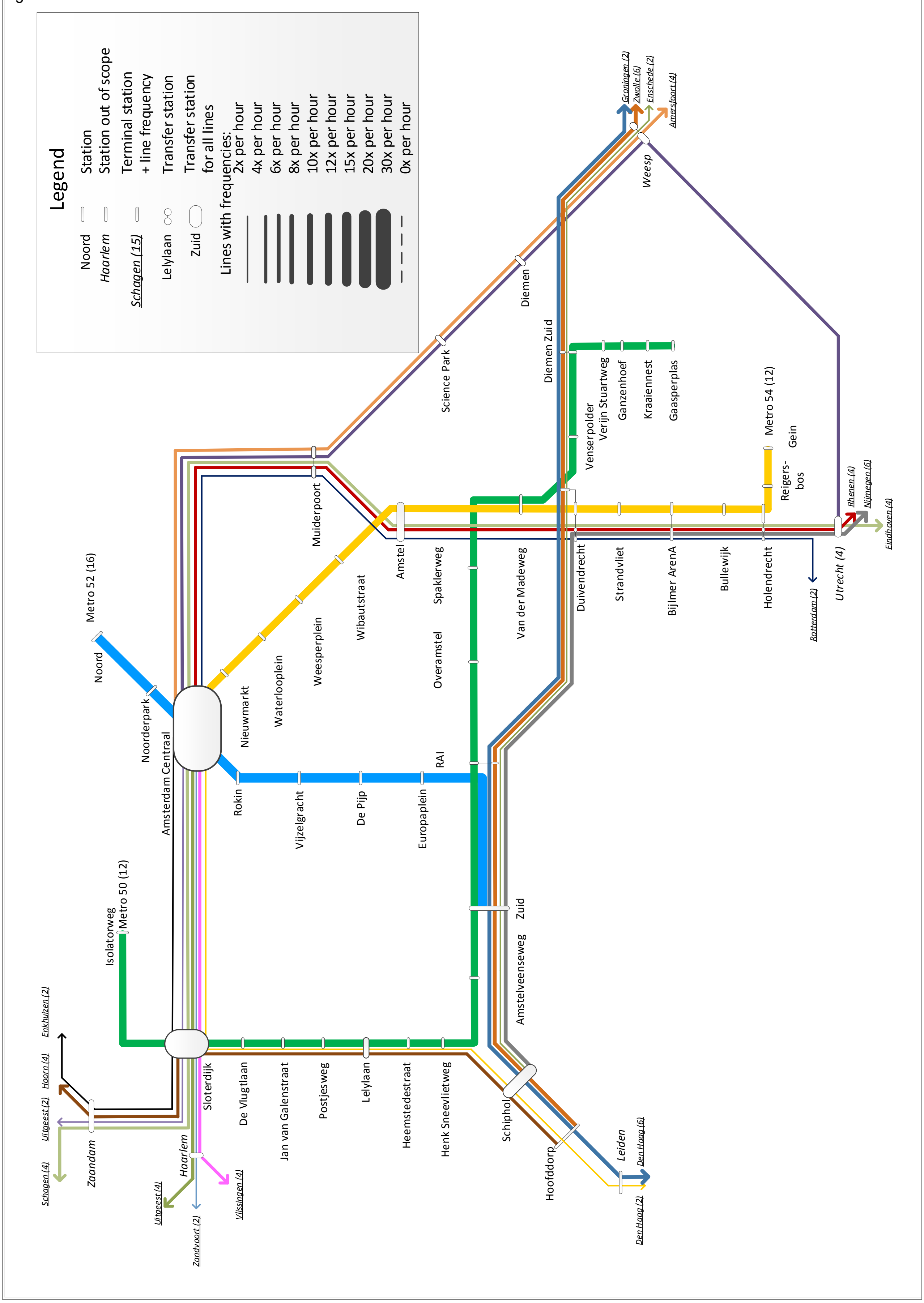


Figure 2.7: Metro Network Amsterdam 2040



3

Compatibility Issues

In the previous chapter the possible future for public (rail) transport in the Netherlands was discussed. The goal of this research is to investigate if interoperability between rail systems might be an improvement for this future. This chapter will investigate the compatibility issues that rail systems have.

Railway systems consist of many components, which all must be properly integrated: trains, tracks, stations, signaling and control systems, monitoring, maintenance and the impact on cities, landscape and people. This chapter will analyse these components in order to answer the following question: *What compatibility issues are there between metro and train systems?*

Before the system analysis is performed, a short introduction to the systems under investigation is given. The chapter will continue with an introduction to each of the system characteristics under investigation continued with an analysis of the Dutch national railway followed by a similar structured analysis on the urban rail transit system. This chapter will finish with an assessment of the compatibility issues that the two systems have.

Note that this section contains the highlights of the system analysis, Appendix B contains the complete version of this system analysis.

3.1. Systems Under Investigation

Train System

For train system, the Dutch national railway system will be used, which consists of the ProRail Network when looking at infrastructural aspects, and the trains of the Nederlandse Spoorwegen (NS) when the subject is the rolling stock.

Urban Rail System

There are many different terminologies for rail systems that are not considered to be a part of the national railway system. Urban rail transit system or light rail are examples of terms that are used. The Dutch Ministry of Transport, Public Works and Water Management defines light rail as follows: “Light rail is a rail-based public transport concept aimed at journeys with distances of 10 to 40 kilometres between a central city and its direct area of influence, or exclusively aimed at the more rural region. The vehicles have many entry and exit points, fast acceleration and short stopping times, sufficient top speed and can often be adapted to enable them to use the infrastructure of existing train, express trams and metro trains” (Ministerie van Verkeer en Waterstaat, 1997). This section will focus on the characteristics of a metro rail system that is defined by the International Association of Public Transport as: “Metropolitan railways are urban, electric transport systems with high capacity and a high frequency of service. Metros are totally independent from other traffic, road or pedestrians. They are consequently designed for operations in tunnel, viaducts or on surface level but with physical separation”(UITP, 2009).

Because there are so many different terminologies for the urban rail network, and because there are no (inter)national standards for metro systems, it is difficult to generalize on the characteristics of a metro network. So the choice is made to focus one one specific urban transport network: the metro network of Amsterdam.

3.2. Infrastructure

The railway infrastructure normally consists of the following components: rails, sleepers ballast, subballast, the base and a formation layer. The entire system can be separated in a superstructure (rails, sleepers ballast and subballast) and a substructure (formation layer and base) as shown in Figure 3.1. The track section of the railway infrastructure ensures safe operation of the rolling stock (vehicles) at the scheduled speed.

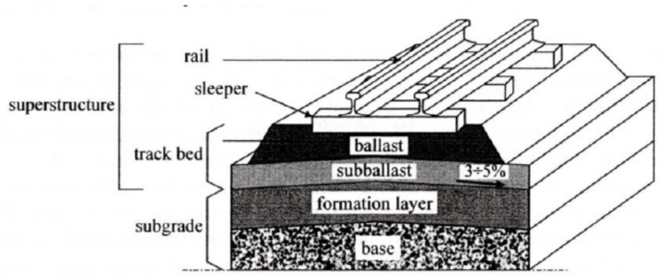


Figure 3.1: Track System (Profillidis, 2006)

3.2.1. Track Gauge

The track gauge is defined as the distance between the inner sides of the rails, measured 14 mm below the rolling surface (Figure 3.2)(Profillidis, 2006).

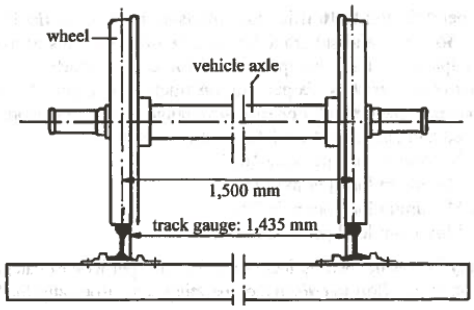


Figure 3.2: Standard Track Gauge (Profillidis, 2006)

Train System

Track gauge: the nominal rail gauge throughout the entire network is 1435 mm, in accordance with EN 13848-1 (minimum 1430mm, maximum 1450mm).

Urban Rail System

The track gauge on the Noord/Zuidlijn (and other metro networks in the Netherlands) is 1435 mm.

3.2.2. Rail Profile

The rails support and guide the wheels of rail vehicles. The rail profile that is currently used the most is the flat bottom or Vignoles type rail (Profillidis, 2006). This type of rail was formulated based of the need to join rail lengths together, which can be realized with so called fish plates. Rail profiles are identified with their weight per meter of length followed by the letter E and a serial number.

Train System

The most common used rail profile on the Dutch railway network is: 54 E1 (NP46 and UIC 60 can also be found)(Dimensions can be found in Appendix B.1.1).

Urban Rail System

The rail profile that is used on the Noord/Zuidlijn is 49 E1 (Dimensions can be found in Appendix B.2.1).

3.2.3. Axle Load

The load per axle and traffic load (tonnage) depends principally on track equipment and are the critical factors for track and subgrade fatigue. UIC classified these axle loads for standard gauges in five categories that are shown in Table 3.1(Railways, 2017).

Table 3.1: Line Categories Axle Load

Line Category	Maximum Mass per Axle	Maximum Mass per Linear Metre
A	16t	5.0 t/m
B1	18t	5.0 t/m
B2	18t	6.4 t/m
C2	20t	6.4 t/m
C3	20t	7.2 t/m
C4	20t	8.0 t/m
D2	22.5t	6.4 t/m
D3	22.5t	7.2 t/m
D4	22.5t	8.0 t/m
E4	25t	8.0 t/m
E5	25t	8.8 t/m

Train System

The allowable axle loads on the sections of the Dutch network are shown on the map in Appendix C, Figure C.1. ProRail has the following rules about axle loads on their network (Prorail, 2018):

- Load class C2 is permitted throughout the network.
- On large parts of the network, including all route sections that are part of the international freight corridors, loading class D4 is permitted under the special transport conditions.
- The rail vehicle must not be loaded heavier than the highest value allowed for that vehicle.

Urban Rail System

For most urban rail systems, the vehicles are designed specific for the rail network present and vice versa. That is why a lot of the characteristics are not specified in standards. For the axle load of the Noord/Zuidlijn, the vehicle axle load does not exceed 12 ton or 2 ton/m, if this is translated to the standard a load class of A would suffice. But it is not clear if the infrastructure can handle heavier vehicles.

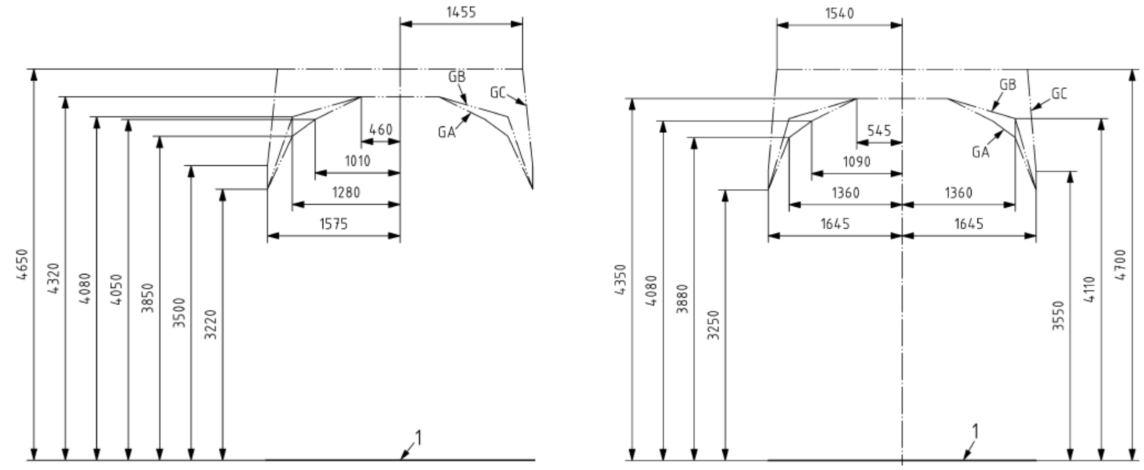
3.2.4. Load Gauge

The load gauge (static or dynamic) is the minimum external border required to remain free around the rolling stock. There are different loading gauges that depend on the width of rolling stock and the spacing between the axes of the two tracks:

- Static load gauge: minimum external border that must remain free when the train is not moving.
- Kinematic load gauge: minimum external border that must remain free while the train is moving.

Train System

The four different load gauges described for the ProRail network are : G2, GC, NL-1 and NL-2, for G2 and GC there are static as well as kinematic gauges, for NL-1 and NL-2 there are only kinematic gauges (Prorail, 2018). More information about these load gauges can be found in Appendix B.1.1. Figure 3.3 shows the kinetic loading gauge for GC, the profile used most in the Netherlands.



(a) GC Static

(b) GC Kinetic

Figure 3.3: Reference profile of static and kinematic gauges GC(Nederlands Normalisatie Instituut, 2017)

Urban Rail System

As stated before, there are no standards that describe the characteristics and infrastructural demands of an urban rail system, so the load gauge for the metro system is based on the dimensions of the vehicles. For metropolitan railways, the kinematic load gauge requires special attention as they run through tunnels for the majority of the time. Figure 3.4 shows the dynamic and static load gauge of the Noord/Zuidlijn.

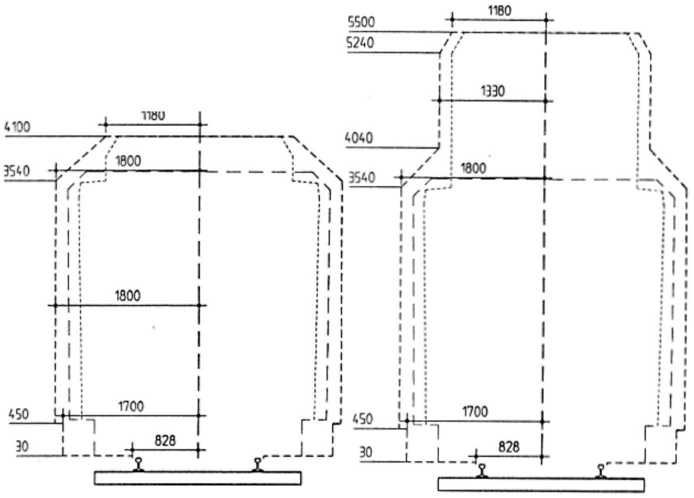


Figure 3.4: Loading Gauge GVB Metros in tunnels (left) and in open air (right) (Ontwerpbureau Noord/Zuidlijn, 1998b)

3.2.5. Radius of Curvature

The curve radius is the radius of the curvature circle that describes the axis of a railway in the horizontal or vertical plane. The minimum curve radius of a track depends on the operational speed of vehicles on that rail, the cant (rate of elevation (height) between the two rails) and the cant deficiency (is present when a vehicle's speed on a curve is greater than the speed at which the components of wheel to rail force are normal to the plane of the track).

Train System

For railways in the Netherlands, the curve radius has a minimum of 190 meters on track sections where the maximum speed is 40 km/h, when a higher maximum speed is allowed the minimum radius is 400 meters. At platforms, ProRail applies a horizontal curve radius that generally is not smaller than R=1000m. Curve radii smaller than 250m occur in incidental cases owing to spatial restrictions(Prorail, 2018).

Urban Rail System

The Noord/Zuidlijn had the following guidelines for the design of the track (Ontwerpbureau Noord/Zuidlijn, 1998b).

- R < 500 m for cant deficiency of around 100 mm
- 500 m ≤R < 1000 m for a cant of 20 mm
- 1000 m ≤R for no cant

3.2.6. Power Supply

Rolling stock must have a power supply in order to travel on the rails. This section will describe the available power supply on the infrastructure of the railway system.

Train System

In the map in Appendix C, Figure C.3, information can be found about the different power supplies on the Dutch railway network. Most track sections are equipped with 1500 V DC, 4000 A via an overhead line. The standard height of the overhead contact line in relation to the top edge of the rail is +5.50m. A different height may apply at the location of structural works, although the overhead contact line remains outside the loading gauge that is applied locally.

Urban Rail System

Usually, a metro network is supplied with power via a third rail (750 V) , the metro network of Amsterdam has different power supplies throughout the network as a result of some level crossings. The different power supplies for each vehicle (line-specific) will be discussed in the section rolling stock (3.4). If there is an overhead line, the desired height of this line in relation to the top edge of the rail is + 5,50 m. At structural works this height is 4,0 m. + top of the rail. Figure 3.5 shows the cross-section of how electrification via a third rail works.

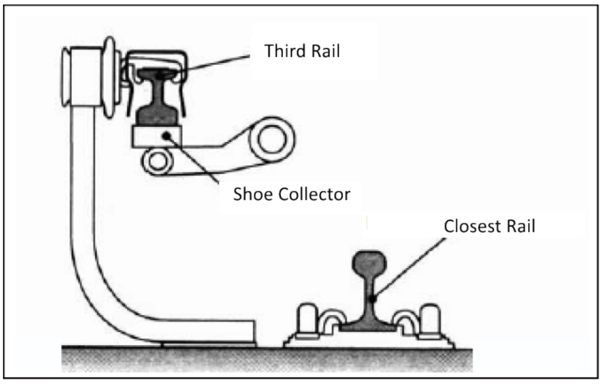


Figure 3.5: Cross-section Rail and Third Rail (GVB Rail Services, 2015)

3.2.7. Stations and Nodes

The layout of a railway network can be mapped out by all of the stations, turnouts, crossings and nodes that it contains. This section will describe the dimensions of the different stations and platforms.

Train System

The track plan of the Dutch Railway system is mapped out extensively with information on stations, number of platforms, types of railroad turnouts and more. Appendix D, Figure D.1, shows a part of such a plan for the route between Amsterdam Zuid and Schiphol.

ProRail has started the: ’Adjust Platform Height Accessibility’ programme aimed at bringing all platforms in the Netherlands to the standard height (based on European regulations and national agreements regarding rail accessibility). An adjusted platform meets the following standards(Prorail, 2018):

- The platform height is at 760mm +top of rail
- The nominal distance between the edge of the platform to the centre of the track is 1700mm, with a maximum of 1735mm

The different platform length present on the ProRail network can be found on the map in Appendix C, Figure C.5 and range from 90-340 meters.

Urban Rail System

The specifications for the platform dimensions for the Noord/Zuidlijn are determined in the document ”Handboek Spoorontwerp” (Ontwerpbureau Noord/Zuidlijn, 1998a):

- The platform height is at 1040 mm + top of rail
- The nominal distance between the edge of the platform to the centre of the track is 1580 mm in the desired situation (exceptions exist based on cant, radius of curvature and type of platform (convex/concave))

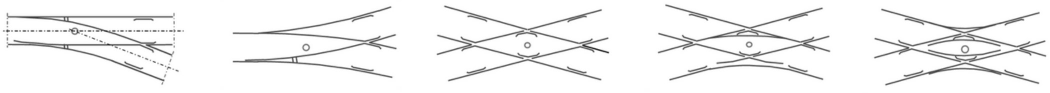
Platforms along the metro network of Amsterdam have a minimum length of 130 meters (123 meters on the Noord/Zuidlijn)(Ontwerpbureau Noord/Zuidlijn, 1998a).

3.2.8. Turnouts and Crossings

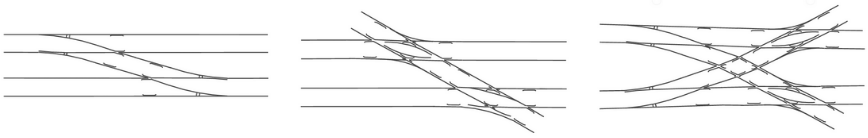
If a train has to change its course from one track to another, a turnout is necessary. There are three different forms of turnouts(Profillidis, 2006):

- Simple, or multiple turnouts, allowing a track to be split in two (or sometimes three) and the moving rail vehicle to change course.
- Crossings, where two tracks meet at grade with no change of course.
- Turnout crossings, combining the functions of turnouts and crossings.

Variations of these types are shown in Figure 3.6.



A: Standard turnout B: Symmetrical turnout C: Diamond crossing D: Single slip E: Double slip



F: Two turnouts combined to join two parallel tracks

G: Single slip and double slip junction

H: Two turnouts and two double slips with central diamond crossing

Figure 3.6: Type of Railroad Turnouts (Dollevoet, 2018)

Train System
On the ProRail network the rules for the infrastructure design state the following about the turnouts and crossings present with corresponding maximum speeds. The fraction indicates the angle that the turnout makes (tangent of the turnout angle) (Hofstra et al., 2016):
Standard Turnout

- 40 km/hr: 1:9
- 60 km/hr: 1:12
- 80 km/hr: 1:15
- 80 km/hr: 1:18
- 140 km/hr: 1:29

Symmetric Turnouts

- 50 km/hr: 1:9
- 100 km/hr: 1:15
- 125 km/hr: 1:20

(Double/Single) Slip Switch Preferably not used. In route sections with a section speed higher than 80 km/h these type of turnouts are not allowed at all.

- 40 km/hr: 1:9

Crossings Cross-turnouts are preferably not be applied when the track distance is less than 5.5 meter. The use of two switches is then preferred to a crossing. In track sections, with a track section speed higher than 80 km/h, crossings are not allowed at all.
Around stations the situation might be different as speeds are very low, more information about the turnouts and crossings around stations can be found in the corresponding trace plans.

Urban Rail System
The specifications for the Noord/Zuidlijn state the following about the types of turnouts and crossings present with corresponding maximum speeds and curves of radius (Ontwerpbureau Noord/Zuidlijn, 1998a):
Standard Turnout

- 25 km/hr: 1:6 , R=100 m
- 40 km/hr: 1:7 , R=190 m
- 40 km/hr: 1:9 , R=190 m
- 50 km/hr: 1:9 , R=300 m
- 70 km/hr: 1:14 , R = 760 m

(Double/Single) Slip Switch

- 40 km/hr: 1:9 , R=190 m
- 25 km/hr: 1:6 , R=100 m

3.2.9. Track Sections (network-configuration)

A track section is a succession of connecting timetable points and free lanes, starting and ending in a service point. Examples of service points are: stations, stops, connections, movable bridges, and locations relevant to material handling and the planning and control of personnel services. A track section can consist of one or multiple tracks. Each different track section has it's own speed limit.

Train System
The map in Figure C.5 (in Appendix C) shows the network configuration of the Dutch railway system. The Figure shows where there are single, double or multiple tracks with corresponding distances between the nodes. Figure B.6 shows the corresponding maximum travel speeds.

Urban Rail System
Figure D.3 (in Appendix D) shows the network configuration for the metro system of Amsterdam. The Figure shows how the tracks are laid and what stops there are.

3.3. Safety and Communication Systems

Safety is a key aspect of any rail system, and one of the boundary conditions described in Section 2.2. Railway systems are fitted with signalling systems, as well as safety and communications systems to ensure the safe and controlled flow of traffic. Correct signaling is needed for safety reasons, the driver has to be warned early on about possible dangers on the track and this is achieved by correct signals and alarms. This subsection will describe all of the different subsystems for safety and communication.

3.3.1. Train Control System

The function of a train control system is to prevent collisions between trains and ensure safe movement of a train from one track to another.

Train System
A railway vehicles speed control is not just monitored by the driver, there is a train control system that kicks into action in the event of human failure. For the Dutch railway system, ERTMS/ECTS is the system that is currently being implemented.

The European Train Control System (ECTS) the signalling and train control component of the European Rail Traffic Management System (ERTMS). The system calculates and communicates the safe maximum speed and the maximum distance that the train is allowed to travel for each train with the driver. If one of these permitted values is exceeded, an on-board system takes over the control. ECTS enables the standardization of different national train control systems and it is the basis for interoperability between the on-board and line-side equipment.

ERTMS can be applied on three different levels (more information about these levels can be found in the extended system analysis in Appendix B.1.2)

- *ERTMS Level 1* Track to train communications, point-to-point train safety system with fixed blocks, and conventional train detection.
- *ERTMS Level 2* Continuous communications between the train and the radio block centre, cabin signalling based on radio-communication, conventional train detection, fixed blocks.
- *ERTMS Level 3* Conceptual moving block technology, cabin signalling based on radio-communication, the train reports its own position, fixed or moving blocks.

Urban Rail System
The new vehicles for the Noord/Zuidlijn had to be equipped with at least Automatic Train Protection (ATP) and Automatic Train Operation (ATO). The ATO system at least has the functions automatic driving and brakes, station stop and door control. In the future, conversion to automatic operation is possible, but small changes to the rolling stock (the driver's cab for instance) need to be made.

The metros that were chosen for the Noord/Zuidlijn are the *Urbalis* metro by the manufacturer Alstom. The following sections describe the safety and communication systems present in this metro(system).

For the entire Amsterdam metro system, (including the Noord/Zuidlijn) Communication Based Train Control (CBTC) is implemented or will be implemented in the near future. CBTC ensures safe train separation whilst minimizing the amount of way-side and track side equipment. The system uses the telecommunications between vehicle and track for traffic management and infrastructure control. This type of system makes sure the exact position of a train is known more accurately than with the traditional signaling systems which results in shorter headways, more efficiency and safety whilst managing the railway traffic. The CBTC system used in the Noord/Zuidlijn includes: cab signaling, an automatic train control system and automatic train operation.

3.3.2. Signalling Systems

A signalling system monitors the relationship between the position of trains, track occupation and signalling to ensure safe operation. Additional safety systems use automatic train control to monitor the maximum speed and correct signal performance.

Train System

The main purpose of this signalling is safety, but this type of safety also ensures the traffic regularity. Signalling enables capacity optimization. Light signalling happens continuously and automatically. Light signalling is active when two trains run on the same track and determines whether any other train is present at some point of the track(Profillidis, 2006). Figure 3.7 shows how light signalling works on the ProRail network.

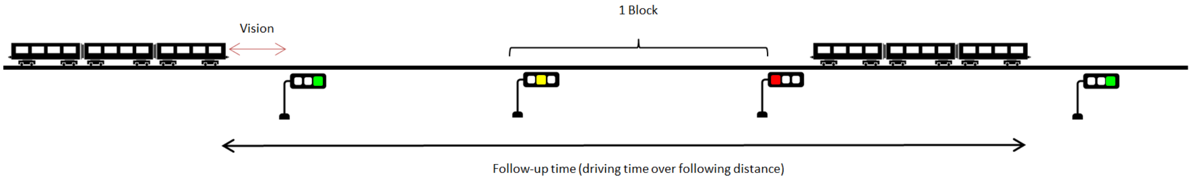


Figure 3.7: Light Signalling

Urban Rail System

With the CBTC system discussed earlier, the metro determines its own location, remembers it and communicates it to other trains. The system uses moving blocks to enable the shorter headways. Moving blocks are equivalent to giving the following CBTC train a movement authority up to the exact rear-end location of the lead CBTC train. As the lead CBTC train moves forward, given the movement authority, the following CBTC train is advanced in each communication cycle by and from the zone controller (Pascoe and Eichorn, 2009).

3.3.3. Traffic control systems

Train System

ProRail is responsible for the coordination of train traffic for all parties that use the Dutch railways on a daily basis. They ensure that trains can run according to the timetable, this process is largely automated: turnouts, signals and bridges are automatically operated. When conflicts occur or exceptions to the regular timetable are made, the national traffic control of ProRail takes action, which restores the trains as quickly as possible. The national traffic control of ProRail operates from the Operational Control Centre Rail (OCCR) in Utrecht, the joint control centre of ProRail, several transporters and contractors. The OCCR has an emergency centre that in direct contact with police, fire brigade and other emergency services in case of calamities (ProRail, 2018b).

Urban Rail System

Traffic control for the Noord/Zuidlijn is achieved with the use of the ICONIS Integrated Control Centre (Alstom, 2011). This system gives infrastructure managers and their agents complete control over the network operations. The system integrates ATS (Automatic Train Supervision), SCADA (Supervisory Control And Data Acquisition), Infotainment (Passenger Information), Security as well as optional functions. The traffic controllers get constant supervisory information on all trains and stations. The ICONIS system can work with fixed block or moving block operations and all train control systems worldwide (Alstom, 2011).

ICONIS can interface with both CBTC and ERTMS systems, as well as with the various maintenance support systems of the interlocking and control systems.

3.3.4. Communication systems

Train System

The Dutch railways, managed by ProRail, are fitted out with GSM-R, an internationally standardised digital radio-communication system. GSM-R is suitable for data communication between ETCS systems and voice communication between the driver and traffic control.

Urban Rail System

The communication system for the Noord/Zuidlijn includes a radio system along the infrastructure of the entire metro network track that will be communicate with the vehicles. This radio system operate based on the Wi-Fi standard and will operate in the license-free 5 GHz band.

3.3.5. Train Detection Systems

It is important that the integrity of a train as a whole on a track section is ensured. This section describes the train detection systems that verify that. Detection systems can be classified according to different criteria : Axles or wheels of the rail vehicle, the body of the rail vehicle, other passive parts of the rail vehicle (e.g. the pantograph) or by particular active communication devices on the train(Theeg and Vlasenko, 2009).

Train System

On the Dutch Railway network several train detection systems are active to have enough information about track occupation. Which train detection systems are in use on which route section is shown on a map in Appendix C, Figure C.8. The two most used systems will be discussed below.

A way of detecting if there is a train on a particular section of the track is by using a track circuit. In this detection system, a current flows from a battery through the rails, if an approaching train reaches the section the axles short circuit the current, if this happens a signal that was green, turns red.

In contrast to the track circuit, the axle counting system uses indirect detection. The track section is clear if the same number of axles entered at the beginning have left the track section at the end. If this condition is not fulfilled, the track section will be considered occupied.

Interlocking is a key function of a safety system ensuring the safe technical movement of trains. The interlocking system receives information about track occupation and the position of movable track elements, evaluates this information and allows movements via signals (Theeg and Vlasenko, 2009).

Urban Rail System

Train detection is incorporated with moving block based CBTC system. If a mix of vehicles (CBTC and non-CBTC) use the same track, axle counters could be incorporated to use for train detection of non CBTC trains.

3.4. Rolling Stock

The term rolling stock is another word for any vehicle that can travel on rails. To asses the differences between two systems, it is important to take the vehicles that travel on them into account. The rolling stock will be assessed on four different levels:

- **Geometric Characteristics**
  length, width, height, floor height, loading gauge, doors, wheel diameter
- **Mechanic and Dynamic Characteristics**
  weight, power, maximum speed, operating speed
- **Operational Characteristics**
  axle load, train control system
- **(Electrical) Traction System**

Train System

For this section, the characteristics of the trains that use the ProRail network that could be involved in track sharing with the Amsterdam metro will be investigated.

The rolling stock currently used by the NS (or in close collaboration with the NS) can be seen in Table 3.2. Information about the specific geometric, dynamic and operational characteristics can be found in the Tables in Appendix B.1.3.

All of the trains operated by the NS have a 1500 V DC voltage, supplied by an overhead line.

Table 3.2: Rolling Stock Active on ProRail Network

Sprinters	Intercitys	International Transport and High Speed Trains
SLT (4 or 6 Carriages)	VIRM (4 or 6 Carriages)	Thalys
FLIRT (3 or 4 Carriages)	DDZ (4 or 6 Carriages)	Intercity Direct (ICD)
SNG (3 or 4 Carriages)	ICM (3 or 4 Carriages)	Intercity Express (ICE)
	ICNG (5 or 8 carriages)	IC Brussels
		IC Berlin

Urban Rail System
Table 3.3 shows the main characteristics of the different metro vehicles used by the GVB on the urban rail network of Amsterdam. For this section, the metros that will be used on the Noord/Zuidlijn (M5) will be investigated more in-depth. The Metropolis M5 is a metro vehicle produced by the company Alstom. This metro was purchased for the Noord/Zuidlijn but it can operate on all of the metro lines of the Amsterdam metro network. The website of the supplier of the metros, Alstom provides information about the specific geometric, dynamic and operational characteristics that can be found in Appendix B.2.3.

Table 3.3: Specifications of the Amsterdam Metro Vehicles (GVB, 2018)

Metro-Type	Metropolis (M5)	CAF (M4)	Express Tram (S1 and S2)
Length	116,2 m	30 m	30 m
Width	3,00 m	2.65 m	2.65 m
Weight	190 ton	48 ton	48 ton
Max Speed	70 km/u	70 km/h	70 km/h
Power	4x 4 x 200 kW	6 x 70 kW	6 x 77 kW
Power Supply	750 V	750 V	600/750 V
Seated Capacity	178	66	64
Standing Capacity	782	184	169

The different electrification systems on the metro network of Amsterdam are:

- **Oostlijn (Gaasperplaslijn (53), Geinlijn (54))**: Third rail 750 Volt
- **Amstelveenlijn (51)** This is a tram/metro combination with: Third rail 750 Volt between the central station and station Zuid and an overhead line of 600 V between station Zuid and Westwijk
- **Ringlijn (M50)**: Third rail 750 Volt
- **Noord/Zuidlijn (M52)**: Third rail 750 Volt

Even though most of the lines are powered via a third rail, all of the GVB rolling stock is equipped with a collapsible pantograph. This is used in the maintenance yard, where power is supplied via an overhead line (750 V).

3.5. Stakeholders

When the integration or interoperability of two systems is up for discussion, technical aspects are not the only things that could be an issue. The different stakeholders and political interests will also play a role.

Train System
ProRail is responsible for the railway network in the Netherlands: construction, maintenance, management and safety. ProRail divides the available slots on the track, arranges all train traffic, builds and manages stations and creates new tracks. They also maintain the existing tracks, points, signals and level crossings.

Other Stakeholders There are multiple carriers that have an access agreement with ProRail and use the track, of which the biggest is the NS, but more parties in passenger traffic, freight traffic and other (non-)railway undertakings are stakeholders in the national network. It is clear that the more stakeholders involved, the more difficult introducing a new player can be. All of the traffic companies want to have the best possible use of the network. If a new player gets involved that is interested in occupying the network for a certain amount of time, it might cause conflict with stakeholders already involved. Transporters need a concession to use the ProRail network. NS has the so called ”Hoofdrailnet” (mainline rail network) concession. Formally, the concession holder of the mainline rail network (the Ministry of Infrastructure and Water Management) has to grant permission to all new players on the network.

Urban Rail System

For the metro network of Amsterdam, the organizational structure differs from the national railway network. The GVB owns the concession of the Amsterdam area and is also the operator on the lines.

For the build of the Noord/Zuidlijn, the lead is the Municipality of Amsterdam, more specifically the departments Metro and Tram and Metro- and Tram-network. These departments are assisted by several contractors and engineering firms for the build.

3.6. Network

This section will go more in-depth on the network characteristics of the system, like the different network levels present, their stop patterns and the network capacity.

Train System

For trains, there are minimal stopping times at each station that are shown in Table 3.4 (Hofstra et al., 2016): These stopping times are purely based on technical vehicle characteristics.

Table 3.4: Station Stopping Times

Train Type	Min. Stopping Time
High-Speed line	2 min
Intercity	0,9 min
Sprinter	0,7 min

The minimum station time stated above are scheduled at small stations. At larger stations more time is needed for (de)boarding and transferring passengers, therefore 1 minute of buffering is added. This buffer time can also be used to absorb delays. Examples of stations where this buffer time is added are Amsterdam Central and Amsterdam Zuid (full list in Appendix B.1.5).

A standard time of 2 minutes applies to cross-platform connections, for a cross-platform connection between two Intercity trains 3 minutes is used, for non cross-platform connection a standard of 6 minutes is applied.

The times allowed to reverse passenger trains, a time between 10 and 15 minutes is sought. If necessary, a shorter turnaround time of at least 4 minutes can be used. On the main rail network this can only be done if there is a switch operator, on regional lines it can also be done without the switch operator (Hofstra et al., 2016).

The time tabling for the Dutch rail has a base that is called the Basic Hour Pattern (Basis Uur Patroon), a timetable that repeats every 60 minutes. To this base the extra trains in peak hour are added, in the evening, at night and in the weekend other deviations might occur. More about this Basic Hour Pattern can be found in Appendix B.1.5.

Urban Rail System

This section will describe the different network characteristics of the different lines of the Amsterdam metro.

Line 50 has 20 stations and an average speed of 36km/h, line 51 has 29 stations and an average speed of 30 km/h, line 53 has 14 stations and an average speed of 34 km/h, line 54 has 15 stations and an average speed of 33.2 km/h. All of the lines mentioned above have the same frequency table as can be seen in Table 3.5.

Table 3.5: Frequencies lines 50, 51, 53, 54

Peak Hour	Peak Hour Vacation	Off Peak	Off Peak Vacation	Evening	Evening Vacation	Saturday and Sunday	Saturday and Sunday Vacation
8/hour	6/hour	6-8/hour	4/hour	4-6/hour	4/hour	4-6/hour	4/hour

Because the Noord/Zuidlijn is not in operation yet, the timetabling is not entirely sure yet. For the first couple of months of operation, the timetable will be less frequently than planned due to safety issues. The desired frequencies are shown in Table 3.6.

Table 3.6: Frequencies Noord/Zuidlijn

Peak Hour	Peak Hour Vacation	Off Peak	Off Peak Vacation	Evening	Evening Vacation	Saturday and Sunday	Saturday and Sunday Vacation
12/hour	12/hour	12/hour	8/hour	12/hour	8/hour	12/hour	8/hour

A rule of thumb of 20 seconds applies to the stopping time at stations for metros of the Amsterdam metropolitan region (Garritsen et al., 2017).

3.7. Compatibility Issues

Now that the systems at hand have been analysed, an assessment of the compatibility issues that the systems have can be made. For this, every characteristic discussed previously will be addressed, and a judgement will be made if a compatibility issue is present.

3.7.1. Infrastructure with Rolling Stock

First the compatibility issues between the infrastructure and the rolling stock will be discussed.

Track Gauge

Track gauge is not a compatibility issue, the track gauge of both systems is 1435 mm.

Rail Profile with Wheel Profile

This compatibility issue here is the wheel-rail interface: the wheels of the vehicle must be suitable for the infrastructure (rails, turnouts and crossings). The Dutch railway system mainly have the 54 E1 profile and the metro system of Amsterdam has the 49 E1 Profile. Usually, metro wheels are smaller and narrower than train wheels. This means that when trains ride the metro infrastructure, no compatibility issues will arise, but the metros have a higher chance of derailment due to their wheel characteristics, especially at turnouts and crossings. The cause of the compatibility issue of the rail profile is shown visually in Figure 3.8.

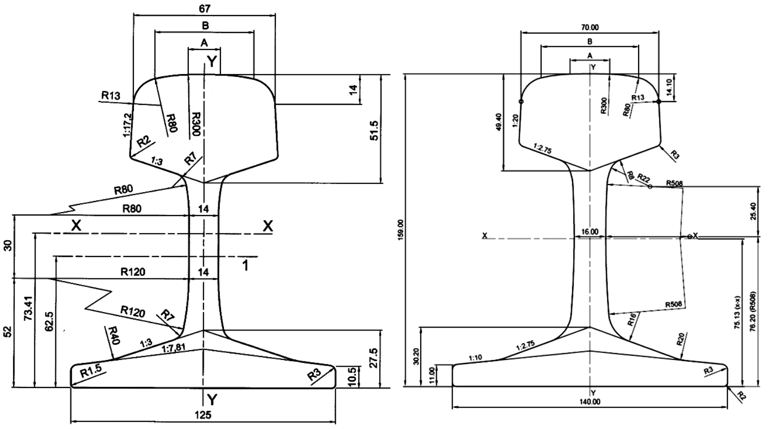


Figure 3.8: Rail Profile Comparison 49 E1 (left) and 54 E1 (Right) (Nederlands Normalisatie Instituut, 2018)

Axle Load

On the ProRail network, a minimal load gauge of C2 is permitted throughout the network, this equals 20 tonnes of 6,4 tonne/meter. The M5 metro has an axle load of 12 tonnes, so this will not present a compatibility issue.

On the GVB metro network, a maximum axle load cannot exceed 12 tonnes or 2 tonne/meter. All of the NS rolling stock has an axle load higher than this, so this would present an compatibility issue.

Load Gauge with Geometric Characteristics

The minimal load gauge for the ProRail network around the Amsterdam Metropolitan Region is NL1 or NL2, the M5 metro fits within these norms.

The dimensions of the load gauges for the Amsterdam metro show that these will be too small for the rolling stock used by the NS. The maximum dimensions of the vehicles used on the metro network when compared to the NS vehicles show compatibility issues. The width of the metros used in Amsterdam is 3005 mm, the height is 3770 mm, this means that width wise, no issues would arise, but the height of the NS material would be an issue.

Radius of Curvature

The radius of curvature will not present a compatibility issue *if* the rolling stock does not exceed the maximum speed at the route sections.

Power Supply with Electrical Traction System

The ProRail network and NS trains have a traction system of 1500 V DC supplied by an overhead line. The Amsterdam metros use 750 V DC via a third rail except on line 51 which is partially supplied with 600 V DC via an overhead line. All of the GVB rolling stock has a collapsible pantograph, none of the NS trains have a shoe collector for a third rail.

The power supply will be a compatibility issue.

Stations and Nodes

The platforms alongside the ProRail network are in the process of being adjusted, if the platforms are adjusted, they will have a height of 760 mm + top of rail and a width of 1700 - 1735 mm from the platform to the centre of the track. This means that these platforms will be to low and to wide for the metro rolling stock.

The platforms alongside the GVB network have a height of 1040 mm + top of rail and a width of 1580 - 1623 mm from the platform to the centre of the track. This means that these platforms will be incompatible with the NS rolling stock.

The stations will be a compatibility issue, it will differ per type of rolling stock how this incompatibility will present itself.

Turnouts and Crossings

The turnouts and crossings on the different traces should not present any problems. However, the Hoekse Lijn (see Section 4.1.2) has showed that because the metro uses smaller wheel diameters problems will occur with double slip switches with a ratio of 1:9 (Engelse Wissel) and unguided point pieces. There is a risk of derailment in these cases because the gap at the point part of these crossings is too big for the metro wheels (Schipholt, 1993).

3.7.2. Safety and Communication Systems

Safety on the rail network must always be the number one priority. This section describes the possible compatibility issues that might occur between the two networks. All of the characteristics discussed as part of the safety and communication systems can be led back to the compatibility issues between CBTC and ERTMS (which will be installed on the ProRail network by 2040). These compatibility issues will influence the safety and performance of the overall integrated system and will be discussed here. Currently there are no standards that specify the interoperability of these two systems for urban areas.

A comparison between CBTC and ERTMS Level 2 can be seen in Table 3.7.

Table 3.7: Comparison ERTMS Level 2 and CBTC (Chabanon, 2013)

Characteristics	**CBTC**	**ERTMS Level 2**
Architecture	Wayside, Onboard, Radio Communication, Fixed Transmission Network and Traffic Control Centre (ATS)	Wayside, On board, Radio Communication, Fixed Transmission Network
Train Detection	Train Based	Track Based
Radio	Proprietary or Standard Usually Operating around 2.4 or 5.8 GHz	GSM-R
Level of Automation	High: ATO, UTO (Driver less)	Manual
Headway / Capacity	High: 30 TPH and Higher	Up to 22-24 TPH
Safety Level	High: Vital Safe Train Separation, Continuous Overspeed Protection	High: Vital Safe Train Separation, Continuous Over speed Protection
Interoperability	None	Fully Interoperable
Traffic Regulation Functions (ATS)	Advanced Set of Functionalities Included in the Products	Not Included in the Standard.

The main differences between ERTMS and CBTC are Critical Software (2014):

- **Interoperability** Strongest point of ERTMS. Not yet available for CBTC systems.
- **Flexibility** ERTMS allows for a smoother migration from conventional systems without disrupting the operational services.
- **Automatic Train Operation (ATO)** Available in CBTC systems. It is still in development for ERTMS.
- **Moving block principle** Available in CBTC systems. It allows for shorter headways and, consequently, increasing the capacity. It is still in development for ERTMS (Level 3).

CBTC can conceptually be compared to ERTMS level 2/3, but the Metro infrastructures are way less complex than the railway infrastructures ERTMS was designed for. The difficulty with CBTC systems is that almost every system is different, each supplier has its own solutions whereas ERTMS systems must comply with the Technical Specifications for Interoperability (TSI) issued by the European Railway Agency.

All of the above leads to the conclusion that there will be a compatibility issue between the CBTC system used on the Amsterdam metro and the ERTMS system that will be implemented on the ProRail network.

3.7.3. Stakeholders

The compatibility issues that could arise between stakeholders present on both networks are outside the scope of this research. The goal of this research is to identify how interoperability will influence the performance of the urban rail network. Political issues will not be addressed in performance.

3.7.4. Network

The headways of metro systems are lower than those of regional trains amongst other differences in operational behaviour. If interoperability were to be achieved, the timetables of the two systems could interfere with the capacity of the network at hand. The current timetabling of both the NS and GVB might change, but this will not be seen as a compatibility issue.

The connection of two different networks will be an issue, the two infrastructures are currently not yet connected. The metro network and the train network will have to be connected.

3.8. Conclusions

This chapter aimed to answer the question: *What compatibility issues are there between metro and train systems?*.

Table 3.8 shows what compatibility issues will arise when interoperability between a metro- and train system is the goal. This table consequently answers the first research question. The column Metro →Train tells if a compatibility issue will arise when running a metro on the train track and the column Train →Metro shows if a compatibility issue will arise when running a train on a metro track.

Table 3.8: Compatibility Issues

Characteristic	**Compatibility Issue? Metro →Train**	**Compatibility Issue? Train →Metro**
Track Gauge	No	No
Rail Profile	Yes	Yes
Axle Load	No	Yes
Load Gauge	No	Yes
Radius of Curvature	No (If correct speed)	No (If correct speed)
Power Supply	Yes	Yes
Stations and Nodes	Yes	Yes
Turnouts and Crossings	Yes for 1:9 Double Slip Switch No for all other switches	No
Saftey and Communication Systems	Yes	Yes
Stakeholders	No	No
Network	Yes	Yes

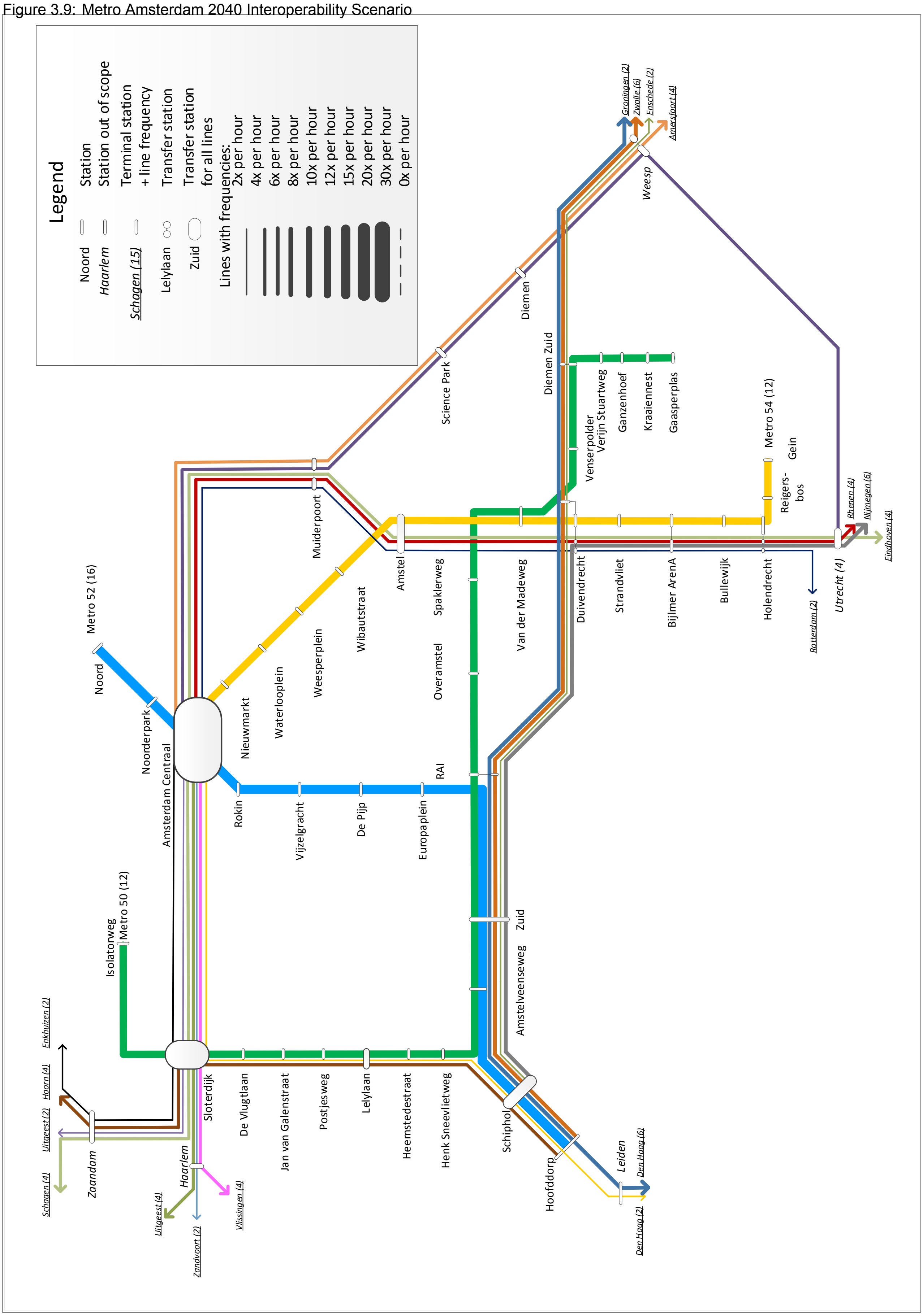
Choice of Interoperability

The compatibility issues that occur between Train →Metro are insurmountable without changing the NS fleet or the GVB infrastructure drastically. The NS rolling stock is for instance too heavy (Axle Load) and too high (Load Gauge) for the GVB infrastructure.

For the remainder of this research the choice is therefore made to focus on the interoperability between Metro →Train. In the next chapter, design alternatives for the compatibility issues stated in the table above will be presented.

Figure 3.9 shows the network of the Amsterdam metropolitan area for the chosen interoperability that will be researched in the remainder of this research. This interoperability entails the continuation of the Noord/Zuidlijn towards Schiphol and Hoofddorp on the mainline train-track.

Figure 3.9: Metro Amsterdam 2040 Interoperability Scenario



4

Design Directions

In the previous chapter, the Dutch national railway system and the metro system of Amsterdam were compared and their compatibility issues were listed. The eventual goal of this research is to gain more insight in the possibilities and advantages of the interoperability of these two systems. This chapter aims to answer the research question: *What design alternatives with corresponding costs and actions are there to overcome these compatibility issues?*

This chapter will begin with a literature research into industry examples of integrated transport systems where two different rail systems have achieved interoperability. The three different systems that will be investigated are: Train, Tram (type of urban rail) and Metro (type of urban rail). Special attention will also be given into systems where interoperability between different safety and communication systems was achieved (namely CBTC and ERTMS).

A study will then be performed to identify possible design directions that can be used to overcome the compatibility issues found in Chapter 3. After that the corresponding costs and actions needed to implement the design directions found will be examined and listed. If more than one design alternative is found, a multi criteria analysis will be performed to choose between the different design directions.

4.1. Integrated Rail Transport Systems

This section will discuss industry examples where interoperability between Trains, Trams and Metros was achieved. Only projects that will provide information and insights interesting for the metro-train interoperability under investigation will be discussed.

4.1.1. Tram - Train

Karlsruhe

The Karlsruhe model, named after the city in Germany where it is implemented, was the first project in a European city where track sharing was implemented for light and heavy rail vehicles. The model is based on the interoperability of trams and trains. For the suburbs and villages around the city of Karlsruhe a direct connection to the city centre is created, using both the (heavy)railway network and the existing tram network. On the mainline network, there is a mix between the (express)trams and regular trains (Phraner, 2002).

The tramline and trainline have different electrification systems in Karslruhe, so the vehicles that used both networks needed to have a dual electrification system. A DC/AC system with on-board transformer and rectifier was chosen. The change between one system to another is carried out automatically and on the move. The height of the pantograph is adjustable, as the height of power tram lines is about 4,7 meters and 5,2 meters for heavy rail. The electrical components needed for this dual electrification system are shown in Figure 4.1, these components are all located in the middle of the train(Inter Connect, 2010).

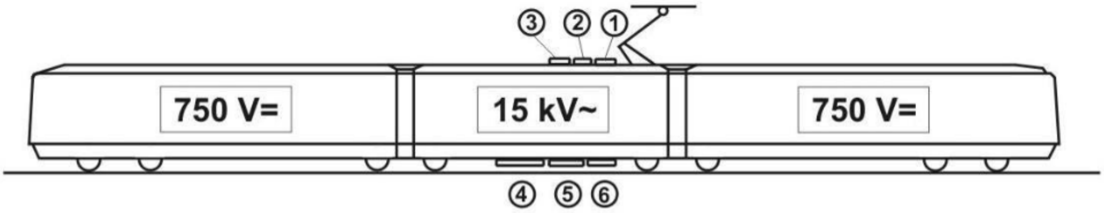


Figure 4.1: Electric components of TramTrain vehicles (Inter Connect, 2010)

1. Disconnecter
2. Sensing device (feeler to identify current voltage)
3. Circuit breaker
4. Transformer (to bring 15000 V to 750 V)
5. Rectifier (to bring AC to DC)
6. Condenser

The electrification wasn't the only incompatibility the two systems had, the safety and communication systems of the two networks were also incompatible. The vehicles that are operative on both networks (trams) are equipped with the necessary equipment to be compatible with the German National Railway (Deutsche Bahn) signalling (Railway Technology, 2018). The interoperability between the two different safety and communication systems still needed more research. Because of the big differences in construction and operation between German tram and heavy railway standards a new operation guideline and standard has been created to make track sharing possible.

Finally, the vehicle-platform interface was designed in a way that enabled safe entering and exiting of the vehicles on different platforms heights and the wheel geometry of the vehicles was optimized for the different rail profiles on the route.

RandstadRail

RandstadRail is a light rail and express bus network in Zuid-Holland that has been in use since 2006. The network links the route of two former railway lines to the tram network in The Hague (with operator HTM) and the metro network in Rotterdam (with operator RET). The rolling stock on the two mentioned railway lines has been replaced by high-speed trams (HTM) and express trams/metros (RET). RandstadRail is a hybrid system of low-floor tram-train-like carriages used between The Hague and the city of Zoetermeer, and high-floor metro-like carriages between The Hague and Rotterdam

For the Randstadrail, alterations and renovations to the infrastructure were necessary. One of the most important changes was the physical disconnection of RandstadRail from the Dutch national railway network. The overhead line voltage has been changed from 1500 V to 750 V. The route is completely separate from the national rail network and any alternating connections were removed. The platforms were also raised by a few centimetres on the The Hague side, resulting in a floor-level entry (Gemeente Den Haag and DSO/Beleid/V&I, 2002). On the stations that were situated on the Rotterdam side, the platforms had to be raised a few centimetres. The five stations that are on both lines and are served by two different types of vehicles, each with a separate floor height, are provided with a platform with height differences. On the The Hague side are low-floor platforms, on the Rotterdam side the high-floor platforms.

The rail profile present on the old mainlines is 54 E1 that is used on all heavy rail sections in the Netherlands, but the metro of Rotterdam has the 49 E1 rail profile. When the line first became operative, the incompatibility in the wheel-rail interface resulted in some stabilization problems of the vehicles when driving on the mainline as the wheels were too conical. The wheels of the vehicles also had more wear when they were driving on the metro network. The wheels of all of the rolling stock were redesigned and grounded on a lathe until a perfect shape for both rail profiles was created. After the alterations no more stabilization issues occurred. The turnouts present on the mainline were also altered slightly to better guide the metro vehicles.

A side note here is that the adjustments made to the wheels initially seemed to be an adequate solution for the Randstadrail, but in the first months of operation the system had nine derailments. As a result of these derailments, multiple investigations were initiated. The goal of one of these investigations was (among others) to identify if the rail/wheel interface could have caused a derailment (Inspectie Verkeer en Waterstaat, 2007).

The conclusion of this research was that the technical aspect that resulted in the derailment of the RandstadRail vehicle was the operation of the specific turnout were the derailment occurred. The turnout on which the derailment took place had previously been damaged. It is presumed that the damage was done to the switch during the construction phase. Immediately before the derailment, the transfer was destroyed by a train. The result was that the next train was wrongly granted permission and derailed due to an incorrect exchange position.

Additional investigation by the Dutch research council for safety resulted in the following conclusion(Onderzoeksraad voor Veiligheid, 2008): “The RandstadRail project was not safe enough to start operation, there were no clear guidelines from the outset to ensure safety and testing as insufficient.”

These conclusions led to the following recommendations to the Ministry of Transport, Public Works and Water Management:

- Make sure that regional rail projects such as RandstadRail are covered by the operation of the Railways Act (article 94).

- Incorporate in the regulations that the Normative Document Safety Light rail is obligatorily used as an instrument for guaranteeing safety

The turnouts at Randstadrail were adjusted and no more incidents have happened since.

To prevent collisions between the trams and other vehicles or persons, various safety measures have been taken at RandstadRail. The maximum speed is limited to 70 km/h. The security system is designed so that the trams automatically brake when the maximum speed is exceeded or when a red sign is ignored. There is a track safety system in place (ZUB 222c) combined with an axle counter system.

The rolling stock used in and around The Hague that is operated by HTM is a light rail tram train vehicle with an overhead line. The metro that runs from The Hague to Rotterdam is operated by the RET and runs partly as an express tram, with electricity supply by means of an overhead line. For the other part the electrification system switches to a third rail and the vehicles continues as a metro. All of the electrification is supplied as 750 V DC.

The RandstadRail has a section where rolling stock operates partly as a tram and partly as a metro partly on existing train infrastructure, so it could also be classified under Section 4.1.2. Train - Metro and under Section 4.1.3 Metro - Tram.

4.1.2. Train - Metro

Hoekse Lijn

The Hoekse Lijn is a project by the Rotterdam City Region to improve public transport. For this project, the existing mainline train route between Schiedam and Hoek van Holland will be changed from a regular railway line to a metro. At the end of the line, in Hoek van Holland, a kilometre of new track is constructed with the new station: ’Hoek van Holland Strand’ (Gemeente Rotterdam, 2018).

What is interesting about this project is that the line will still be used by freight trains that will continue their route at Schiedam on the main railway network of ProRail. This freight transport will only take place outside rush hours and regular passenger trains will not be operative on the new altered line. Electrification on the Hoekse Lijn will be via an overhead line, the voltage of 1500 V that was used for the trains will be lowered to 750 V for the metros. The metros that will operate on this line will have the possibility to switch between third rail electrification and electrification via an overhead line. The freight trains will be powered by diesel engines.

The newly built platforms of the metro stations are designed for a minimum gap width between the metro vehicles and the platform. Freight transport rolling stock is wider than metro vehicles so they would then not be able to pass these platforms. In order to prevent collision between the platform and freight trains a so called “gauntlet track” is constructed next to the stations, see Figure 4.2. This type of track layout will be laid at the stations along the route where freight transport will be operative. This track layout will enable the freight trains to safely pass the stations. The light rail equipment will use the existing tracks. For the distance between the two tracks 470 mm is handled(Rotterdam, 2014).

Figure 4.2: The Gauntlet Track at Schiedam Station (Gemeente Rotterdam, 2018)

The entire route of the Hoekse Lijn follows the existing track but improvements have been made, certain curve radii around platforms were removed to minimize the cant of vehicles during stops. The experience that the RET gained during the Randstadrail was used to determine the best possible wheel-rail interface. The turnouts were also altered slightly to better guide the metro vehicles, the regular freight trains will still be able to use these turnouts.

4.1.3. Metro - Tram

GVB Line 51

Line 51 of the Amsterdam metro network is a metro-tram combination. The route from Central Station to Station Zuid is a metro line, there are no level crossings and the power is taken off via a third rail. At Station Zuid, the pantographs are unfolded, and the system switches to electrification via the overhead line. The metro network has a voltage of 750 V and the tram network has a voltage of 600 V so the vehicles are equipped with a voltage transformer. Figure 4.3 shows the duality in power supply.

On the tram network, the load gauge is smaller: the metro network has a load gauge that is suitable for equipment with a width of 3,00 meters, the tram network for a width of 2,65 meters. To compensate this difference in width, collapsible foot-boards are used on the metro trajectory; these steps are collapsed when the vehicle is on the metro line and folded in when the vehicle is on the tram line.

As a result of the smaller profile, only a specific section of the Amsterdam metro fleet can run on the total line. Four train sets of the S3 series, which are also used on line 50 and are as wide as the trams of line 51, have pantographs and can also run on the Amstelveenlijn (the tram section of the line). Conversely, the express tram equipment of line 51 can be used on all metro lines if necessary.

The metro/tram line 51 is outdated and renovation of the line is planned. The current express tram 51 between Westwijk and Amsterdam Zuid station will be converted into a safe, fast and reliable tram connection with Amsterdam Zuid as the start/final stop. The metro section of the line will continue to exist but with separate vehicles. Rails, crossings , overhead lines and technical systems are renewed or get major maintenance (Amstelveenlijn, 2018).


(a) Line 51 Third Rail (Mauritsvink)

(b) Line 51 Overhead Line (Flyingjoost)

Figure 4.3: Dual Power System Line 51 Amsterdam

RET Line E
Parts of the Rotterdam metro network operate on a network that can be seen as a metro network as well as an (express) tram network. This is achieved by rolling stock that can switch between electrification systems (overhead line and third rail). This is shown in Figure 4.4, Line E is part of RandstadRail. The Randstadrail was already discussed in-depth in Section 4.1.1.


(a) Line E Third Rail (FLJ, 2014)

(b) Line E Overhead Line (Boudewijn Deurvorst)

Figure 4.4: Dual Power System Line E Rotterdam

4.1.4. Safety and Security Interoperability (CBTC - ERTMS)

Istanbul - Marmaray Project
The Marmaray line is a rail project in Istanbul that connects the European and Asian side of the city via a tunnel under the Bosporus.

This project is the first in the world where two different signalling systems are active on the same railway line. The two systems are ETCS Level 1 and CBTC. The ETCS Level 1 system is active for the mainline trains and the CBTC system is used for suburban trains. Both systems are aided by a common wayside signalling subsystem as a back-up(interlocking, wayside signals, train detection etc.)(UIC, 2013). Control for both suburban and mainline trains is done from a single control centre (Siemens, 2014).

The infrastructure is equipped with both types of train control systems. The network consists of a two-way triple track, one part equipped with the ERTMS Level 1 system and used for mainline intercity trains, the other two parts are used for mass transit commuter trains and are equipped with both a CBTC system for passenger service and an ERTMS Level 1 system for the freight transport. The rolling stock of the suburban system are metro trains fitted with CBTC to run with a headway of 90 seconds and mainline trains equipped with ETCS Level 1 with a design headway of 180 seconds (Shirlaw, 2008).

London - Crossrail

The new Crossrail city link that is currently under construction in London is also interesting when it comes to safety systems. The line consists of three sections, all three with a different signalling system (Johnson, 2014). The signalling will be a mixture of ETCS 2 on the western branches, CBTC with ATO on the core and branch (with a possible later upgrade to ETCS), and Automatic Warning System with Train Protection and Warning System (ATW/TPWS, The national signalling system of the UK) on the eastern part.

The rolling stock that will be active on the Crossrail is designed to compliant with all standards required for interoperability including the Technical Standards for Interoperability (TSIs)[1]. The train has ETCS as its core train protection system. In addition to ETCS the trains are equipped with technical modules to support the current English national train protection systems (AWS/TPWS) and also the Siemens Trainguard CBTC system deployed in the Crossrail Central Section. (Network Rail, 2015).

4.1.5. Conclusions

All of the industry examples of rail interoperability discussed in this section provide lessons that can be used in this research. In this section, these learnings will be discussed.

Integrated railway systems and interoperability between railway systems have many advantages. The two most important ones are the broadening of the public transport network without the need for major investments and the minimization of the amount of transfers needed for passengers.

From the Karlsruhe model many lessons can be learned. It is a railway system which used dual electrification, so the rolling stock is equipped with height adjustable pantographs and can operate on 750 V DC and 15kV Ac. The signalling systems are also adaptable to the different rail networks and a new guideline was created to enable track sharing. The wheels of the rolling stock were adjusted in a manner that would allow them to run without problems on both superstructures. The platforms on the Karlsruhe were also adjusted to serve several types of vehicles.

The RandstadRail was created with many references to the Karlsruhe, it has vehicles with dual electrification systems, altered rail profiles and a mix between trams and metros. The main difference is that on the RandstadRail there is no mix with the national railway trains. There are however situations where two different vehicles call at opposite platforms, the height difference is overcome by a low platform on one side and a higher platform on the opposite side. This model shows that government agencies in the Netherlands are willing to look at new and innovative railway solutions.

The Hoekse Lijn is another interesting Dutch project, a section of the national railway section converted to serve metro vehicles. The use of gauntlet track where railway tracks run parallel on a single track next to the platforms to enable freight traffic if necessary could be of use in this research. The metros that will run on this route will also switch between third rail electrification and an overhead line. The mix between the freight traffic and the metros is also interesting when we look at safety and communication solutions.

The Amstelveenlijn (Line 51) of the Amsterdam metro system might be the most interesting of all integrated systems discussed in this section. It shows interoperability by the GVB in the city of Amsterdam, the same operator and city as in the Noord/Zuidlijn case under investigation. It uses different electrification systems and voltages and has expandable foot-boards to compensate for the gauge difference between vehicle and platforms.

What the Marmaray project teaches us, is that interoperability between safety systems is achievable. Interoperability between ERTMS Level 1 and CBTC of an urban rail system is achieved on that line. As ERTMS Level 3 and CBTC are based on the same idea, it is likely that interoperability between these two systems will be also achievable. The same goes for the London Crossrail project where three different safety systems were used on the same track.

Overall it is shown by the different successful industry examples that interoperability between different types of railway systems is definitely possible.

---

[1] TSIs are specifications drafted by the European Railway Agency and adopted in a Decision by the European Commission, to ensure the interoperability of the trans-European rail system

4.2. Design Directions

Now that the compatibility issues that will arise are mapped and industry examples have been investigated, possible design directions can be drafted that will provide solutions to these issues. Design directions will be proposed for metros of the GVB that will run on both their own infrastructure as well as the ProRail infrastructure. The compatibility issues that occur when NS trains use the GVB network will not be addressed (as discussed in the conclusion of Chapter 3).

4.2.1. Rail Profile

The issue of incompatibility due to different rail profiles on the networks in combination with the wheel profile of the rolling stock can be solved by changing the wheel geometry. It is possible to design a wheel profile that ensures safe operation and the necessary alterations to the wheels can be made during the maintenance of the rolling stock to keep the costs low. The points of interest are the depth, width and angle of the wheel with respect to the head from the rails: the rails must be sharpened at the angle the wheel makes.

This type of design alternative was used in the Karlsruhe project, the Randstadrail and on The Hoekse Lijn. Here, the wheels and wheel flange have been altered in a way so that they could operate on different types of rail profiles (tram, train and metro). These alterations do require precise control and maintenance of the wheel sets.

The design solution that is proposed for the issue of derailment risk due to wheels smaller than railway requirements resulting in insufficient guidance in turnouts and crossings is as followed:

- **Technical:** Change the wheels of the metro rolling stock to provide a profile that is suitable for several types of rail. This can be done by alterations (deepening and widening) of the current wheels. And the switches of the heavy rail infrastructure need to be altered slightly so they can serve both metros and trains.

- **Regulatory**: Make sure that correct guidelines are instated that describe rail interoperability.

4.2.2. Power Supply

The incompatibility in power supply lies in the voltage (750 V and 1500 V). All of the GVB metro's are already equipped with a collapsible pantograph necessary on the maintenance yard.

The Karlsruhe model showed an example of how the difference in voltage can be overcome by installing a transformer on the train. There are several other industry examples that show that interoperability of power systems is possible, the Thalys for instance, is currently equipped with three different power systems (25 kV 50 Hz, 1,5 kV and 3 kV).

So the design direction is: Equip the rolling stock with a traction installation suitable for two traction energy systems (750 V and 1500 V). At the transition between two voltage systems a voltage lock is required. Equipment in the vehicle detects the required voltage and ensures switching of the installation. This changeover can take place either whilst driving or at a station,depending on the implementation of the systems. At this changeover, the pantograph must be folded out, and the voltage transformer must be activated.

Equipping the metro infrastructure of Amsterdam with an overhead line is not an option as it wont fit in the load gauge of the network. Equipping the ProRail infrastructure with a third rail is not an option as it wont fit in the geometric characteristics of the trains.

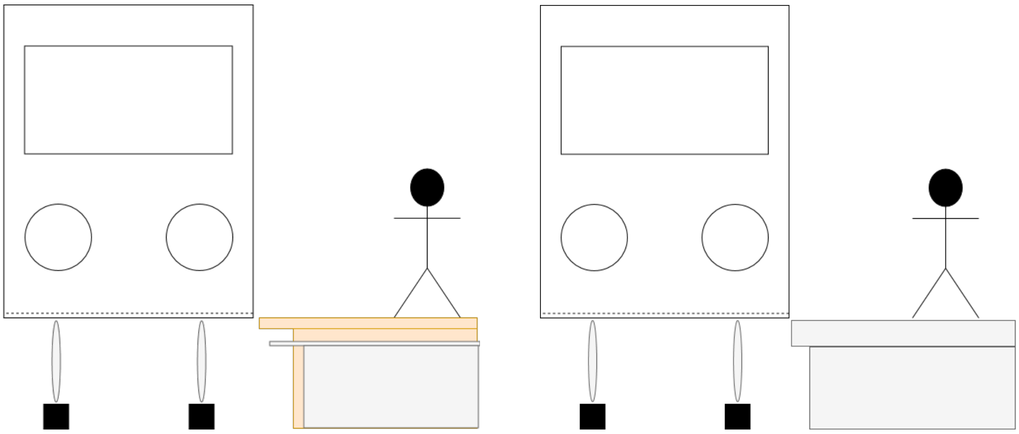
4.2.3. Stations and Nodes

The compatibility issue that needs solving when it comes to the platform geometry's illustrated in Figure 4.5.a, the gap that a passenger would have to cross when getting in and out a metro vehicle on a ProRail platform would be 120 mm wide and 280 mm high.

A design direction could be to raise the platforms along the ProRail network so that they have the right dimensions for the GVB metros. This is shown in Figure 4.5.b.

This has the following advantages and disadvantages:

+ Simple, economic and reliable solution
+ Provides step free access to vehicle
- Platform (and adjacent track) can only be used for metro type vehicles
- Causes difference in platform levels (difficult for cross-platform transfers)



(a) ProRail Platform Dimensions (Grey) Layered on GVB Platform Dimensions (Orange)

(b) Raise Platform

Figure 4.5: Gauntlet Track Options

Another solution could be to equip the metros with a step that allows passengers to (dis)embark the vehicle. Two possible solutions are shown in Figure 4.6.a.

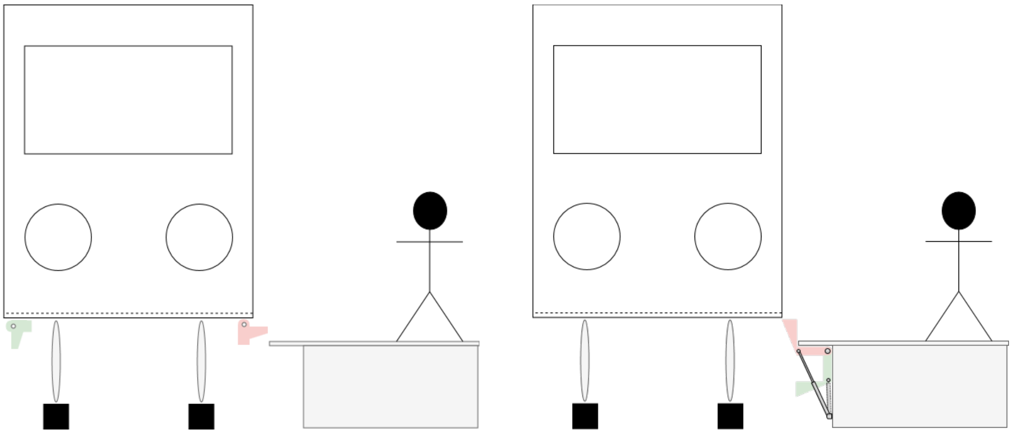
The solution of equipping the metros with a step has the following advantages and disadvantages:

+ Platform (and adjacent track) can be used by both metros and trains (with different dimensions)
+ Steps only need to be folded out once (when transferring networks)
+ Cross-platform transfers are step free
- Mechanical solution that might be prone to defects
- More expensive and complicated solution than raising the platforms

Figure 4.6.b shows a design alternative that consists of adding a step to the platform edge to bridge the gap between the metro and the platform.

The solution of equipping the platforms with a step has the following advantages and disadvantages:

+ Platform (and adjacent track) can be used by both metros and trains (with different dimensions)
+ Cross-platform transfers are step free
- Steps need to be folded in/out every time a different vehicle arrives
- Mechanical solution that might be prone to defects
- More expensive and complicated solution than raising the platforms

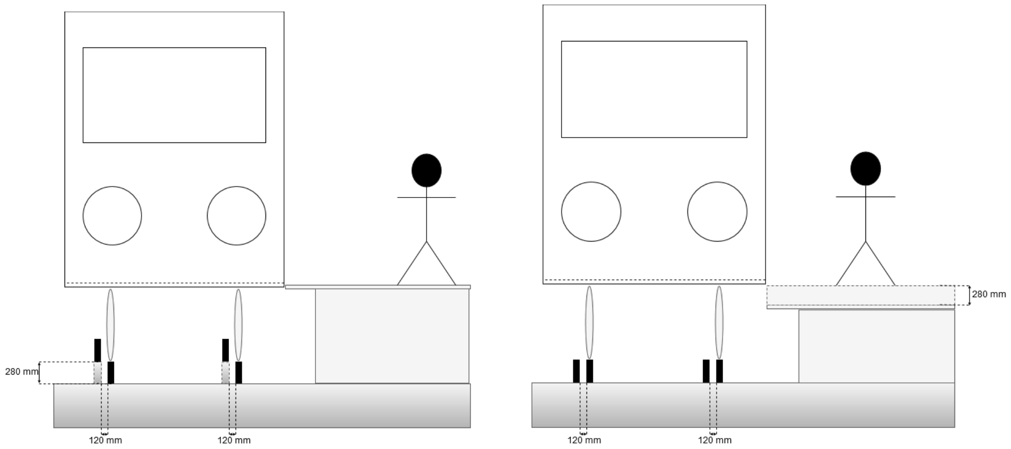


(a) Step Metro (Red=Folded Out, Green=Collapsed)

(b) Step Platform (Red = Folded Out, Green = Collapsed)

Figure 4.6: Step Options

A final design direction that could be chosen is creating a so called "Gauntlet Track" in which tracks run parallel on a single track bed and are interlaced such that only one pair of rails may be used at a time (as was described in 4.1.2 for the Hoekse Lijn). This type of track layout can be used at the stations (Schiphol and Hoofddorp) to minimize the gap between the metros and the platform. It must be said that the difference between the rails (120 mm) is smaller than the base width of the two rail profiles (125 and 140 mm), so alterations to the rail base are needed. The difference in height can be gapped in two different ways, the first, shown in Figure 4.7.a. is to also create a height difference between the two tracks, the second, shown in Figure 4.7.b.is to make a section of the total platform length higher. Figure 4.8 shows a top view of what a gauntlet track layout looks like and Figure 4.9 shows a side view of what raising part of the platform length would look like. Figure 4.10 shows the top view over the track section between Schiphol and Hoofddorp and the influence of the platform alterations. These location of the heightened platforms were chosen to avoid the high-speed trains which use the outer tracks, to spread out the transfer passengers along the track-length at Schiphol, and to ease the turnaround of the metro vehicles at the tail tracks present at Hoofddorp station.



(a) Gauntlet (Horizontal and Vertical)

(b) Gauntlet (Horizontal)

Figure 4.7: Gauntlet Track Options

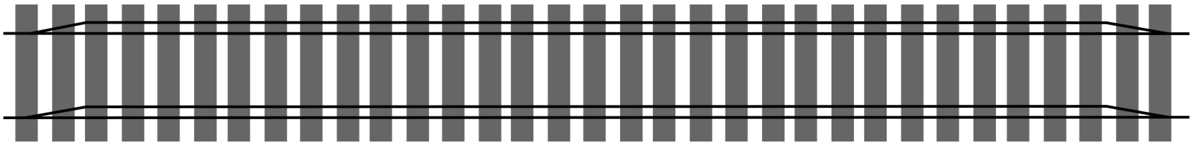


Figure 4.8: Top View Gauntlet Track Layout

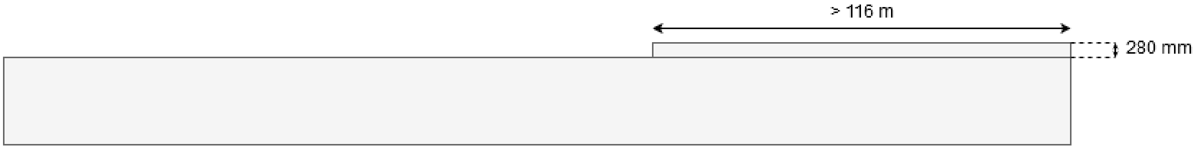


Figure 4.9: Different Platform Heights (Metro Length is 116 m)

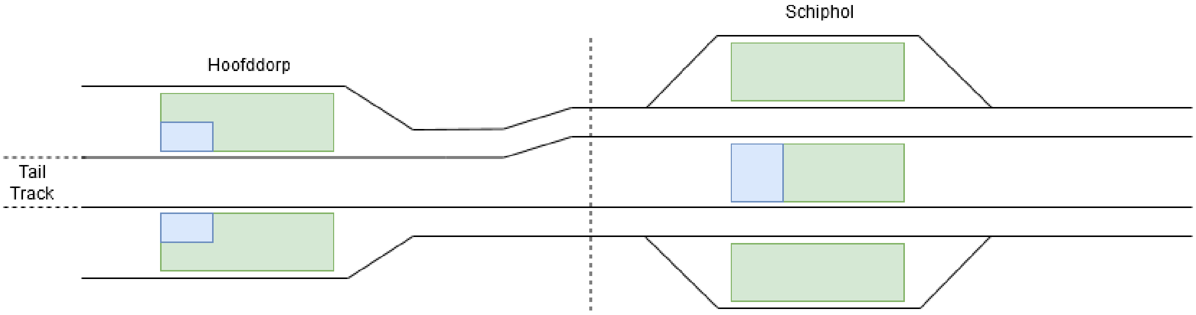


Figure 4.10: Top View Platforms Schiphol and Hoofddorp (Blue = Raised Metro Platform, Green = Normal ProRail platform)

The solution of a gauntlet track with both a vertical and horizontal difference (Figure 4.7.a) has the following advantages and disadvantages.

+ Platform (and adjacent track) can be used by both metros and trains (with different dimensions)
+ Cross-platform transfers are step free
+ Provides step free access to vehicle
- Solution needed for base width of rail
- This type of solution has never been executed

The solution of a gauntlet track with only a horizontal difference (Figure 4.7.b) has the following advantages and disadvantages.

+ Platform (and adjacent track) can be used by both metros and trains (with different dimensions)
+ Provides step free access to vehicle
+ Robust solution
- Solution needed for base width of rail
- Mainline trains cannot use the *full* platform length (<284 on Schiphol, <224 for Hoofddorp)[2] The tracks that will be altered will be able to serve trains up until this length, longer trains need to use the other platforms or using the doors at the altered section of the platform is not barrier free.
- Causes difference in platform levels (difficult for cross-platform transfers)

---

[2] The trains serving Hoofddorp are sprinters (max 270 m), the trains serving Schiphol are sprinters, Intercity's (max 400 m) and international trains (max 400 m).

Some of the design solutions proposed for the gap between the vehicle and the platform were immediately seen as not feasible by the industry specialists, the reasons for infeasibility were the following:

- Step metro (Figure 4.6.a): prone to defects
- Step platform (Figure 4.6.b): prone to defects
- Gauntlet track (horizontal and vertical Figure 4.7.a): no experience and unnecessarily complex

So the design directions proposed for the issue of a gap that is too big to cross due to platform and vehicle dimensions are the following:

- Changing the platform dimensions completely (Figure 4.5.b)
- Gauntlet Track (horizontal) (Figure 4.7.b)

4.2.4. Turnouts and Crossings

The lessons that were learned in the Randstadrail will provide design directions that can be used for sections that contain turnouts and crossings.

As said before about the rail profile, clear rules and standards must be set in place to avoid derailment, slower speeds might be necessary when metro rolling stock is active on the ProRail infrastructure. Double slip switches with a 1:9 ratio must be avoided. Lessons can be learned from the RandstadRail and Hoekse Lijn where slight alterations were made to the turnouts and crossings to better serve both the metros and regular trains.

4.2.5. Safety and Communication Systems

There are currently no standards that define the functional requirements for interoperability between CBTC with ERTMS/ETCS. In the Dutch law there are only sections that describe the interoperability between the mainline national/regional train network with foreign mainline train networks, full interoperability with other rail systems is never discussed. Clear standards will provide metro operators and national railway operators a unified operational concept that will provide maximum safety. This section will describe some of the research already performed on this topic.

The paper by Schmelzer describes a technical proposal for the standardization of CBTC systems based on the ERTMS/ETCS standard. The proposal focuses ERTMS Level 1 (Schmelzer, 2015).

The European research project NGTC (Next Generation Train Control)has the main goal to analyse the similarities and differences of the required functionality of ETCS(Level 3) and CBTC systems, and to determine the achievable commonality level of architecture, hardware platforms and system design(CENELEC, 2014). The results of this research included the following (Gurník, 2016): “The introduction of ATO to the ETCS system will greatly increase the functional interoperability with the urban train control systems. Most of the ATO and ATP functions are present in both the mainline and urban train control systems. There are still differences between both systems, but with more research on the topic, it is expected that a greater functional convergence can be achieved. The convergence between the mainline and urban systems could also be increased by specifying additional functionalities for the mainline network, such as ATS. Performance requirements for the mainline and urban network are not currently comparable due to the different operational requirements of the applications in each network.” The NGTC is part of the Shift2Rail initiative, this is an initiative of the European Union and market parties. It is a good sign that the European Union is making an effort into the creation of standards that will help with the achievement of interoperability. But Dutch law will have to change as well to enable rail interoperability of any kind on the Dutch network.

In the Netherlands, there are laws that describe the use of the mainline railway (Hoofdspoorwet), it is highly unlikely that that the metros of the GVB will comply with all requirements described in this law. It is necessary that an exemption to this law will be made for the track section where trains and metros will be operating side by side.

All of the above mentioned shows that effort is definitely being made to create a standard that describes the interoperability between ERTMS and CBTC. However, many more hours of research need to be performed by the parties involved to create a common (European) standard and new Dutch laws.

If extra research will result in a conclusion that CBTC and ERTMS systems cannot function together properly enough to meet all of the safety requirements, another design direction is to equip the GVB Rolling stock with a double safety and communication system. The metros will have two systems, the one that is already present that can communicate with the CBTC infrastructure, and one that can communicate with the ERTMS/ETCS infrastructure. This will result in metros that can be operative on both infrastructures.

The design alternatives for the compatibility issues between the safety and communication systems are the following:

- Create interoperability between CBTC and ERTMS Systems
    - More research has to be performed into CBTC and ERTMS interoperability, with the focus on the Alstom CBTC system.
    - A (European) standard must be drawn up that describes this interoperability
    - A Dutch law will have to describe the exemptions to the safety rules on the track section where interoperability is to be achieved
- Equip the GVB Rolling stock with the correct ERTMS (Level 2) security system that would enable switching between the two systems.
    - Alstom provides this solution for their vehicles
    - A Dutch law will have to describe the exemptions to the safety rules on the track section where interoperability is to be achieved.

The first seems like a more elegant solution, no extra hardware, but alterations to the software. But it does require research and the creation of standards, all of which have to be created before 2040.

4.2.6. Network

The design direction for this issue is fairly straightforward, a design must be created to connect the metro infrastructure with the rail infrastructure.

4.3. Costs and Actions

Now that the different design alternatives have been inventoried, the necessary actions and costs to realize them can be estimated. This will illustrate the amount of time, effort and money that will be involved with enabling interoperability between metros and trains on the track section between Amsterdam Zuid and Hoofddorp.

4.3.1. Rail Profile

The design solution proposed for the issue of the risk of derailment due to wheels smaller than railway requirements resulting in insufficient guidance in turnouts and crossings is:

Change the wheels of the metro rolling stock that provide a profile that is suitable for several types of rail. This can be done by alterations (deepening and widening) to the wheels of the metros.

These alterations can be performed during the planned big maintenance, the costs for this can be seen as negligible as they will be part of the maintenance costs and all of the necessary equipment is already present in the maintenance yard of the GVB.

The regulatory changes needed are discussed later on in 4.3.7.

4.3.2. Power Supply

The design direction chosen to deal with the compatibility issue of the power supply is to equip the metros of the Noord/Zuidlijn with a dual traction system. There are two options: refurbishment of the current metro fleet, or have the dual system included in every new metro vehicle that is purchased for the Noord/Zuidlijn. Industry experts at the GVB predicted that the costs would not differ that much between a pre-installed electrification system and the costs for refurbishing a metro.

Installing this system on the current metros will cost about €150.000 per metro. To alter the current fleet of 28 metros would cost **€4.200.000**.

4.3.3. Stations and Nodes

Only the feasible solutions for the compatibility issue concerning the platforms will be discussed, being raising the entire platform (Figure 4.5.b) or using a gauntlet track with a partially heightened platform (Figure 4.7.b-4.10)

Raising Platforms

The costs needed for raising the platform include the following:

- Remove hardening = €30/m
- Unearthed soil = €15/m
- Replacing cables and pipes = €22,50/m
- Remove platform wall = €50/m
- Installing the platform wall on soil improvement (new) = €350/m
- Application of sand (new) = €37,50/m
- Application hardening (new) = €25/m
- TFP[3] by a factor 3

Total appointed direct construction costs is €530/m.

Total investment costs excluding VAT €530 x 3 = €1.590/m. €1.600/m Is used for the investment costs excluding VAT.

Changing the dimensions at Schiphol (platform length = 400m) would cost: €640.000/platform. Changing the dimensions at Hoofddorp (platform length = 340 m) would cost: €544.000/platform.

Because the metro will run in two directions, at each station two platforms will have to be altered to serve the metros. This will lead to the total costs of: **€2.368.000**.

A result will be that at Schiphol there will be four platforms left for train operation and two at Hoofddorp.

Gauntlet Track

The costs needed for installing a gauntlet track include the following:

- Track costs = €550/m
- Turnouts = €150.000/turnout
- Raising the platform = €530/m

At Schiphol station the total platform length is 400 meter, if 200 meter of this platform would be appointed for metro stops this would result in a total appointed direct construction cost of: €516.000 per platform. Total investment costs (excluding VAT) would be: €1.548.000/platform.

At Hoofddorp station the total platform length is 340 meter, if 200 meter of this platform would be appointed for metro stops this would result in a total appointed direct construction cost of: €516.000. Total investment costs (excluding VAT) would be: €1.548.000/platform.

Because the metro will run in two directions, at each station two platforms will have to be altered to serve the metros. This will lead to the total costs of: **€6.192.000**.

---

[3] TFP (Train Free Period) A predetermined period in which the railway infrastructure is temporarily taken out of operation due to (maintenance) work on the track.

4.3.4. Turnouts and Crossings

On the section of the mainline track where metros will be operative, all of the double slip switches will be avoided as a precaution, this will not be a problem as there are no double slip switches between Amsterdam Zuid and Hoofddorp Station (see Figure D.1. in Appendix D). Alterations to the present turnouts and crossings are also necessary, these alterations will cost around €30.000 per turnout on the mainline rail this concerns 2 crossings meaning **€60.000**.

4.3.5. Safety and Communication Systems

As stated before, the issue of incompatibility between the different safety and communication systems is a very complex one. The design alternative involves more research, the creation of a standard, changes in the law ans possible alterations to the rolling stock.

To get an idea of the costs involved when the rolling stock will have to be equipped with a system that is compatible with ERTMS, several industry examples were used:

- The existing metro infrastructure of Amsterdam was recently completely equipped with CBTC, the existing rolling stock that was not compatible with CBTC yet, was renovated. The costs for the total project of renewing all of the safety and communication systems of the Noord/Zuidlijn was 188,3 million, of which 9,3 million was reserved for the alterations to the 62 metro vehicles, resulting in €150.000 per vehicle (Gemeente Amsterdam, 2017).

- Large parts of the Dutch network will be equipped with ERTMS, so the NS trains have to be made compatible with this system. The costs of equipping an existing train with ERTMS are around €300.000 (around 15% of the cost of the entire locomotive)(Europeese Rekenkamer, 2017).

- If the rule of 15% of the entire metro price is used, the costs would be 15% of €6.000.000 resulting in €900.000 per metro.

The average of the numbers above results in €450.000 per metro. So the estimated costs of equipping the the 28 metros that are currently operative on the Noord/Zuidlijn with ERTMS would be **€11.250.000**.

It is more difficult to estimate the costs that will be involved with creating a new standard. The NGTC project[4] started in 2012 with a budget of €11 million aiming to produce a European standard that embraces ATO, DTO (Driver less Train Operation) and UTO (Unattended Train Operation) requirements. The costs for the creation of this standard will be left out of scope for this research as they are based on knowledge gained.

If the interoperability will be described in a standards, some software alterations will still be necessary to the metro rolling stock, these costs are estimated at €100.000 per metro. To alter the current fleet of 28 metros this would cost **€2.800.000**.

Achieving full interoperability between CBTC and ERTMS seems to be the most elegant solution but it does require additional research which will cost a lot of time and money. It is difficult to say if this interoperability between these systems will be achieved and will be described in a standard by 2040 or at all. So the risks in this design alternative are high because it might not be feasible.

4.3.6. Network

A design must also be executed to connect both of the infrastructures after station Amstelveenseweg to the mainline rail, this will also consist of new turnouts and infrastructure, the costs for this project are be estimated at **€43.000.000** as calculated in Table 4.1.

---

[4] Discussed in section 4.2.5

Table 4.1: Price Estimations for Connecting Infrastructures

Component	Amount	Unit Price	Direct Construction Costs	Indirect Construction Cost	Investment Cost
Turnouts	6	€175.000	€ 1.050.000	€1.680.000	€2.688.000
Rail	1400 m	€550	€770.000	€1.232.000	€1.971.200
Overhead Line	1400 m	€340	€476.000	€761.600	€1.218.560
Safety System	60%	€770.000	€462.000	€739.200	€1.182.720
Cables and Pipes	1400 m	€50	€70.000	€112.000	€179.200
Connection Traffic Management System	1 Post	€500.000	€500.000	€800.000	€1.280.000
Groundwork	2700 m^3	€20	€54.000	€86.400	€138.240
Earthwork	400 m^2	€3.000	€12.000.000	€ 19.200.000	€30.720.000
Adapt Overhead Line	2 Times	€150.000	€300.000	€480.000	€768.000
Soundproofing	600 m	€2.000	€1.200.000	€1.920.000	€3.072.000

4.3.7. Rules and Regulations

The focus of this research is on the technical incompatibilities between the metro rolling stock and the train infrastructure. However, a big issue that arises when talking about this interoperability, is the regulatory one. This section describes the steps that should be taken on this front and can be seen as a part of safety as a boundary condition.

Currently there are no standards, laws or regulations anywhere in the world, that describe the type of interoperability that is the subject of this research. Almost every design solution created for the technical compatibility issues that arise, requires an additional regulatory solution that describes which requirements this technical solution must meet. This standard will have the goal to provide guidance on the technical and regulatory issues that need to be resolved before track sharing is permitted and will have to cover (Griffin, 2001): the wheel set geometry and vehicle suspension requirements, crash worthiness, braking system performance, vehicle gauging requirements, the visibility and audibility of vehicles, overhead electrification warnings, requirements for heavy rail vehicles that share tracks with light rail vehicles, signalling systems, station design, line side signing, rule book requirements, radio systems, electrical power supplies and the safety of people on or near the line.

All of the non-technical compatibility issues are out of scope for this research, but they have to be mentioned nonetheless. Laws about rail-use will have to change, standards need to be drafted and statements that describe the use of the railway-network need alterations.

For the remainder of this research, these costs and actions will not be taken into account, but they must not be forgotten. If the changes to the rules and regulations will not happen, interoperability can not be achieved.

4.4. Decision on Design Alternatives

The previous section aimed to give insight in the different costs and actions necessary to achieve the interoperability between metros and train infrastructure. For two design alternatives there were multiple design directions so a decision has to be made on the best possible design alternative.

4.4.1. Criteria

The different criteria that the design alternatives will be assessed on are the following:

- **Costs** The total costs involved with implementing this solution.
- **Reliability** A reliable system performs its intended function when conditions are normal.
- **Robustness** Designed or evolved in such a way as to be resistant to total failure despite partial damage. A robust system is likely to have a higher reliability than a system that is less robust.
- **Experience** Has this design alternative already been implemented somewhere (successfully)?
- **Risks** The chances of this solution not being successful or implementable, different per topic, further described per design alternative (a minus means a negative result e.g. a higher risk).

4.4.2. Analysis

In this section, only the compatibility issues with multiple design alternatives will be discussed. Only two compatibility issues had multiple feasible design directions, the platform dimensions and safety and communication systems.

Stations and Nodes

1. Raise the platforms
2. Gauntlet Track

Table 4.2: Multi Criteria Analysis Station Dimensions

	Unit	Raise Platform	Gauntlet Track
Cost	€	2.368.000	6.192.000
Reliability	- -/++	++	++
Robustness	- -/++	++	-/+
Experience	- -/++	++	+
Risks	- -/++	- -	++

- **Reliability** The reliability of both design alternatives is the same, if proper installed, no issues should occur during normal operation.
- **Robustness** The solution of the gauntlet track is less robust due to the two added turnouts and because this solution has not been applied that much in mainline rail systems.
- **Experience** The gauntlet track has been applied in the Netherlands, but there is more experience with the simple heightening of a platform.
- **Risks** The risks in Table 4.2 represent the fact that the design alternative of raising the platforms would mean that these platforms would no longer be usable for the NS rolling stock. This could result in major difficulties for the two stations which will be able to serve a lot less trains than they currently can. Schiphol would go from 6 platforms serving trains to 4 and Hoofddorp from 4 to 2. The advantage that the gauntlet track has in still enabling all train operation on all platforms is so important, that this design direction will be chosen to solve the incompatibility issue of platform and rolling stock dimensions.

Safety and Communication Systems

1. More research into CBTC-ERTMS interoperability and the creation of a European standard that describes this interoperability
2. Equip metros with ERTMS system

Table 4.3: Multi Criteria Analysis Safety and Communication Systems

	Unit	Research + Standard	Metro with ERTMS
Cost	€	2.800.000	11.250.000
Reliability	- -/++	-/+	++
Robustness	- -/++	-/+	++
Experience	- -/++	- -	+
Risks	- -/++	- -	+

- **Reliability** The reliability of the creation of the standard has been graded as average because CBTC/ERTMS interoperability has not been achieved yet and it is not sure how reliable such a system will be.
- **Robustness** For the same reason as with the reliability the robustness for the standard has been described as average.

- **Experience** There is no experience with CBTC/ERTMS interoperability and there is no standard that describes this interoperability. But there are also no metro's (in the Netherlands) that have ERTMS, however Alstom does provide this function on their vehicles.
- **Risks** The risks here are that the creation of a standard that describes the interoperability between CBTC and ERTMS might not be finished by 2040. Meaning that this design alternative has very high risks. It is expected however, that it is possible to create such a standard in the coming 22 years that describes this interoperability. If by 2038, the standard is still not finished, the choice can be made to equip the metros with ERTMS, with still enough time to alter the entire fleet. The design direction where a standard is created has the preference, with the design alternative of equipping the metro fleet with ERTMS will be used as a back-up solution.

4.5. Conclusions

The goal of Chapter 4 was to answer the following sub-research question: *What design alternatives with corresponding costs and actions are there to overcome these compatibility issues?*

4.5.1. Design Directions

Section 4.1 gave insight into industry examples of rail interoperability that provided lessons that were of use to this research. In section 4.2 these lessons were adapted to draft design directions for the compatibility issues at hand. The different design directions found for the respective compatibility issues are the following:

- **Rail Profile**:
  - Change the wheels of the metros to provide a profile that is suitable for several types of rail. This can be done by alterations to the current wheels. The switches of the heavy rail infrastructure need to be altered so they can serve both metros and trains
  - *and* Make sure that correct guidelines are instated that describe rail interoperability
- **Power Supply**: Equip the rolling stock with a transformer installation suitable for two traction energy systems (750 V and 1500 V)
- **Stations and Nodes**: Use a gauntlet track at Schiphol and Hoofddorp and partially heighten the platforms to accommodate different types of rolling stock.
- **Turnouts and Crossings**: Alter turnouts present and connect the two infrastructures (metro and mainline)
- **Safety and Communication Systems**:
  - Achieve CBTC/ERTMS Interoperability
  - *or* Equip metros with dual safety system (ERTMS as an add-on to CBTC)
- **Network:** Connect metro infrastructure to mainline infrastructure
- **Rules and Regulations**: Laws need to be instated that describe the metro-train interoperability.

All of the changes that need to be made onto the infrastructure can be performed whenever it is most convenient in the coming years. For the alterations necessary to the rolling stock a choice has to be made between either refurbishing the current metro fleet that is active on the Noord/Zuidlijn, or to implement the necessary technical requirements pre-installed in new metros that will be ordered for the Noord/Zuidlijn. The estimation for these costs is exactly that, a rough estimation as little data from the metro supplier is available. The last category, the regulatory changes, is out of scope for this research but is discussed shortly nonetheless. This because without the changes in rules and regulations, interoperability can never be achieved. This research can however be used to emphasize the importance and benefits of the interoperability and be a incentive for the decision makers to start processes that will lead to changes in rules and regulations.

It seems that all of the design directions for the technical incompatibilities are fairly straight forward. They can be achieved by alterations to the infrastructure and the rolling stock. The changes to the rolling stock can be done as refurbishments to the current fleet or they could be included in the program requirements drafted when new vehicles will have to be ordered. If the line will be extended, more metros will be necessary anyway to cope with the capacity.

If full interoperability and seamless rail networks is truly the goal of the stakeholders involved, more effort should be put into the composing of the necessary standards and laws that describe the interoperability between the rail systems. The issues in the safety and communication systems are significant and will take time to overcome.

The design directions described in this chapter (and more design directions to issues between other rail systems) should be included in a standard that will describe the restrictions for rail interoperability between mainline and urban systems. This standard will have the goal to provide guidance on the technical and regulatory issues that need to be resolved before track sharing is permitted and should (at least) cover: the wheel set geometry and vehicle suspension requirements, crash worthiness, braking system performance, vehicle gauging requirements, the visibility and audibility of vehicles, overhead electrification warnings, requirements for heavy rail vehicles that share tracks with light rail vehicles, signalling systems, station design, line side signing, rule book requirements, radio systems, electrical power supplies and the safety of people on or near the line.

4.5.2. Costs and Actions

The second part of the research question was the determination of the costs and actions involved with the found design directions, the result are shown in Table 4.4. For some of the design directions found, the necessary costs cannot be seen as straightforward as the others. Mainly because these costs involve regulatory changes which need to be initiated and executed by the state. These regulatory actions that need to be taken are the more complex part of the solution. The legislation on the route section where interoperability will be achieved will have to change. And also the creation of a standard that describes the interoperability is a tedious process. The costs of creating these laws and standards are difficult to estimate as they are indirect costs that are not based on physical purchases but on knowledge gained.

Also, for the changes needed to the rolling stock, the decision still has to be made whether to change the current fleet of metros, have the changes implemented when new metros are ordered or both. The lifespan of a metro is about 30 years, the design directions to solve the compatibility issues with the rolling stock consist of a lot of alterations to the metros. It is preferred to implement alterations in new metros than to alter the metros when they are already operative for three reasons:

- Installing the necessary technologies from the start is easier than implementing them later.
- No metros will have to be taken out of the rotation
- From a cost perspective, there will be little to no difference.

Total Investment Costs

The total investment cost to achieve interoperability will be anywhere between **€56.252.000** and **€64.702.000**, depending on whether or not full CBTC/ERTMS interoperability will be achieved.

It is interesting to see that the majority of the cost lay in connecting the two networks, more than preparing each individual system for interoperability.

If the above mentioned investment costs are calculated back to one hour of operation for the aspired start date in 2040 assuming:

- Start date in 2040
- Year of 300 days
- 16 Operating hours a day

This would result in an investment cost between **€558** and **€642** per hour of operation.

Table 4.4: Costs and Actions

Compatibility Issue	Design Direction	Costs	Actions
Rail Profile	Change wheel dimensions	X	Alter wheel dimensions
Power Supply	- Dual Traction System	€4.200.000	Equip metros with a transformer to bring 1500 V DC to 750 V DC
Stations and Nodes	Gauntlet Track	€6.192.000	- At the mainline stations, install a Gauntlet track - At the mainline stations, raise part of the platform
Turnouts and Crossings	Alterations to Turnouts	€60.000	Make turnouts slightly wider to better serve metros (trains can still use these turnouts
Safety and Communication Systems	CBTC/ERTMS Interoperability	€2.800.000	- Research into CBTC/ERTMS interoperability - Creation of laws and standards
	Metros with ERTMS	€11.250.000	Equip current fleet with ERTMS or have ERTMS as a standard installed in new metros
Network	Connect Metro Line to Mainline	€43.000.000	Connect Metro Line to Mainline

5

Model

The goal of this research is to gain insight in the possible improvements that interoperability between metros and train infrastructure could have on the performance of a public transport network. To do this, the different issues that obstructed interoperability and design alternatives to overcome these issues were mapped. The next step is to asses how these changes will effect the performance of the urban rail network. This chapter will deal with the research question: *How can the effect of interoperability on the performance of the urban rail network be modelled?*.

This chapter will describe the process of choosing the model that was best suited to answer this question. After the choice for a model has been made the different aspects of the chosen model are highlighted.

5.1. Model Choice

This section will describe the process that was completed in the search of finding the correct model for this research. A model will have to be chosen that best suits the needs of this research and that will help answering the research questions. The different requirements to the model, criteria based on which the models were compared and the eventual model comparison will be dealt with in this section.

5.1.1. Requirements

To determine what model best to use for the research question stated above, the input and desired output of the model are described in Table 5.1 below. The goal is to determine the stopping patterns and frequencies per line and use them to determine the level of performance based on the Key Performance Indicators whilst maintaining the level of safety.

Table 5.1: Model Requirements

Input	KPIs	Decision Variables	Boundary Conditions
Infrastructure: - Stations - Nodes	Accessibility	Stopping Patterns	Safety and Sustainability
Pool of Lines: - Train Lines - Metro Lines - Interoperable Lines	Passenger Satisfaction	Frequencies	
Capacity: -Vehicle Capacity - Infrastructure Capacity	Costs		
Passenger Demand			

5.1.2. Model Comparison

Now that the requirements to the model are clear, different existing models that have similar goals are compared from literature to choose the model best suited for this research. The objective of the model should be the optimization of stopping patterns and frequencies of public transport lines. Table 5.2 shows a comparison between different models that aim to optimize (a combination of) the following variables:

- Route Set
- Frequency
- Stop Pattern
- Line Spacing
- Timetable

The models aim to asses the network on (different combinations) of costs. The Table is based on the information in Appendix D. The models in Table 5.2 were chosen to compare because they are all so called Transit Network Planning frameworks. A Transit Network Planning is a framework to design a public transport network from scratch.

The different criteria on which the models were assessed will be shortly discussed.

Passenger Assignment

This criterion describes how passengers choose their stop. Most of the models use static passenger assignment, where the passengers are assigned to a specific station beforehand. This has as a result that all of the stations need to be served because passengers cannot choose their stop. Only in the research by Merlijn van Beurden (Van Beurden, 2017) passengers are allowed to choose from different stations as access or egress station. This allows for a more dynamic trade-off between operator costs and passenger costs, as not all stations have to be served in order to meet all demand.

Capacity constraints

Capacity constraints that are used are: fleet size, vehicle capacity, link capacity and node capacity. These were chosen because they indicate the limitations of the system.

Demand satisfaction constraints

The demand satisfaction means whether the passenger demand has to be fulfilled. Most models require that the complete passenger demand has to be satisfied or include a penalty for unsatisfied demand.

Multiple services

Multiple services means that some sort of distinguish is made between service levels (e.g. speed, dwell time, capacity etc.). For the studies that assessed multiple services there are two types, studies that pre-determined the routes of each service, and studies that did not. This last type implies rail interoperability as all vehicles that travel on rail have the option to use all of the rail corridors. Every service is allowed to stop at or skip any station that has a rail connection.

Network

The type of network that the specific model is applied to. Either an application to a fictional network or an existing network.

(Correct) Interoperability?

For this research the feasibility of interoperability and the necessary adjustments to the network are of specific interest. None of the models investigate the necessary costs and actions to achieve this interoperability. The research by Van Beurden (2017) does assume interoperability, but does so on all rail corridors and does not mention its feasibility itself. It assumes generalised fictive interoperability, and does not mention any specifics on this interoperability.

Table 5.2: Model Comparison

Model	Passengers can choose their stop?	Capacity Constraints?	Demand Satisfaction Constraints?	Multiple Services?	Network	(Correct) Interoperability?
Ceder and Wilson(1986)	✗	✓	✓	✗	Fictional	✗
Van Nes (2002)	✗	✗	✗	✓	Fictional	✗
Fan and Machemehl (2008)	✗	✓	✗	✗	Fictional	✗
Goosens et al.(2006)	✗	✓	✓	✓	Dutch train	✗
Borndörfer et al.(2006)	✗	✓	✓	✗	None	✗
Lin and Ku (2014)	✗	✓	✓	✓	Taiwan rail	✗
Schmid (2014)	✗	✓	✓	✗	Fictional	✗
Arbex et al. (2015)	✗	✓	✓	✗	Mandl's (1980) benchmark network	✗
Yue et al. (2016)	✗	✓	✓	✓	Chinese network	✗
López-Ramos et al.(2016)	✗	✓	✓	✓	Seville and Santiago	✗
Gu et al. (2016)	✗	✓	✓	✓	Idealized line	✗
Van Beurden (2017)	✓	✓	✓	✓	Fictional& Amsterdam rail	✗

5.1.3. Chosen Model: Stopping Pattern and Frequency Optimization Model (Van Beurden, 2017)

Based on the table above, it can be quickly seen that the research performed by Merlijn van Beurden (Van Beurden, 2017) commissioned by Royal HaskoningDHV and the TU Delft will be the best suited to achieve the goals stated above. What stands out from this model is that passengers' origins and destinations were not fixed to stops, but to zones. These zones are connected to one or more stations via a fixed network that is not part of the optimisation (buses, trams, walking etc.). Therefore, passengers can choose a station, or even use only the fixed network. This freedom in route choice allows passengers to choose alternatives to skipped stations, so the consequences of stopping patterns can be examined adequately.

The main research question of the MSc Thesis for which this model was created was: "Given a public transport passenger demand, a network with multiple services and a set of possible lines, what are the optimal stopping patterns and frequencies for each line, while satisfying capacity constraints?" For the model described in this thesis, the different characteristics are:

- **Decision Variables**: Stopping pattern and frequency
- **Passenger Assignment**: Static and zones
- **Capacity Constraint**: Node capacity, link capacity and vehicle capacity
- **Demand satisfaction constraints**: 100 %, but not all stations need to be served
- **Assessment criteria**: Generalised passenger and operator cost

- **Multiple services considered**: Yes
- **Optimization method**: Genetic Algorithm (Heuristic)
- **Application to network**: Fictional network and the Amsterdam train and metro network

5.2. Model Formulation

In this section, the model that will be used for this research will be described mathematically. The mathematical model formulation, used solver, implementation and validation of the model will be described in more detail. First the different parameters will be introduced, followed by the objective function and the corresponding constraints. The solver that is used for this model is also discussed and finally something will be said about the validity of the model.

5.2.1. Parameters

Table 5.3 shows all of the parameters used in the model (Van Beurden, 2017).

Table 5.3: Parameters (Van Beurden, 2017)

Parameter	Unit	Meaning
N	[]	Set of nodes (OD)
N^s	[]	Set of stations ($N^s \subseteq N$)
N^Z	[]	Set of centroids ($N^Z \subseteq N$)
A	[]	Set of links
A^T	[]	Transit links ($A^T \subseteq A$)
L	[]	Pool of lines
F	[]	Set of frequencies
$t_{a,l}^{iv}$	[minutes]	In-vehicle travel time on link $a(a \in A^T)$ for line l
$t_{z,i}^{walk}$	[minutes]	Walking time from centroid z to station i
$t_{i,l}^{dwell}$	[minutes]	Dwell time of line l at station i
X_s	[]	Number of tracks at station s
θ_s	[]	Number of platforms at station s
k_a	[]	Number of tracks on link $a(a \in A^T)$
y_l	[passengers]	Capacity of a vehicle on line l
$\lambda_{x,y}$	[passengers]	Demand between x and y ($x \in N^Z, y \in N^Z$)
$q_{l,a}$	[passengers]	Passenger occupancy of line l on link a
$\tau_{l,s}^{stop}$	[]	Binary value, line l stops at station s (1) or not (0)
$w_{l,f}$	[]	Binary value, line l has frequency f or not
ϕ_l^{max}	[]	Maximum load factor of a vehicle on line l
Φ_l	[minutes]	Minimum headway for line l
μ	[€]	Costs for unserved demand
β_l^{iv}	[€]	Costs per in vehicle travel minute
β_l^{cr}	[€]	Costs for crowding
β_l^{wait}	[€]	Cots per waiting minute
β^{walk}	[€]	Costs per walking minute
β^{tr}	[€]	Transfer penalty
β_{unsat}	[€]	Unsatisfied demand penalty ($Cost_{pax}^{max}$)
β_l^{disp}	[€]	Costs per dispatched train
β_l^{op}	[€]	Costs per train operating hour

5.2.2. Decision Variables

Table 5.4 shows the decision variables of the model(Van Beurden, 2017).

Table 5.4: Decision Variables (Van Beurden, 2017)

Decision Variable	**Units**	**Meaning**
$f_l(w_{l,1}, ..., w_{l,f})$	[veh/hr]	Frequency of line l
$s_l(\tau_{l,1}, ..., \tau_{l,n}$	[yes or no]	Stopping pattern of line s

5.2.3. Objective Function

In the objective function, the sum of passengers (Access-, Waiting, In-vehicle and egress-times combined with a transfer penalty) and operator cost (Fixed- and Variable- Costs) are minimized. Each of the costs depend on the input of the model and a number of variables that follow from the solution or the assignment model, which will be explained in the following sections.

The input of the model is the network of the city of Amsterdam (study area). Within the study area there are different area's, and each area has a centroid with a passenger demand (Origin-Destination). For the passengers that need to travel out of or in to the study area, the passenger demand is accumulated at so-called gates at the edges of the network. The study area has two types of transport networks: the underlying network that is not optimized (buses, walking etc.) and the network to be optimized that consists of the rail infrastructure under investigation (metros and trains).

So in short, the network consists of a set of nodes N and a set of links A. Nodes can be either stations (N^s) or centroids (N^Z), links can be either transit links (A^T) or walking links (A^W).

This leads to the following objective function:

$$min\Big\{\text{Access time + Waiting time + In-vehicle time + Transfer Penalty + Egress Time}$$

$$\text{+ Unsatisfied demand penalty + Fixed Costs + Variable Costs}\Big\}$$

With all parameters this leads to:

$$\begin{aligned}
min\Big\{ & \sum_{z \in N^Z} \sum_{i \in N^s} \beta^{walk} \cdot t^{walk}_{z,i} \cdot q_{z,i} + \sum_{l \in L} \beta^{wait}_l \frac{30}{f_l} \cdot q_l \\
& + \sum_{l \in L} \sum_{a \in A^T} \beta^{iv}_l \cdot t^{iv}_{a,l} \cdot q_{a,l} + \sum_{l \in L} \beta^{tr}_l \cdot q^{tr}_l \\
& + \sum_{j \in N^s} \sum_{z \in N^Z} \beta^{walk} \cdot t^{walk}_{j,z} \cdot q_{j,z} \\
& + \left(\sum_{x \in N^Z} \sum_{y \in N^Z} \lambda^{unsat}_{x,y} + \sum_{l \in L} max(0, f_l \cdot y_l - q_l) \right) \cdot \beta_{max} \\
& + \sum_{l \in L} \sum_{a \in A^T} \sum_{s \in N^s} \beta^{fix}_l \cdot \left\lceil \frac{(t^{iv}_{a,l} + \tau^{stop} \cdot t^{st}_{l,s} + t^{layover}_l)}{60} \cdot f_l \right\rceil \\
& + \sum_{l \in L} \sum_{a \in A^T} \sum_{s \in N^s} \beta^{var,time}_l \cdot (t^{iv}_{a.l} + \tau^{stop} \cdot t^{st}_{l,s} + t^{layover}_l) \cdot f_l \\
& + \sum_{l \in L} \sum_{a \in A^T} \sum_{s \in N^s} \beta^{var,dist}_l \cdot t^{iv}_{a,l} \cdot t^{iv}_{a,l} \cdot v_l \cdot f_l \Big\}
\end{aligned} \tag{5.1}$$

5.2.4. Constraints

The objective function described above also has to meet a couple of constraints which are described below. These constraints need to be met in order to ensure that the solution is feasible on the network.

Stopping Pattern

Each line set between two points (back and forth) needs to be symmetrical of each other, meaning that back and forth need to stop at the same stations.

$$s_{l,i,j} = s_{l,i,j} \forall l \in L, i \in N^s, j \in N^s \tag{5.2}$$

Frequency

For the frequency the same reasoning as for the stopping pattern applies, each line set has to have the same frequency back and forth.

$$f_{l,i,j} = f_{l,i,j} \forall l \in L, i \in N^s, j \in N^s \tag{5.3}$$

Each line set can also have only one frequency, meaning that lines cannot run both 2 and 4 times per hour.

$$\sum_{f \in F} w_{l,f} = 1 \forall l \in L \tag{5.4}$$

Link Capacity

The capacity entails that the total time needed for all services to pass a point on a link cannot exceed the available time of sixty minutes per track.

$$\sum_{l \in L} \Phi_l \cdot f_l \leq 60 \cdot k_a \forall a \in A^T \tag{5.5}$$

Node Capacity

The capacity of a node is twofold: all vehicles need to be able to pass a node, similar to the capacity of the link, and there needs to be enough “platform time” for all the trains that stop at that node.

$$\sum_{l \in L} \tau_{l,s}^{stop} \cdot (t_l^{dwell} + \Phi_l) \cdot f_l + (1 - \tau_{l,s}^{stop} \cdot \Phi_l \cdot f_l \leq 60 \cdot X_s \forall s \in N^s \tag{5.6}$$

$$\sum_{l \in L} \tau_{l,s}^{stop} \cdot (t_l^{dwell} + \Phi_l) \cdot f_l \leq 60 \cdot \phi_s \forall s \in N^s \tag{5.7}$$

Demand Satisfaction

Altering stopping patterns may cause certain centroids to become disconnected. The demand from and to this centroid will then not be served, leading to unsatisfied demand. It will not be enforced that all demand needs to be served. Instead, each passenger that cannot reach its destination will get the highest generalised travel cost that was observed in the original network (μ), which will be added to the passenger costs.

5.2.5. Solver

The optimization of the stopping patterns and frequencies uses a heuristic genetic algorithm. A genetic algorithm follows the concept of evolution to improve solutions, in which the strong “parent” solutions mate to produce even stronger “children” solutions. This method, based on biology, has been used in most of the researches in Table 5.2. A set of likely start solutions is used to minimize the running time. It is important to note that an optimal solution is not guaranteed with this type of solver, it is possible that the solution is a so called sub-optimal solution, meaning that more optimal solutions are present. A longer running time of the model does limit the chances of the final solution being a sub-optimal one.

5.2.6. Implementation

The model is implemented using the programming language Ruby(Ruby, 2018) and the passenger assignment software OmniTRANS (DAT.Mobility, 2018).

The input for the model consisted of the network topology, the track and station infrastructure and its capacities, track alignments, a pool of lines to be optimized, potential stations per line, an origin-destination matrix, and a fixed underlying network (Van Beurden, 2017). This fixed underlying network was created with an adapted version of the public transport model of the Amsterdam Metropolitan region, the Verkeerskundig Noordvleugelmodel (VENOM) (Vervoerregio Amsterdam, 2016). This network consists of the public transport network as it is modelled in the VENOM2016 public transport model, scenario 2040 High, with some adaptations. The biggest difference is that all bus lines that do not reach the study area (Amsterdam Metropolitan Area) have been eliminated, as well as all links outside the Amsterdam metropolitan area that do not carry a relevant transit line. The passenger demand in to and out of the study area is modelled by the aggregation of zones without OV link to Amsterdam at stations on the edges of the study area.

5.2.7. Validation

For the research by Van Beurden it was difficult to safeguard the validity, this because the outcome of the model is a combination of both operator and customer costs for 1 hour of morning peak rush hour traffic in the year 2040. These numbers could not be verified but this section gives some explanation about how the validity of the model could be explained.

The research by van Beurden describes how the validity of the model was checked by a series of numerical experiments on a smaller test network.

The model created was based on the public transport model of the Amsterdam Metropolitan region. VENOM is an initiative of fifteen partners in the Amsterdam Metropolitan Area (regions, municipalities and provinces) and is an arithmetic tool with which effects of projects, measures and policies on the available space, mobility and infrastructure can be investigated. All partners within VENOM have their own data (regional networks, socio-economic data (inhabitants, jobs, etc.), matrices and traffic counts) which help building the model. By combining the regional and local models, the consistency of the model is improved. The VENOM model is validated and calibrated by back casting. This is a form of exploration of the future in which one or more desired future images are formulated and then translated back to the present.

Another way in which the validity of the model is guaranteed is the values of the different parameters (Table 5.3). All of these parameter were drawn up with the help of different industry experts. Information from public transport agencies from Amsterdam (GVB) and Rotterdam (RET) was used. The outcomes of the research by Van Beurden were also communicated to these industry experts for confirmation. The outcome was that, although it was difficult to completely verify the results, they seemed to be feasible. That information, combined with the validity of the VENOM model to begin with, ensurers the validity of the model used to a certain extent.

5.3. KPIs

As stated in Section 5.1.1, one of the requirements to the model was that a translation could be made to the different Key Performance Indicators. This chapter deals with the research question on how the effect of interoperability on the performance can be modelled. The KPIs found in chapter two were very general, now that the model has been chosen, the different KPIs can be further specified, the KPIs found in Chapter 2 will be used as the category, and be specified as can be seen in Table 5.5.

Table 5.5: KPIs

Performance Category	**KPI**
Accessibility	Train Kilometres Provided [km]
	Unserved Demand [# Passengers]
	Stop Use [Access/Egress Passengers & Transfer Passengers]
Passenger Satisfaction	Walking Distance [€]
	In-Vehicle Travel Time [€]
	Waiting Time [€]
	Transfers [€]
Costs	Operator Cost [€]

5.4. Conclusion

The goal of this chapter was to answer the research question: *How can the effect of interoperability on the performance of the urban rail network be modelled?*.

After a literature research into available models it can be concluded that the research performed by (Van Beurden, 2017) proved to be valuable to this research based on the following similarities to this research:

- The research focusses on the metropolitan area of Amsterdam
- The research presents a given infrastructure and passenger demand used to optimize line frequency and stopping patterns
- The research allows for interoperability on the lines

But it also has differences which need to be adapted to adequately suit this research.

- Interoperability is assumed on all of the lines
- Interoperability is assumed in both ways (train →metro and metro →train)
- The plans for the Amsterdam network are not applied (unbundling)

The Key Performance Indicators were further specified based on the categories found in Chapter 2. The new KPIs are:

- Train Kilometres Provided [km]
- Unserved Demand [# Passengers]
- Stop Use [Access/Egress Passengers & Transfer Passengers]
- Walking Distance [€]
- In-Vehicle Travel Time [€]
- Waiting Time [€]
- Transfers [€]
- Operator Cost [€]

After the necessary adjustments to the model have been made, experiments can be executed which results will help answer the final research question. The next chapter will describe this.

6

Amsterdam Case Study

This chapter deals with the final research question: *What is the effect of interoperability on the performance of the urban rail network of the Amsterdam metropolitan area?*. The goal of this question is to find out how (and if) the timetables of the systems will change when interoperability is an option. A question will also be if these changes are an improvement to the current timetables based on the performance indicators discussed in Chapter 2.

Five different experiments that will be analysed and modelled were drawn up to help answer the research question at hand. The experiments all describe a different usage of the rail network in and around Amsterdam. They will be judged on their performance on the following KPIs: train kilometres provided, unserved demand, stop use, walking distance, in-vehicle travel time, waiting time, transfers and operator cost.

6.1. Experimental Plan

The rail network around Amsterdam consists of three types (Train, Metro and Tram), of which two (Train and Metro) are of interest to this research. The different infrastructures are shown in the Figures 6.1.a, c and e. The experiments will focus on changes to the metro lines and the influence on the performance of the rail network. The train lines will remain unchanged, but their frequency and stopping patterns are also optimized in the optimization experiments. The goal is to investigate the performance of the network in these different scenarios.

For the optimization experiments (4 and 5) it was ensured that the same amount of runs (250 runs) would be used to best compare the results. These optimization runs were terminated when no (significant) new solution was found for a certain amount of time. It is important to note that an optimal solution is not guaranteed for this model, it is possible that the solution is a so called sub-optimal solution, meaning that more optimal solutions are present. A longer running time of the model does limit the chances of the final solution being a sub-optimal one.

6.1.1. Experiment 1: 2019 With Planned Timetable

The first experiment has the goal to find out how well the current situation is equipped to cope with the future. It will calculate the current situation meaning that the infrastructure and timetable of 2019 will be used combined with the passenger demand for 2040 (Figure 6.1.b). This experiment will set a base case for 2019.

6.1.2. Experiment 2: 2040 With Planned Timetable

The second experiment will investigate how well the plans released by the municipality of Amsterdam for 2040 (Figure 6.1.d) will cope with the 2040 passenger demand. It will use the unbundled metro network (as discussed in Section 2.1.4) with corresponding timetable and the original train timetable. It will calculate how this network deals with the 2040 passenger demand. This experiment will show the influence the current plans have on the performance of the urban rail network. This experiment will set the case for 2040.

6.1.3. Experiment 3: 2040+ With Planned Timetable

The third experiment will first look at interoperability in rail systems, it will extend the plans of 2040 with interoperability (2040+) between station Zuid and Hoofddorp. The timetable of the planned situation for 2040 will be used with 2040 passenger demand (Figure 6.1.f). This experiment will set the case for 2040+.

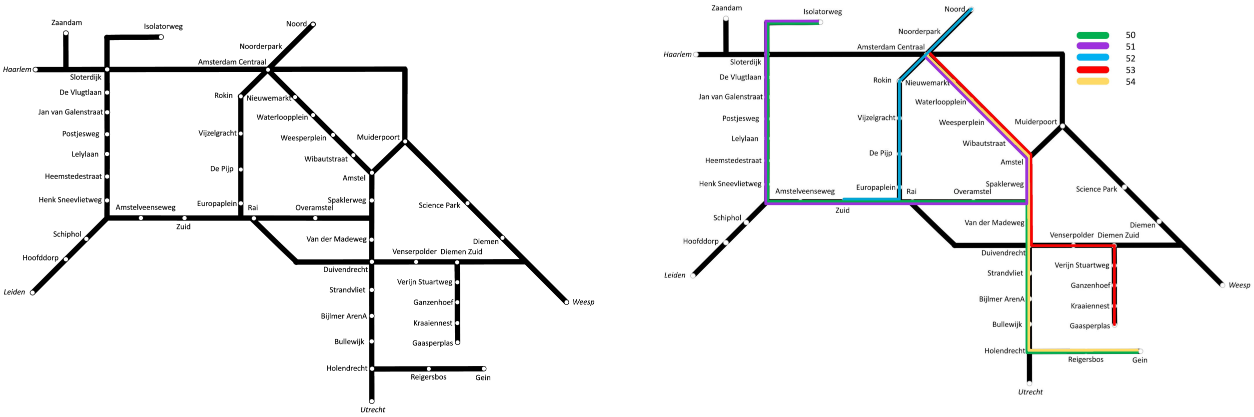
6.1.4. Experiment 4: 2040 Optimization

While experiment 2 was aimed at the infrastructure of 2040 with the *planned* timetable for 2040, this experiment is aimed at optimizing that scenario. The 2040 infrastructure with underlying train network (Figure 6.1.d) will be used combined with 2040 passenger demand. The experiment will optimize the frequency and stopping patterns based on a combination of costs. This experiment will determine whether a more optimal frequency and stopping pattern is possible for the future case.

6.1.5. Experiment 5: 2040+ Optimization

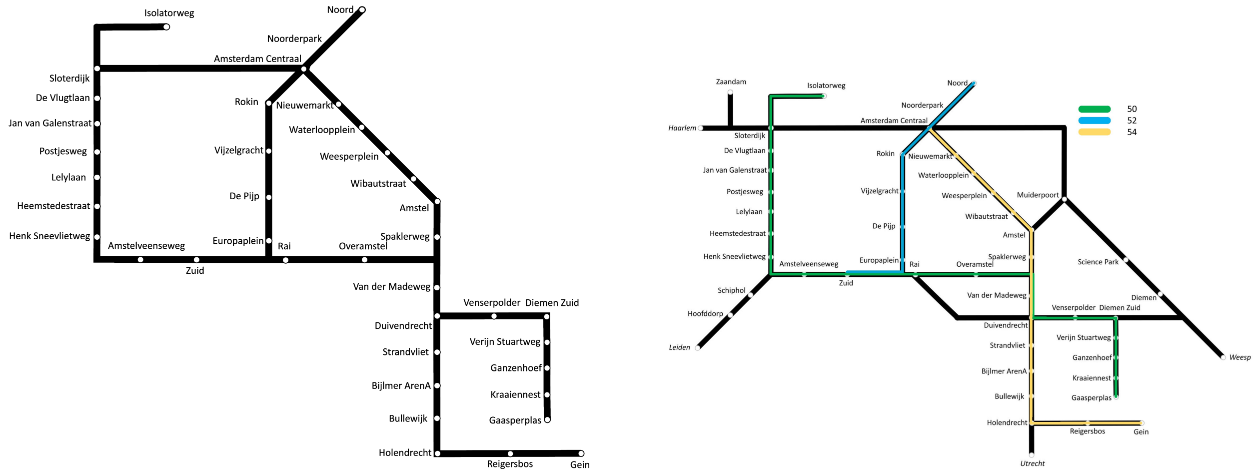
This experiment will optimize the frequency and stopping patterns for the 2040 infrastructure with interoperability (2040+). Where experiment 3 was aimed at the infrastructure of 2040+ with the *planned* timetable for 2040, this experiment is aimed at optimizing that scenario. The 2040+ infrastructure with underlying train network (Figure 6.1.f) will be used combined with 2040 passenger demand. The experiment will optimize the frequency and stopping patterns based on a combination of costs. This experiment will show if a more optimal frequency and stopping pattern is possible for the future case with interoperability.

Initial results showed that when experiment 5 was executed, the model early on eliminated the continuation of the Noord/Zuidlijn to Schiphol and Hoofddorp out of the set of possible solutions. The continuation of the Noord/Zuidlijn thus did not prove to have enough financial benefits for the model. When experiment 5 was finished, its results resembled the results of experiment 4. To truly investigate the influence of the interoperability on the performance of the network, the choice was made to supplement the results of this experiment with the continuation of the Noord/Zuidlijn. The results of this experiment will truly show how the interoperability (combined with optimized stopping patterns) will influence the performance of the urban rail network of Amsterdam.



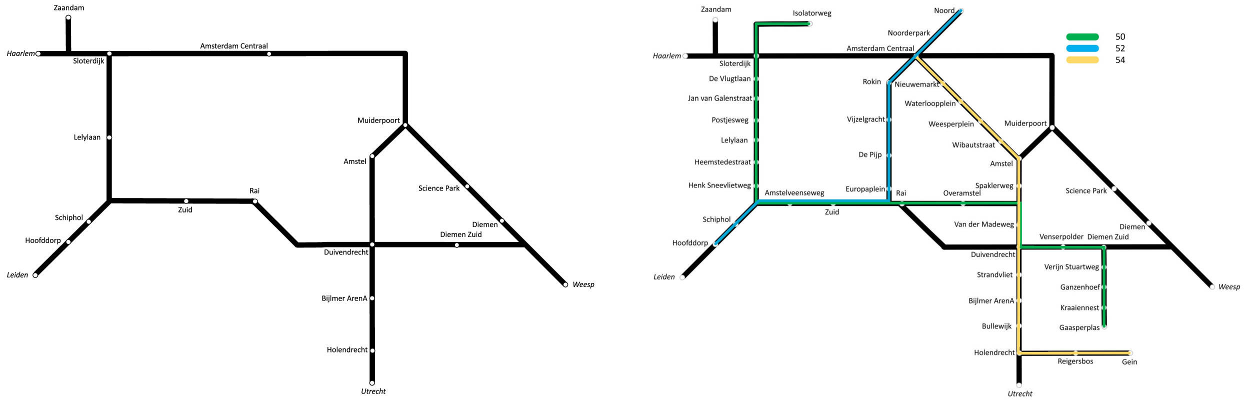
(a) Total Rail Infrastructure Amsterdam

(b) Metro Configuration 2019



(c) Metro Infrastructure Amsterdam

(d) Metro Configuration 2040



(e) Train Infrastructure Amsterdam

(f) Metro Configuration 2040+

Figure 6.1: Experimental Set-up

6.2. Results

This section will describe the results of the different experiments. For this section the results are structured in the same way as the predetermined KPIs.

6.2.1. Frequencies, Stopping Patterns and Vehicle Capacity

The purpose of the used model is to optimize the frequencies and stopping patterns (timetable) of the different metro and train lines based on costs. For the first three experiments there was no optimization but a calculation of the current timetable. Figures 6.2-6.6 show the different stopping patterns and frequencies of the train lines. For Experiments 4 and 5, this figure illustrates the optimized situation and the outcome of the optimization model.

Another result of the optimization model were the vehicle capacities, these are shown in Table 6.1 below.

Table 6.1: Vehicle Capacities Experiments

Experiment	**1**	**2**	**3**	**4**	**5**
Metro 50	1000	1000	1000	500	1000
Metro 51	1000	0	0	0	0
Metro 52	1000	1000	1000	500	700
Metro 53	1000	0	0	0	0
Metro 54	1000	1000	1000	500	300
Vlissingen - Amsterdam	1200	1200	1200	900	900
Zandvoort - Amserdam	700	700	700	1300	900
Uitgeest - Amsterdam	700	700	700	0	0
Amsterdam - Uitgeest	700	700	700	0	0
Eindhoven - Schagen	1200	1200	1200	900	1000
Amsterdam - Enkhuizen	700	700	700	0	0
Hoofddorp - Hoorn Kersenboogerd	700	700	700	1000	1500
Groningen - Den Haag	1200	1200	1200	1200	800
Zwolle - Hoofddorp	700	700	700	800	1500
Enschede - Schiphol	1200	1200	1200	1500	600
Utrecht - Amsterdam	700	700	700	700	700
Amesfoort - Amsterdam	700	700	700	0	0
Nijmegen - Schiphol	1200	1200	1200	800	800
Rotterdam - Amsterdam	700	700	700	1200	800
Rhenen - Amsterdam	700	700	700	900	1300
Amsterdam - Den Haag	1200	1200	1200	0	0

Figure 6.2: Experiment 1 (2019)

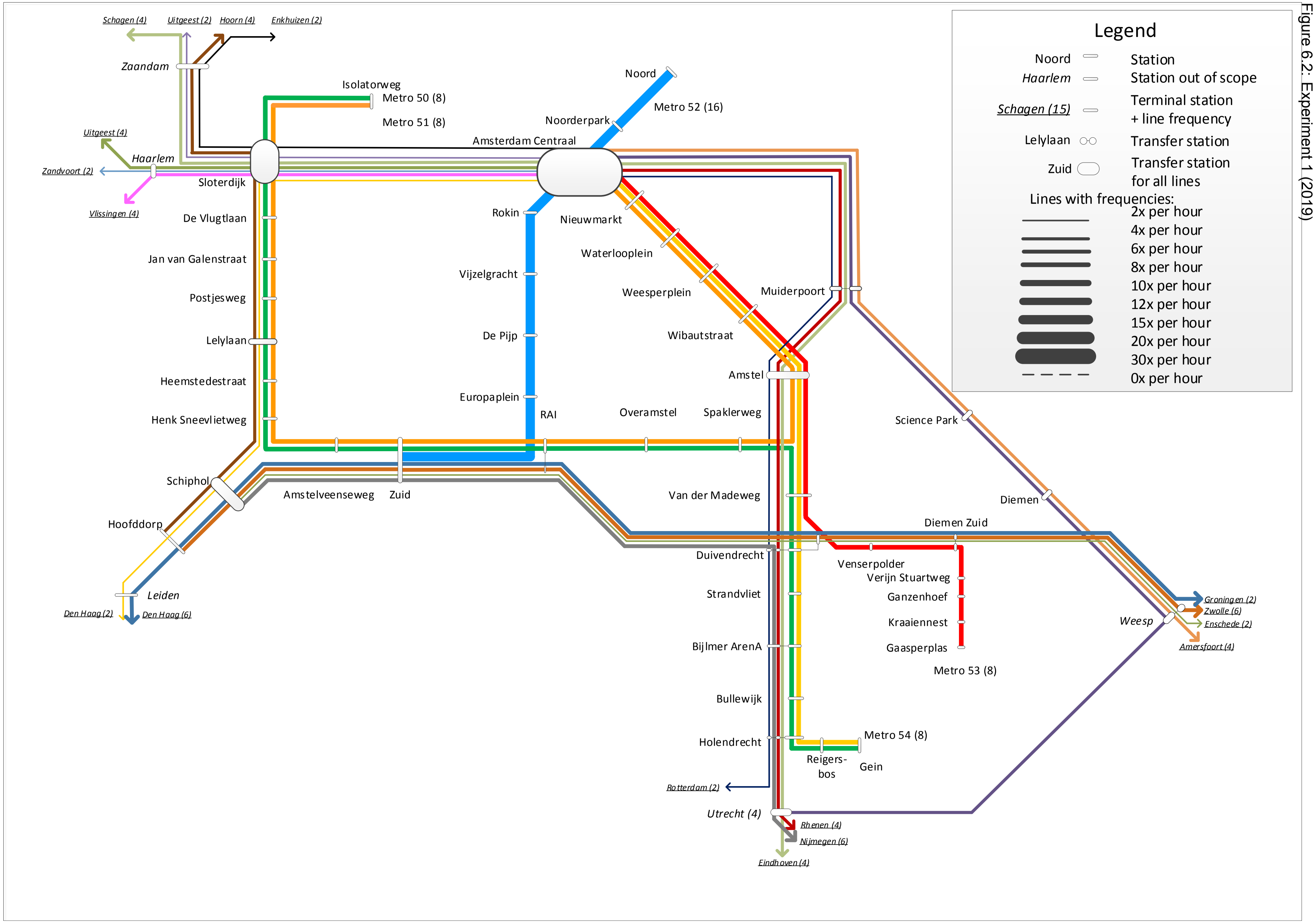


Figure 6.3: Experiment 2 (2040)

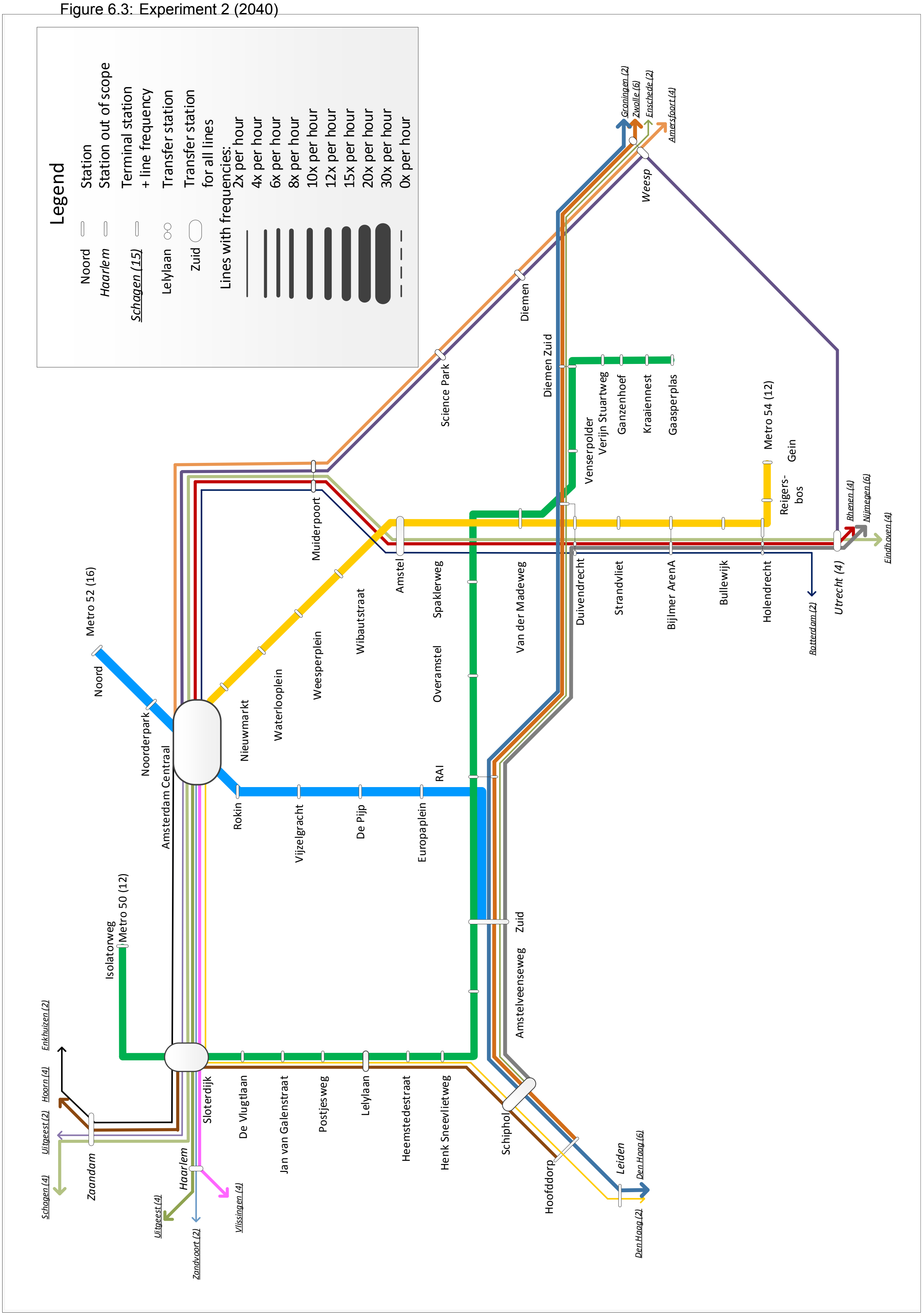


Figure 6.4: Experiment 3 (2040+)

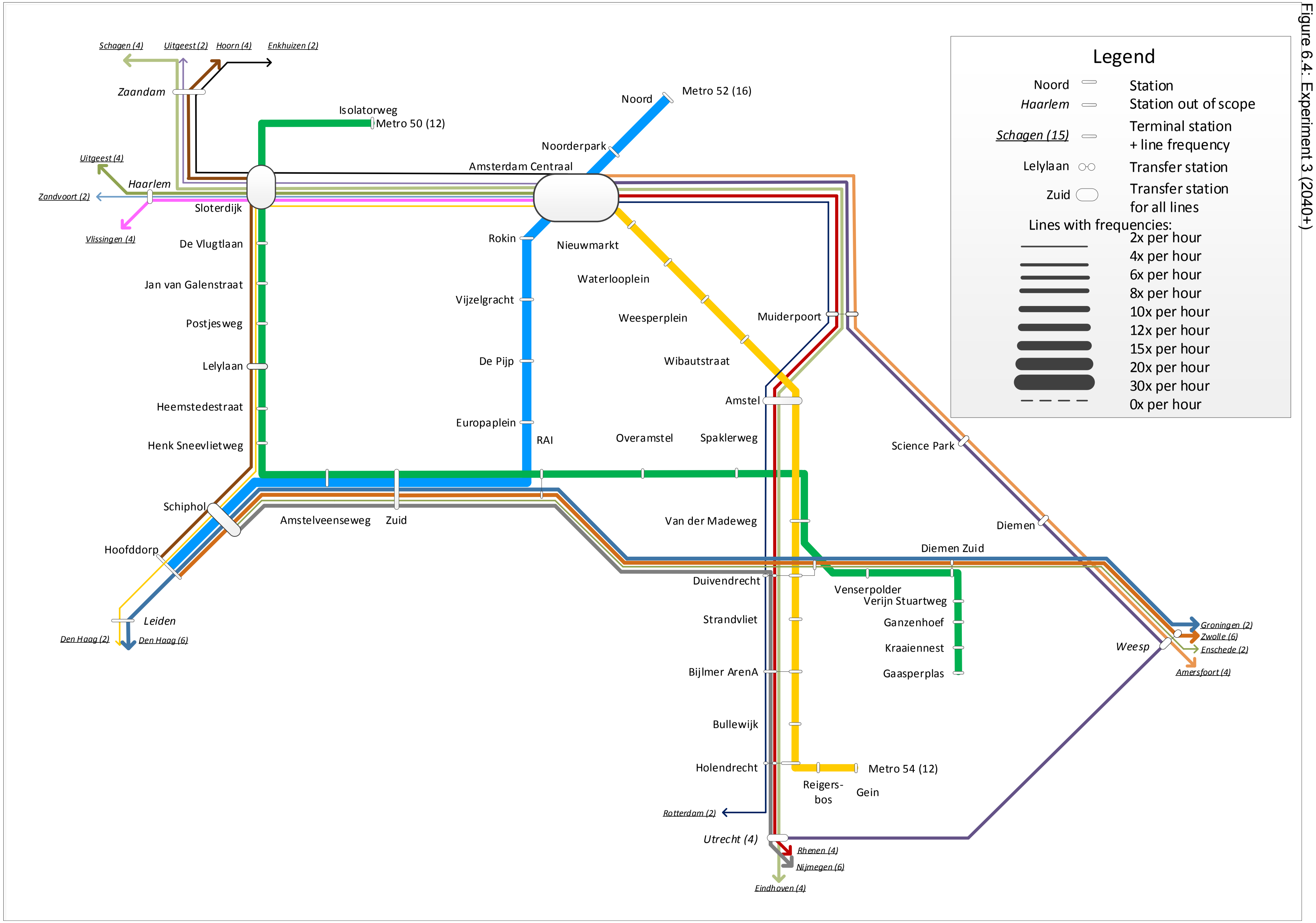


Figure 6.5: Experiment 4 (2040 O)

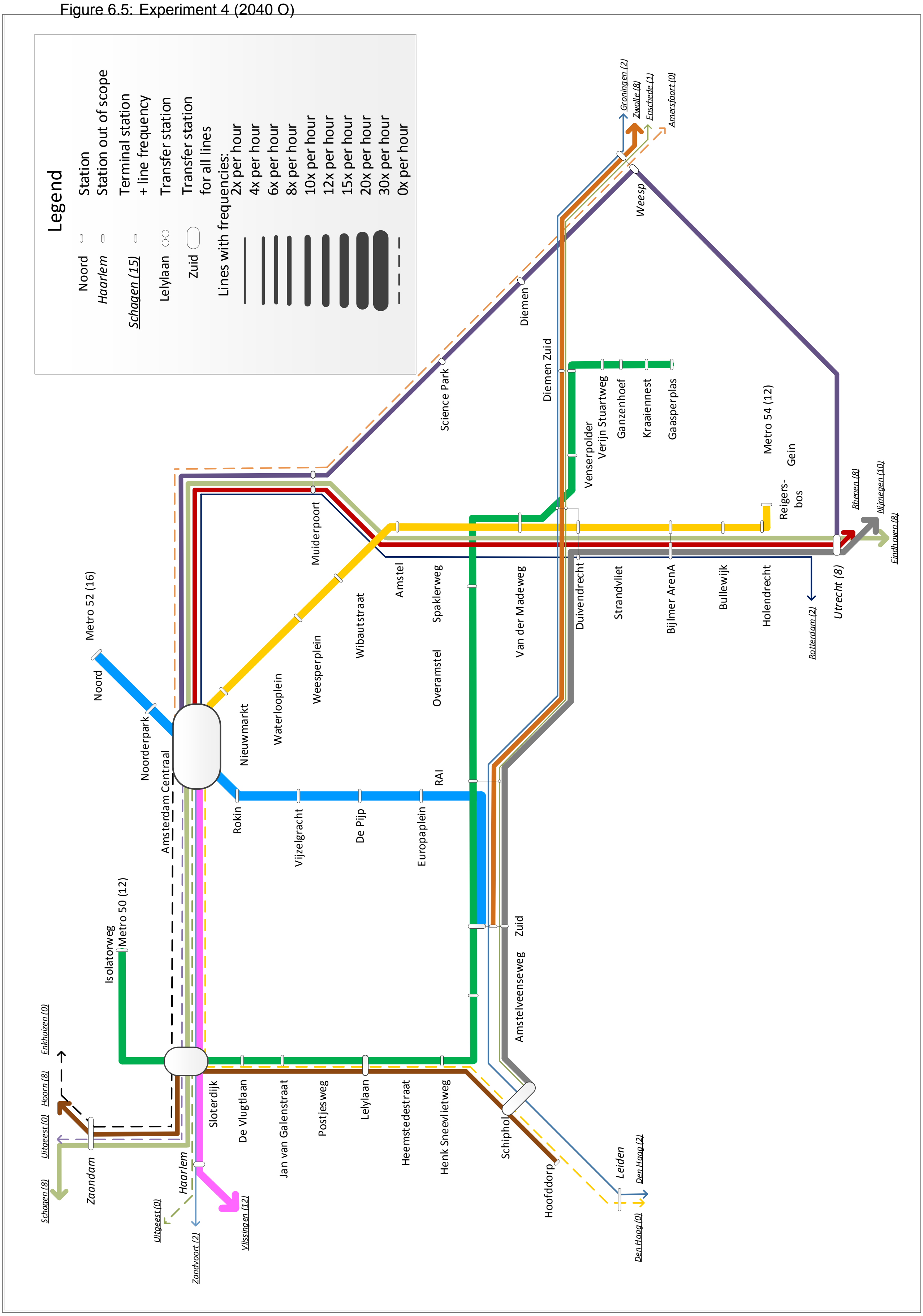
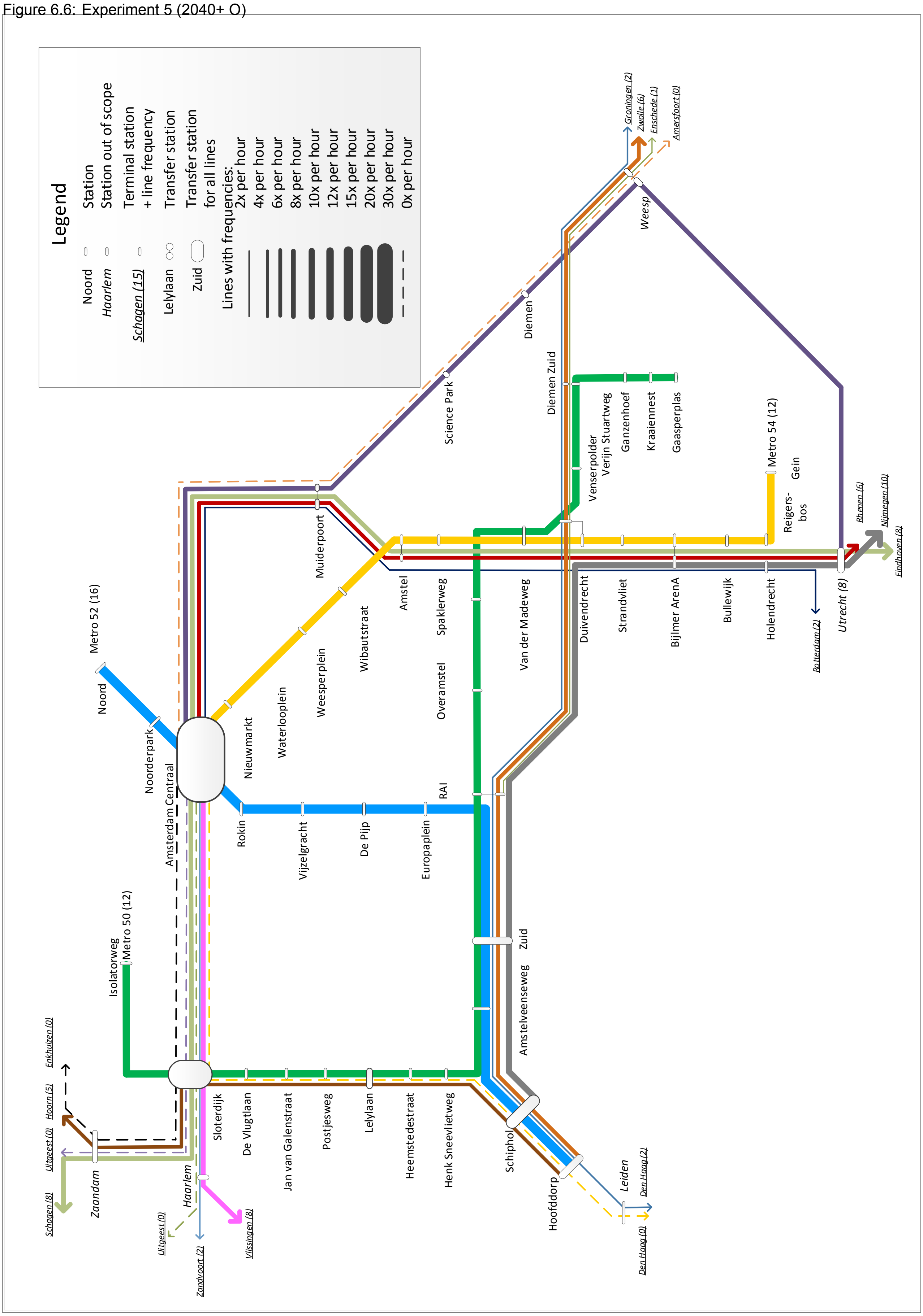


Figure 6.6: Experiment 5 (2040+ O)



6.2.2. Train Kilometres Provided

The train kilometres are calculated as followed:

$$TrainKilometres = \sum_{l \in L} LineDistance_l * LineFrequency_l$$

with:

- $LineDistance$[km]: The total distance of line l
- $LineFrequency$: The frequency of line l

Table 6.2 shows the amount of train kilometres provided per experiment, the higher the number, the better the score of that experiment on this KPI.

Table 6.2: Train Kilometres

Experiment #	1	2	3	4	5
Total [km]	30150	29967	30379	34472	32169
Metro [km]	1218	1035	1035	1035	1447
Train [km]	28932	28932	28932	33437	30722

6.2.3. Unserved Demand

None of the experiments have unsatisfied demand, meaning that all of the passengers have some way of getting to their final destination. An unsatisfied demand of zero does not mean that all travellers use the rail network, this section shows the unserved demand, e.g. how many people use the urban rail network to reach their destination. The total number of passenger trips the model uses is **481 875 passenger trips**.

This result will represent how many people use what lines in one hour of morning traffic. The higher this number is, the better the performance of your system. If more people use the urban rail system this means that this system is more attractive than other means of transport, people will only choose a specific transport method over another one if it is more efficient. Table 6.3 shows the results. Table 6.4 shows the average passenger distance per metro line.

Table 6.3: Passengers per Experiment

Experiment #	1	2	3	4	5
Total Passengers	449.556	448.466	449.191	444.178	430.154
Train Total	370.862	372.216	359.903	362.380	346.815
Metro Total	78.694	76.250	89.288	81.798	83.339
Metro 50	9.937	31.086	31.776	31.941	31.730
Metro 51	29.220	0	0	0	0
Metro 52	23.598	26.833	40.085	24.596	35.678
Metro 53	8.275	0	0	0	0
Metro 54	7.664	18.331	17.427	25.261	15.930

Table 6.4: Average Passenger Distance Metro Lines

Experiment #	1	2	3	4	5
Metro 50 [km]	5,17	4,85	4,82	4,80	4,56
Metro 51 [km]	4,84	0	0	0	0
Metro 52 [km]	3,42	3,43	7,26	3,00	6,82
Metro 53 [km]	3,77	0	0	0	0
Metro 54 [km]	3,35	3,07	3,13	3,27	3,23

6.2.4. Stop Use

For the stop usage two factors will be investigated, the amount of access and egress passengers and the amount of transfer passengers. In the National Market and Capacity Analysis (NMCA), a list of stations is listed where several serious transfer bottlenecks will occur in the future (Ministerie van Infrastructuur en Milieu, 2017). For this analysis, the current plans for future renovations to increase station capacity are taken into account. In the Amsterdam urban area there are currently four stations that are seeming to become a bottleneck towards 2040, if these stations can be relieved that will be an improvement of the performance of the network. These key stations are:

- Amsterdam Amstel
- Amsterdam Sloterdijk
- Amsterdam Zuid
- Schiphol Airport

The results in this section will be comparisons between the different scenario's and the base case scenario. In Appendix F the results of the biggest differences (more than 1000 passengers per hour) between each experiment and the base case scenario (experiment 1) will be shown visually, in this section only the results for the above mentioned stations will be listed. Table 6.5 shows the data for the passengers that use the key stations listed above as their first or last stop, Table 6.6 shows the amount of transfer passengers per key station.

Table 6.5: Access/Egress Passengers Key Stations

Experiment	**1**	**2**	**3**	**4**	**5**
Amsterdam Amstel	11.131	10.468	10.107	5.460	7.912
Amsterdam Zuid	13.220	13.765	9.220	13.206	8.975
Schiphol Airport	22.782	22.798	22.703	22.096	21.690
Amsterdam Sloterdijk	22.379	20.549	21.246	20.550	21.034

Table 6.6: Transfer Passengers Key Stations

Experiment	**1**	**2**	**3**	**4**	**5**
Amsterdam Amstel	4.217	2.783	2.734	0	454
Amsterdam Zuid	20.737	19.437	16.364	15.808	15.283
Schiphol Airport	4.497	4.422	6.803	7.891	2.433
Amsterdam Sloterdijk	6.580	7.313	6.938	11.684	9.995

6.2.5. Overall Cost

For this result the costs are calculated as followed:

$$TotalCost = PassengerCost + OperatorCost$$

$$PassengerCost = WalkCosts + InVehicleCosts + TransferCosts + WaitingCosts$$

$$OperatorCost = FixedCosts + VariableCosts + InvestmentCosts$$

This result represent the result of the objective function of the model and it is minimized in the optimization experiments (4 and 5). Table 6.7 shows the results per experiment.

Table 6.7: Total Cost Different Experiments

Experiment #	**1**	**2**	**3**	**4**	**5**
Total Cost [€]	2.740.425	2.741.730	2.722.086	2.382.096	2.387.545

Passenger Satisfaction

As stated above, the costs components are constructed in a certain way. The passenger costs are monetised versions of time spent on the public transport journey. Table 6.8 shows these monetised values per experiment.

Table 6.8: Passenger Cost Different Experiments

Experiment #	1	2	3	4	5
Passenger Cost [€]	2.561.136	2.566.289	2.542.895	2.183.948	2.204.799
Walk Costs [€]	836.991	840.798	835.836	807.768	805.484
In Vehicle Costs [€]	1.112.113	1.121.907	1.111.621	920.141	929.861
Transfer Costs [€]	49.552	49.791	50.308	52.076	47.922
Waiting Costs [€]	562.480	553.792	545.130	403.963	421.532

Operator Cost

For the operator cost the fixed costs are linked to the amount of rolling stock and the variable costs are linked to the frequencies and line usage of these vehicles. For the experiments were interoperability is assumed (3 and 5), the investment costs that were found in Chapter 4 and that were calculated back to one hour of operation are also added, Table 6.9 shows the results.

Table 6.9: Operator Cost Different Experiments

Experiment #	1	2	3	4	5
Operator Cost [€]	179.290	175.441	179.191	198.149	182.746
Fixed Costs [€]	82.261	79.846	81.571	86.907	80.841
Variable Costs [€]	97.029	95.596	96.978	111.241	101.263
Investment Costs [€]	0	0	642	0	642

6.3. Discussion

Now that all of the experiments have been executed the different results of the experiments will be discussed. First the different experiments will be discussed in general after which each of the different KPIs will be discussed separately.

6.3.1. General

Experiment 1: 2019 With Planned Timetable

Experiment 1 set the base case base with which all of the other experiments will be compared. In experiment 1, the unserved demand is the lowest with more people using the urban rail network as their means of transport than any other of the experiments.

Experiment 2: 2040 With Planned Timetable

Experiment 2 showed how the plans of the municipality of Amsterdam would affect the urban rail network around Amsterdam. This experiment shows the highest amount of passengers choosing to travel by train. Out of all of the experiments it has the lowest operator costs, which can be traced back to the decrease in metro lines.

Experiment 3: 2040+ With Planned Timetable

Experiment 3 used the configuration of experiment 2 as a base, but interoperability between metros and trains between station Zuid and Hoofddorp was added by the extension of line 52. In this experiment the metro lines get use most intensive out of all the experiments, a major increase in the use of line 52 can be seen with almost twice as much people using this line when compared to the other experiments.

Experiment 4: 2040 Optimization

In experiment 4, in which the timetable of experiment 2 was optimized, it can be seen that the metro configuration does not change substantially when compared to its base case, the frequencies are the same as in the original configuration but the capacities decrease from 1000 per metro to 500 a metro.

The system optimizes in a way that results in the elimination of 5 train lines when compared to experiment 2. The train lines that remain mostly increase in frequencies thus being able to serve more people. The train lines that remain do skip stations resulting in less transfer possibilities. The experiment has the lowest overall cost as a result of the optimization, this translates to a decrease in passenger costs but an increase in operator costs.

Experiment 5: 2040+ Optimization

In experiment 5, in which the timetable of experiment 3 was optimized, it is interesting to see that the interoperability between metros and trains between station Zuid and Hoofddorp was not part of the result. Apparently this solution proved to be to expensive when compared to other results and was eliminated from the solution set early on in the optimization. The optimization resulted in a timetable similar to that of experiment 4, but less stations were skipped. It is possible that if the experiment would have been run for a longer time, that the results would resemble those of experiment 4 even more. Both experiment 4 and 5 were run the same amount of runs (250 generations). The initial result of experiment 5 was complemented with the extension of the Noord/Zuidlijn to Schiphol and Hoofddorp. This extension resulted in lower overall costs thus being an optimization of the initial result. The final result of experiment 5 will help to best investigate the influence of interoperability and to answer the research question: *What is the effect of interoperability on the performance of the urban rail network of the Amsterdam metropolitan area?*

6.3.2. Train Kilometres Provided

For experiments 1, 2 and 3, the train kilometres are the same for all of the mainline trains as the same timetable is used. For the metro lines experiment 1 has the lowest value (as a result of the unbundling) and experiment 3 has the highest value(due to the extension to the Noord/Zuidlijn).

In the experiment where the 2040 scenario was used and optimized (experiment 4), it is interesting to see that the metro kilometres remained the same as the frequencies of those lines did not change in the optimized version. The train kilometres however did become higher, this is interesting because the amount of lines decreased with five lines. However the train lines that remained increase in frequency eventually resulting in a higher amount of train kilometres.

A similar but less extreme result as in experiment 4 can be seen in experiment 5 with an increase in the metro kilometres by the interoperability and an increase in the train kilometres provided.

The changes in provided train kilometres are visualised in Figure 6.7.

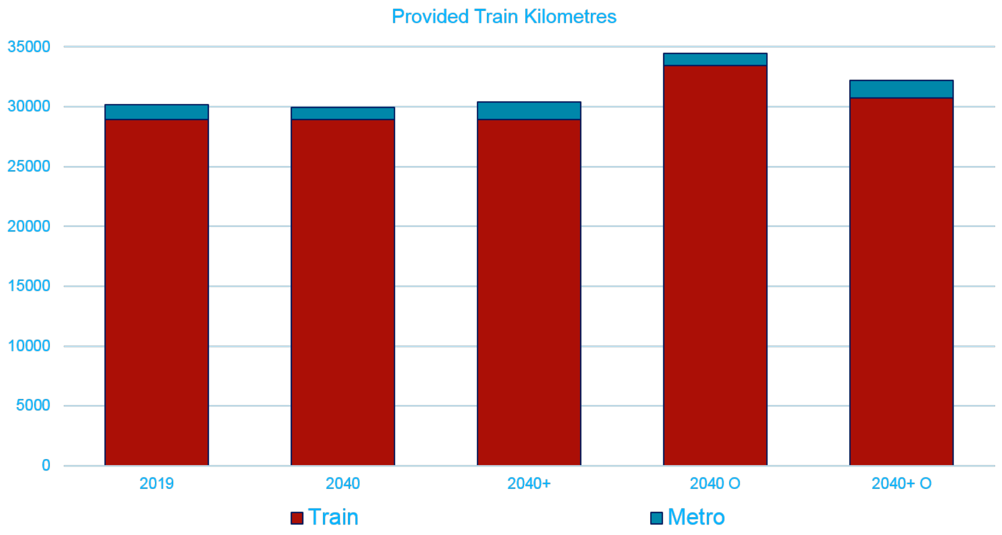


Figure 6.7: Train Kilometres Provided

6.3.3. Unserved Demand

The train kilometres described above only give insight to the amount of lines provided, the line usage shows how much passengers use these lines. This line usage is directly related to the unserved demand, the results represent how many people (out of the 481 875 passenger trips) use the urban rail network.

In experiments 1, 2 and 3, the total amount of passengers is roughly the same, but there is a shift in the modal split, especially between experiments 1 and 3. In experiment 3 less people use the train and more people use the metro. Experiment 3 has the highest metro use out of all the experiments.

In the optimization experiments (4 and 5) a decrease in the total amount of passengers is present. This is interesting because more train kilometres are provided but apparently less passengers use these extra train kilometres.

For the metro line use it can be said that interoperability (as used in experiments 3 and 5) contribute to the overall metro line use, especially on the extended line 52.

Figures 6.8 and 6.9 show the line use of the total rail system and the metro subsystem.

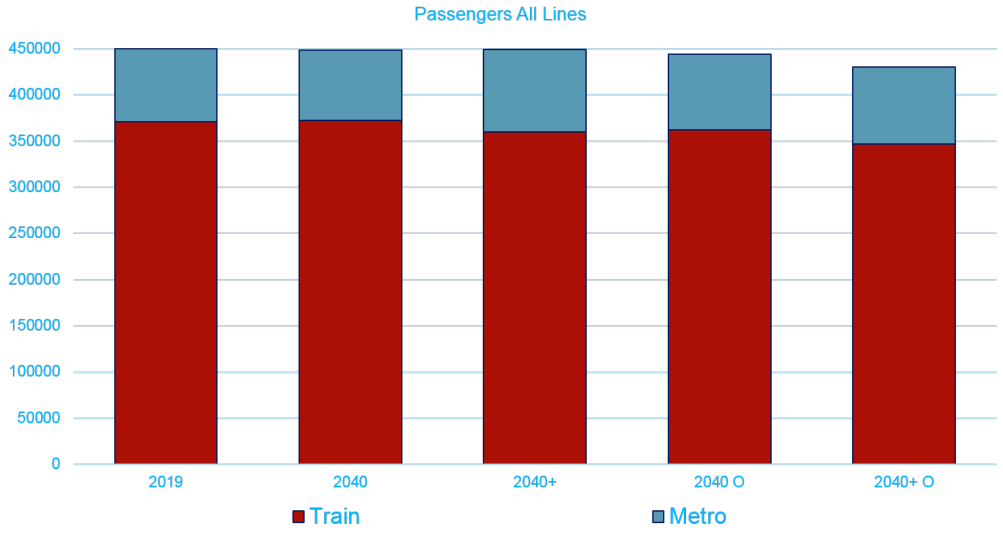


Figure 6.8: Total Passengers

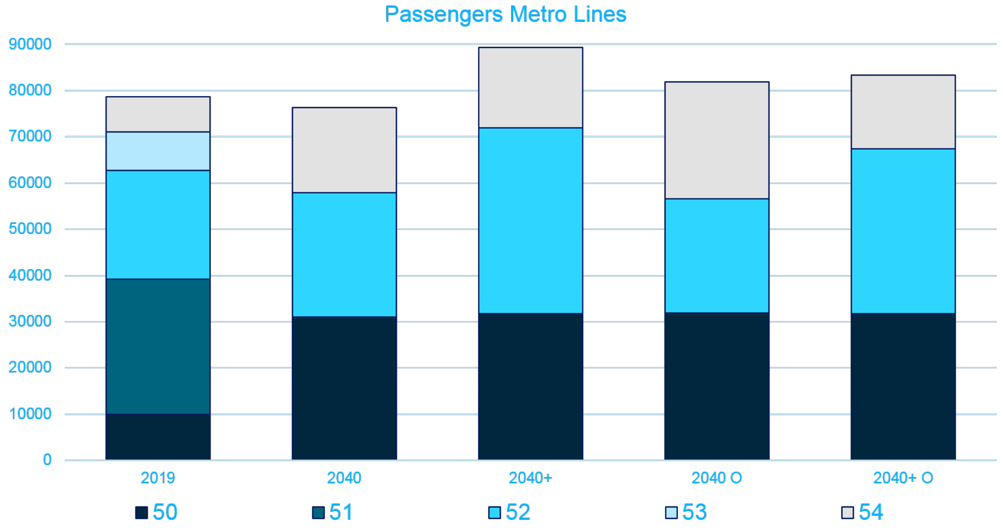


Figure 6.9: Passengers Metro Lines

6.3.4. Stop Use

The results in this section will be comparisons between the different scenario's and the base case scenario. In Appendix F the results of the biggest differences (more than 1000 passengers per hour) between each experiment and the base case scenario (experiment 1) are shown visually. Figures 6.10 and 6.11 show the difference in both access/egress passengers as well ass the difference in transfer passengers.

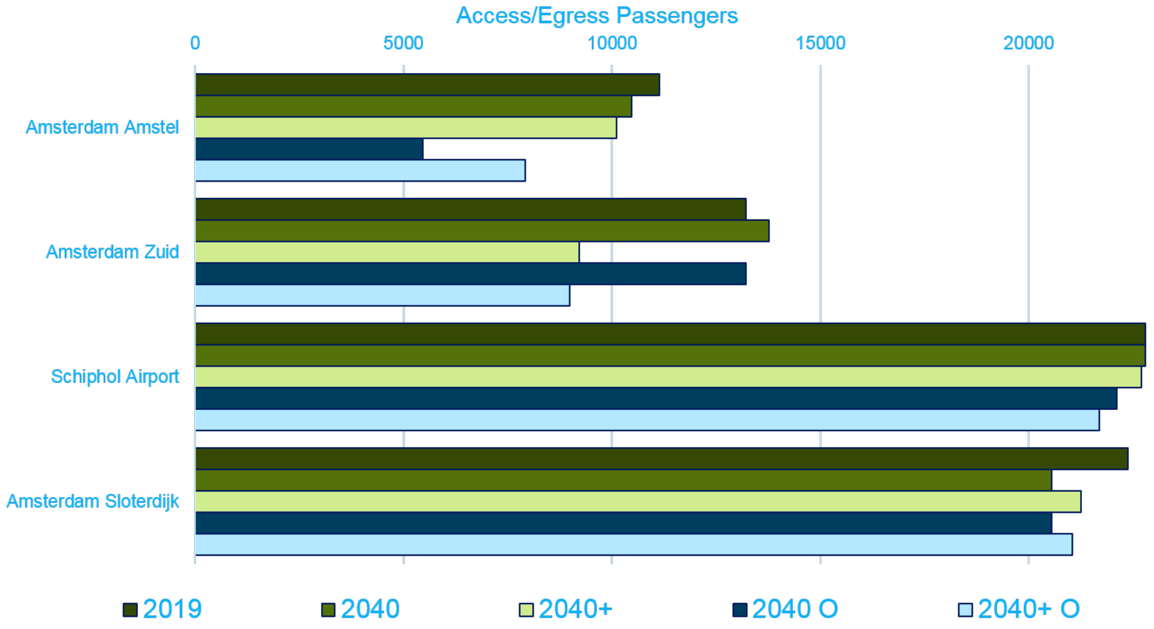


Figure 6.10: Stop Use Access and Egress Passengers

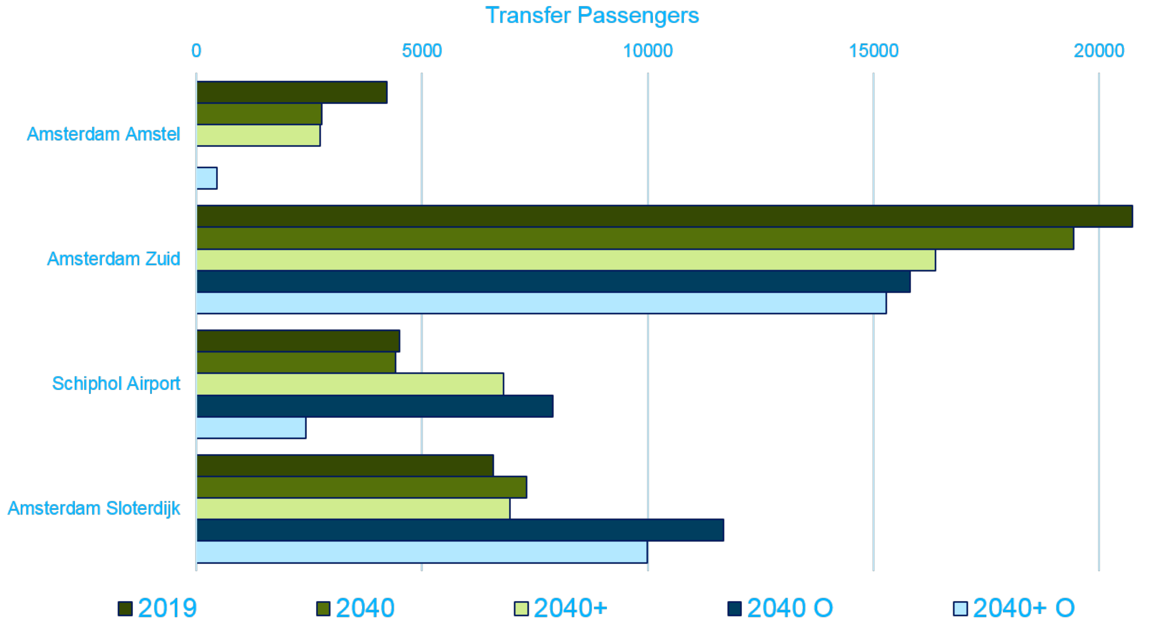


Figure 6.11: Stop Use Transfer Passengers

Experiment 2
The difference between experiment 2 and the base case is the unbundling of the metro network of Amsterdam.

The differences in access and egress passengers between experiment 1 and experiment 2 are not that interesting. Some stations become busier and some less, but all of the stations are able to cope with these extra passengers. The only minor bad change is the increase in passengers at Amsterdam Centraal, this is one of the stations that already is quite busy and where it would be nice if less people used it as their access or egress station. But overall, the changes are not significant. Station Duivendrecht also is used more as a first/last stop.

For the transfer passengers there are some interesting changes, Amsterdam Zuid has a slight relieve and Van der Madenweg gets busier with transfer passengers. Because of the unbundling of the network the amount of transfer stations between the lines decrease and the increase in transfers here makes sense as this is the station where transfers between line 50 and line 53 are possible.

Experiment 3
The difference between experiment 3 and the base case is, in addition to the unbundling of the metro network, the extension of line 52 to Schiphol and Hoofddorp.

For the interoperable state with the current timetable (experiment 3) it is interesting to see that as an access/egress stop, a switch is noticeable from station Zuid (-4000 passengers/hour) to station Amstelveenseweg (+3984 passengers/hour). The stations along line 52 get more crowded in general while the stations along line 54 get less crowded.

For transfers, station van der Madeweg still has a significant increase in transfer passengers and the switch between station Zuid and station Amstelveenseweg can also be seen here. There are also more transfers at Schiphol and Hoofddorp as a result of the extension of line 52. At Schiphol this might present an issue as this is already quite a crowded station.

Experiment 4
The difference between experiment 4 and the base case is, in addition to the unbundling of the metro network, a change in the train network around Amsterdam. Some trains have been cancelled and the remaining trains often have an increased frequency.

For the difference in access and egress passengers results in an increase in Amsterdam Centraal Station that is most noticeable (+5571 passengers/hour) and a decrease at Amstel Station (-5671 passengers/hour). This decrease in Amstel is a result of the fact that no more trains will stop at Amstel station in this optimized timetable.

Because no more trains stop at Amstel there are no more transfers possible at that station resulting in no transfer passengers. The transfer passengers shift to the train stations at the perimeter of the city, such as station Sloterdijk and station Bijlmer ArenA. The increase to van der Madeweg is still present in this scenario as is the shift from station Zuid to station Schiphol, in this experiment however, this is not a result of the continuation of a metro line, but as a result of less trains stopping at station Zuid than in the base case scenario.

Experiment 5
The difference between experiment 5 and the base case is, in addition to the unbundling of the metro network, a change in the train network around Amsterdam. Some trains have been cancelled and the remaining trains often have an increased frequency. The Noord/Zuidlijn was extended to Schiphol and Hoofddorp.

In experiment 5, a lot happens for access and egress stations. For the metro lines stations along line 54 get used less whereas stations along line 52 get busier. The trade-off in passengers between Zuid (-4245 passengers/hour) and Amstelveenseweg (+3638 passengers/hour) as a result of the extension of line 52 is noticeable. A decrease in access/egress passengers is seen at stations Sloterdijk and Schiphol.

The shift in transfer passengers is most interesting at Schiphol where almost a halving in the number of transfer passengers can be seen. These transfer passengers probably switch to Hoofddorp and Amstelveenseweg. Furthermore an increase is seen at station Sloterdijk and a decrease at stations Zuid and Amstel.

Performance

The performance rating for the stop use will be based on how much the found solution relieves the bottleneck stations: Amsterdam Amstel, Amsterdam Zuid, Schiphol Airport and Amsterdam Sloterdijk. A decrease in both transfers as well as access/egress passengers would be an improvement to the performance of the system. Table 6.10 shows how the performance values on stop use is created. Here a result higher than 100 means that this experiment scores higher on this KPI than the base case scenario, a score lower than 100 means that it scores worse. The colours correspond with the level of performance. Finally, the average of all of the separate values is taken for the KPI *stop use*.

Table 6.10: Performance Rating Stop Use

Experiment	**1 2019**	**2 2040**	**3 2040+**	**4 2040 O**	**5 2040+ O**
Access/Egress					
Amsterdam Amstel	100.00	105.95	109.20	150.95	128.92
Amsterdam Zuid	100.00	95.88	130.26	100.11	132.11
Schiphol Airport	100.00	99.93	100.35	103.01	104.80
Amsterdam Sloterdijk	100.00	108.18	105.06	108.17	106.01
Transfers					
Amsterdam Amstel	100.00	134.00	135.17	200.00	189.24
Amsterdam Zuid	100.00	106.27	121.09	123.77	126.30
Schiphol Airport	100.00	101.68	48.71	24.53	145.90
Amsterdam Sloterdijk	100.00	88.86	94.56	22.44	48.10
Stop Use	100.00	105.09	105.55	104.12	122.67

6.3.5. Overall Cost

The result of the cost function gives an indication of both passenger and operator cost. With the passenger cost being a representation of the passenger satisfaction. Here a lower result means lower costs thus better performance. In experiments 4 and 5, an optimization model was used with the goal to minimize the overall costs, so makes sense that in these experiments the overall cost are lower than in the experiments where the original timetable was used (1, 2 and 3).

Figures 6.12, 6.13 and 6.14 show the different components that make up the costs. Overall experiment 4 has the lowest cost and experiment 2 the highest, this is visualised in Figure 6.12.

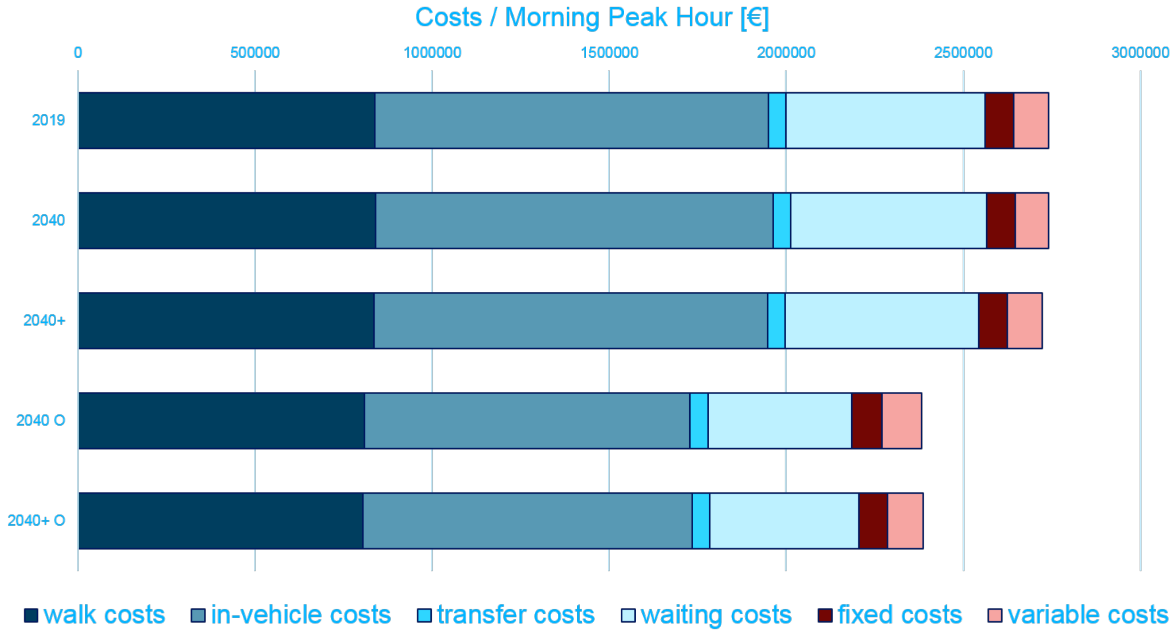


Figure 6.12: Cost Component Comparison

Passenger Satisfaction

From the passengers side the performance of experiment 4 is the highest and experiment 2 is the lowest. In experiment 4, travellers spend the least time in vehicles and the least time on waiting, they do however have to transfer the most. This can be traced back to the fat that in the 2040 optimization experiment, the solution contained fewer train lines than the base case scenario. So the remaining train lines have higher frequencies but passengers do have to transfer more often. In experiment 5, where the optimized timetable is complimented with interoperability, passengers have to spend the least time on walking and they also have to transfer the least. The passenger satisfaction results are shown in Figure 6.13.

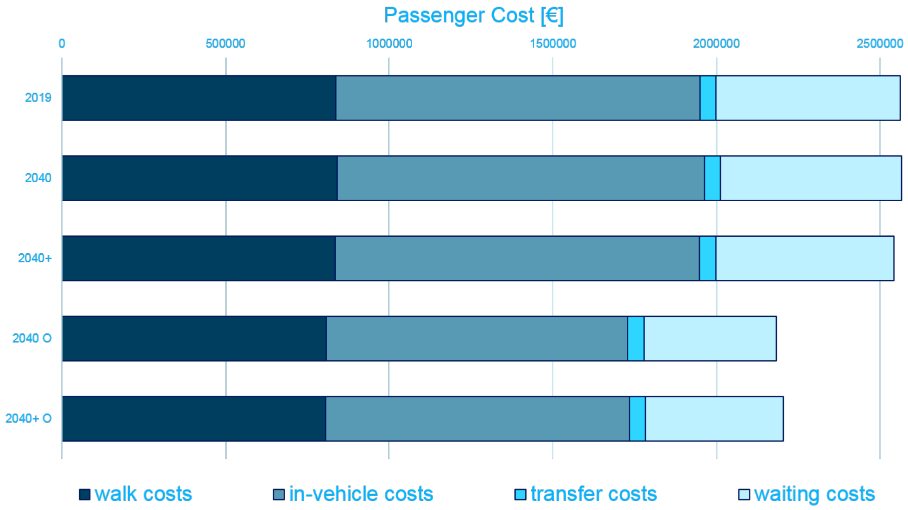


Figure 6.13: Passenger Cost Component Comparison

Operator Cost

From an operator point of view, experiment 1 has the best result and experiment 4 the worst. For the operator costs, the investment costs needed for interoperability are included in experiments 3 and 5. Both the fixed and the variable cost are the highest in experiment 4, this is due to the high frequencies of the trains in the system and the most amount of train kilometres provided out of all the experiments. The operator cost results are shown in Figure 6.14.

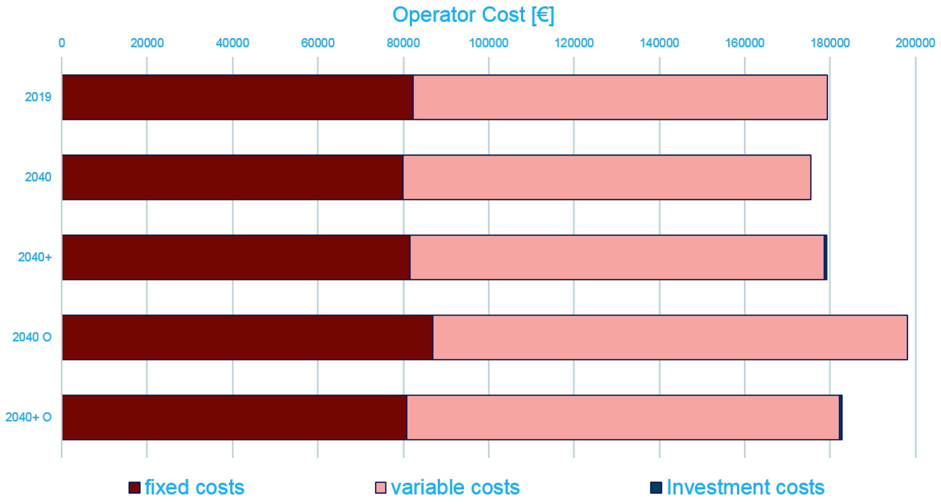


Figure 6.14: Operator Cost Component Comparison

6.4. Conclusions

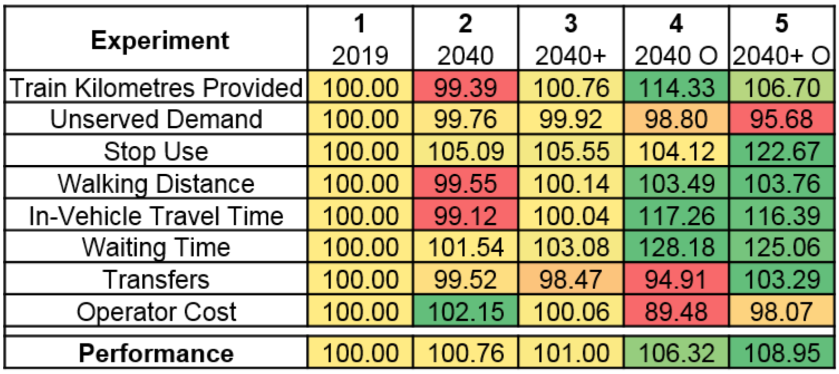
Chapter 6 had the goal to answer the research question: *What is the effect of interoperability on the performance of the urban rail network of the Amsterdam metropolitan area?*.

The effect of the different experiments on the performance of the rail network will be assessed by comparing them (percentage) to the base case scenario (experiment 1). A higher performance than the base case will result in a score higher than 100%, a lower performance in a lower score.

The performance of rail systems is complex to measure, so for the table below the choice was made to use equal count for each of the KPIs. The table already is a simplified representation of the true influence of the different scenarios on the performance and this type of representation was chosen to truly show the complexity and diversity of rail systems. The decision that are taken under consideration in a multi-actor system are about more than just costs.

When all of the experiments are graded all of the performances are added up and the average is taken. The effect of the different experiments on the different KPIs can be seen in Table 6.11. The colours correspond with the level of performance.

Table 6.11: Performance Rating



Experiment	1 2019	2 2040	3 2040+	4 2040 O	5 2040+ O
Train Kilometres Provided	100.00	99.39	100.76	114.33	106.70
Unserved Demand	100.00	99.76	99.92	98.80	95.68
Stop Use	100.00	105.09	105.55	104.12	122.67
Walking Distance	100.00	99.55	100.14	103.49	103.76
In-Vehicle Travel Time	100.00	99.12	100.04	117.26	116.39
Waiting Time	100.00	101.54	103.08	128.18	125.06
Transfers	100.00	99.52	98.47	94.91	103.29
Operator Cost	100.00	102.15	100.06	89.48	98.07
Performance	100.00	100.76	101.00	106.32	108.95

To assess the effect of interoperability, experiments 3 and 5 are the ones to look at, as these are the experiments where the Noord/Zuidlijn continues its path to Schiphol and Hoofddorp. Here experiment 3 uses an original timetable and experiment 5 uses an optimized timetable.

When compared to the 2019 scenario, both of these experiments show an improved performance. It is however more fair to compare experiment 3 to experiment 1 and 2 (the experiments without a timetable optimization), and experiment 5 to experiment 4 (optimization experiments).

When graded from best performance to worst performance the experiments are rated in the following way [1]:

1. ***Experiment 5: 2040+ Optimized***
2. *Experiment 4: 2040 Optimized*
3. **Experiment 3: 2040+**
4. Experiment 2: 2040
5. Experiment 1: 2019

The base case (2019) is does not have optimal performance and improvements are feasible, the current plans released by the municipality of Amsterdam (2040) are an improvement to the base case performance but are still not optimal. When interoperability is added to these plans (2040+) an even better performance is achieved. And when interoperability is combined with an optimized timetable, the biggest improvement to the performance can be achieved.

A side note to this grading has to be made that this performance is based on a predefined set of KPIs. The goal was to sketch as complete an image as possible, but rail systems are very complex and many problems can not be seen as straightforward.

---

[1] Experiments with added **interoperability** are in bold, experiments with *optimized timetable* in italic.

7

Conclusion and Recommendations

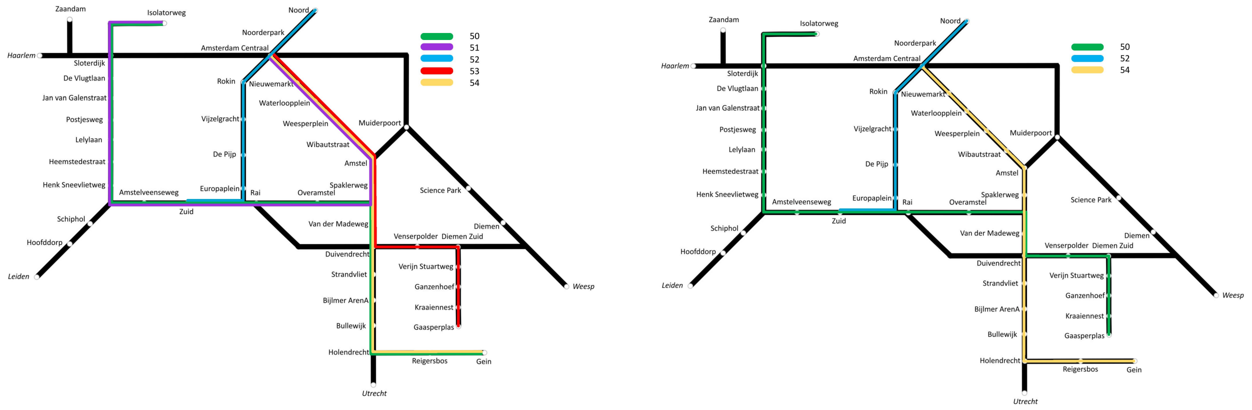
7.1. Conclusions

The problem statement that initiated this research was: Will interoperability of rail systems contribute to an increased level of quality of the public rail network in Dutch cities? The answer to this question could contribute to the public transport network in the Netherlands and the way that stakeholders view interoperability. For the city of Amsterdam a higher level of accessibility could be achieved, combined with the strengthening of the position of Schiphol as a multi-modal hub. The main research question was answered with the help of the following research questions.

What is the base case scenario for the urban rail network of the Amsterdam metropolitan area and how can the performance of this network be assessed?

The proposed base case scenarios are one that describes the current state (2019) and one that describes the planned state (2040). These scenarios and the KPIs they are compared on are:

Scenarios	KPIs
2019 Base Case 2019 Metro Configuration (Figure 7.a) Regular Train Configuration	Accessibility Passenger Satisfaction Costs Safety and Sustainability (as a boundary condition)
2040 Planned Case 2040 Planned Metro Configuration (Figure 7.b) Regular Train Configuration	



(a) Metro Configuration 2019

(b) Metro Configuration 2040

Figure 7.1: Base Cases

What compatibility issues are there between metro and train systems?

Table 7.1 shows if a compatibility issues will arise when interoperability between a metro- and train system is the goal. The column Metro →Train tells if a compatibility issue will arise when running a metro on the train track and the column Train →Metro shows if a compatibility issue will arise when running a train on a metro track.

Table 7.1: Compatibility Issues

Characteristic	Compatibility Issue? Metro →Train	Compatibility Issue? Train →Metro
Track Gauge	No	No
Rail Profile	Yes	Yes
Axle Load	No	Yes
Load Gauge	No	Yes
Radius of Curvature	No	No
Power Supply	Yes	Yes
Stations and Nodes	Yes	Yes
Turnouts and Crossings	Yes	No
Saftey and Communication Systems	Yes	Yes
Stakeholders	No	No
Network	Yes	Yes

The compatibility issues that occur between train →metro are insurmountable without changing the NS fleet or the GVB infrastructure drastically. The NS rolling stock is for instance too heavy (Axle Load) and too high (Load Gauge) for the GVB infrastructure. The choice was therefore made to focus on the interoperability between metro →train. Figure 7.2 shows the network of the Amsterdam metropolitan area for the chosen interoperability that was used for this research.

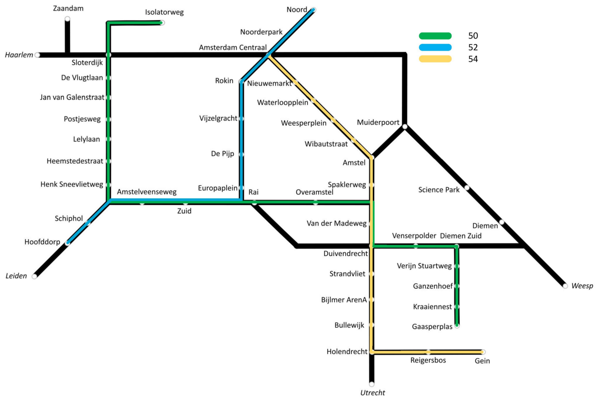


Figure 7.2: Metro Amsterdam 2040 Interoperability Scenario

What design alternatives with corresponding costs and actions are there to overcome theses compatibility issues?

The design alternatives with corresponding costs and actions are shown in Table 7.2. The costs are based on an extension of the Noord/Zuidlijn via Amstelveenseweg - Schiphol and Hoofddorp and assume a metro fleet of 28 vehicles.

The total investment cost to achieve interoperability will be anywhere between **€56 192 000** and **€64 642 000**, depending on the solution chosen for the safety and communication system. If these costs are calculated back to one hour of operation for the aspired start date in 2040 resulting in an investment cost between **€558** and **€642** per hour of operation. The higher value was used for the remainder of the research.

Table 7.2: Costs and Actions

Compatibility Issue	Design Direction	Costs	Actions
Rail Profile	Change wheel dimensions	X	Alter wheel dimensions
Power Supply	- Dual Traction System	€4.200.000	Equip metros with a transformer to bring 1500 V DC to 750 V DC
Stations and Nodes	Gauntlet Track	€6.192.000	- At the mainline stations, install a Gauntlet track - At the mainline stations, raise part of the platform
Turnouts and Crossings	Alterations to Turnouts	€60.000	Make turnouts slightly wider to better serve metros (trains can still use these turnouts
Safety and Communication Systems	CBTC/ERTMS Interoperability	€2.800.000	- Research into CBTC/ERTMS interoperability - Creation of laws and standards
	Metros with ERTMS	€11.250.000	- Equip current fleet with ERTMS or have ERTMS as a standard installed in new metros
Network	Connect Metro Line to Mainline	€43.000.000	Connect Metro Line to Mainline

How can the effect of interoperability on the performance of the urban rail network be modelled?

The effect of interoperability on the performance can be modelled with the model by (Van Beurden, 2017). The KPIs found in the first research question were further specified after the model was chosen as can be seen in Table 7.3.

Table 7.3: KPIs

Performance Category	KPI
Accessibility	Train Kilometres Provided [km]
	Unserved Demand [# Passengers]
	Stop Use [Access/Egress Passengers & Transfer Passengers]
Passenger Satisfaction	Walking Distance [€]
	In-Vehicle Travel Time [€]
	Waiting Time [€]
	Transfers [€]
Costs	Operator Cost [€]

What is the effect of interoperability on the performance of the urban rail network of the Amsterdam metropolitan area?

The base case (2019) is does not have optimal performance and improvements are feasible, the current plans released by the municipality of Amsterdam (2040) are an improvement to the base case performance but are still not optimal. When interoperability is added to these plans (2040+) an even better performance is achieved. And when interoperability is combined with an optimized timetable, the biggest improvement to the performance can be achieved.

Table 7.4 shows in more detail the exact effect of the interoperability on the different Key Performance Indicators. The results are presented as comparisons to the before mentioned base case scenario (2019). The table shows if the experiment has a positive (>100) or negative (<100) effect on that KPI when compared to the base case scenario.

Table 7.4: Performance Rating

Experiment	1	2	3	4	5
	2019	2040	2040+	2040 O	2040+ O
Train Kilometres Provided	100.00	99.39	100.76	114.33	106.70
Unserved Demand	100.00	99.76	99.92	98.80	95.68
Stop Use	100.00	105.09	105.55	104.12	122.67
Walking Distance	100.00	99.55	100.14	103.49	103.76
In-Vehicle Travel Time	100.00	99.12	100.04	117.26	116.39
Waiting Time	100.00	101.54	103.08	128.18	125.06
Transfers	100.00	99.52	98.47	94.91	103.29
Operator Cost	100.00	102.15	100.06	89.48	98.07
Performance	100.00	100.76	101.00	106.32	108.95

All of the optimization experiments score higher than the base case scenario, this means that part of the improvement in performance lies in the optimization of the timetable.

The interoperability has the biggest positive influence on stop use and the passenger waiting time. Overall, the interoperability has a positive effect on the performance of the urban rail network of the Amsterdam metropolitan area.

How will interoperability between metro and train systems affect the performance of the urban rail network of the Amsterdam metropolitan area, given a public transport passenger demand?

During the course of this research one thing became clear, the railway system is complex and every answer has many aspects, conditions and exceptions. The same must be said about the answer to the main research question.

When the different configurations were tested with the public transport demand for 2040, it became evident that there are configurations possible in which the performance of the urban rail system can be improved when compared to the current configuration. The improvements in performance are achieved in twofold:

- An optimized timetable (frequencies and stopping patterns)
- Interoperability between metros and the train infrastructure

Figure 7.3 shows the differences in performance visually, the green experiments are those without an optimized timetable, the blue experiments are those with an optimized timetable. The lightest green (2040+) and lightest blue (2040+ O) are the experiments with interoperability.

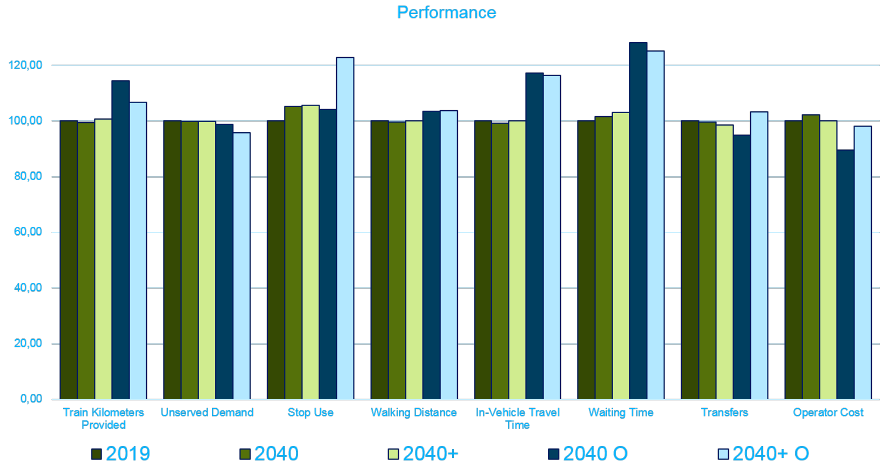


Figure 7.3: Performance Comparison

Overall interoperability between metro and train systems improves the performance of the urban rail network of the Amsterdam metropolitan area.

7.2. Recommendations for Further Research

This section will describe the recommendation for further research, the topic of rail interoperability is extremely interesting and relevant. This research aimed to show the possibilities it contains, but for interoperability to be truly achieved in the future, extensive further research is necessary. The recommendations are grouped by the different themes discussed in this research.

7.2.1. Key Performance Indicators

This research often mentioned the way in which the performance of rail systems can be measured. In Chapter 2 a list of so called Key Performance Indicators was drafted. As mentioned many times before the rail sector is a complex one with many different stakeholders and different stakes involved. This research simplifies the the system and its performance indicators to a certain extent. But if the list of KPIs and the extension to this list as presented in the conclusion of Chapter 5 would be broadened, an even better assessment on the performance of the rail system can be made.

For this research the focus was on KPIs that describe the normal operation of the network. However, it will be very interesting to investigate how the different networks react to disruptions on the network, or what the different political KPIs are that are involved with national decision making.

Performance Rating

The performance of rail systems is complex to measure, so for the performance rating used in this research, the choice was made to use equal count for each of the KPIs. This choice was made because the performance assessed in this research is already a simplified representation of the true influence of the different scenarios on the performance. This was chosen to truly show the complexity and diversity of rail systems. However, as said above in the recommendation about the KPIs, if more KPIs are chosen, it may also be necessary to use other weighting factors and possibly to bundle KPIs.

7.2.2. Compatibility Issues

Chapter 3 researched the different compatibility issues that occur when interoperability between metro and train systems is the goal. Some compatibility issues were left out of scope for this research. These compatibility issues are the ones that deal with operational and political issues. Further research into these other compatibility issues and finding solutions is necessary.

The compatibility issues between the different stakeholders and the political issues that will arise when metro-train interoperability is the goal, were left out of scope for this research. A deeper study into the possible conflicts between the different stakeholders involved would be very valuable.

7.2.3. Design Directions

For each of the compatibility issues that were found between metro- and train system a design alternative was proposed to overcome this issue. Each of these different design alternatives should be researched more deeply and worked out if the interoperability discussed in this research is to be taken from imagination to reality. This further research would also have to include a social cost benefit analysis (SCBA) to help with (political) decision making.

The design direction proposed for the compatibility issue of the safety and communication systems requires more research as was already stated. The design direction proposed an integrated system were CBTC and ERTMS worked together seamlessly. The possibilities of interoperability between CBTC and ERTMS are definitely there, but stakeholders and government agencies should stimulate this research to fully make use of the possibilities.

Major changes in legislation are necessary to achieve the interoperability discussed in this research. Further effort needs to be made to compose the correct rules and regulations necessary for safe interoperability.

7.2.4. Optimization Model

For the modelling part of this research, further research is required to continually improve the model at hand for it to better represent the reality. The recommendation on this subject will be split into two: recommendation on the model and on the solver.

Model

The cost function that is optimized by the model, was not altered for this research. However, further research into the numbers used for this cost function could help with its accuracy.

The model uses both the urban rail network (metro's and trains) and an underlying network of buses. It can be seen in the optimization experiments that the buses are more attractive (cost wise) than the rail system. This can be seen because trains are cancelled and passengers switch from the urban rail network to the underlying network. However, this underlying network of buses does have more degrees of freedom than the rail network and it is tested on a different level. To make the model more accurate, capacity restrictions should be applied to this underlying network.

Currently the model optimizes the frequencies and stopping patterns based solely on a combination of operator and passenger costs. An optimization based on more KPIs as discussed in this research would be very interesting.

Finally the assignment of passenger trips is now also a constant, with the new configurations this assignment can change and should be calculated again for each of the new configurations.

Some more recommendations for the model are:

- Add capacity restrictions on single-level crossings
- Create a more realistic difference between train and metro in terms of:
  - Travel times, ways of acceleration/braking, follow-up times, stopping times
  - Implementing different services: for example, metros and Sprinters have more stations where they can stop than Intercity trains
  - Detailed costs such as: personnel, vehicle and rail maintenance, energy, purchase (these costs are hard to come by due to competitive issues)
  - Different maximum capacities for train and metro
- The plans for new infrastructure in the Netherlands for 2040 are not yet certain, continues improvement of the model in terms of these plans is necessary.
- The passenger assignment of the model: no All-or-Nothing, but distribution over routes with discrete choice model (discrete choice model).

Solver

One of the issues that the solver currently has is that the optimality gap is not known. So when a solution is found, it is never sure how far this solution differs from an optimal one. The relaxation technique can be used for designing approximation algorithms for this optimization problem.

7.2.5. Case Study

The case study was performed to the urban area of Amsterdam, but different case studies could provide important information. For instance, a change in the rail-timetable around Amsterdam could have national impacts from Limburg to Groningen. Deeper investigation in the peripheral phenomena and how they will influence the national rail network is advised. Another interesting case study would be to test interoperability at different locations in the Netherlands such as the Rotterdam - The Hague corridor including RandstadRail.

For the optimization experiment that should have investigated the interoperability in this research (experiment 5), interoperability was left as an option and therefore eliminated from the solution set early on. An additional optimization experiment where interoperability is not optional would be interesting, especially because the final result of experiment 5 shows that if you combine the optimized timetable with interoperability, lower overall costs and an improved performance is achieved.

The KPI *Stop Use* currently deals with only the four bottleneck stations around Amsterdam. The statement was made that a decrease in both access/egress as well as in transfer passengers would be an improvement to the performance. However deeper research is needed to assess exactly how the increase or decrease in passengers will affect each of the different affected stations (as shown in Appendix F). This research bundles all of the trains and their passengers but does not take into account what platforms these trains use and how the passengers use the station. For instance it makes a big impact whether a passenger has a cross-platform transfer or if they have to cross the station and how long they have to wait on their next train.

Bibliography

Alstom. Iconis technology - Brochure. 2011. URL `http://www.alstom.com/Global/Transport/Resources/Documents/brochure2014/Iconis-Brochure-EN.pdf?epslanguage=en-GB`.

Amstelveenlijn. Vernieuwing Amstelveenlijn: waarom nodig en wat gaat er gebeuren?, 2018. URL `http://amstelveenlijn.nl/over-het-project/`.

Renato Arbex and Claudio Cunha. Efficient transit network design and frequencies setting multi-objective optimization by alternating objective genetic algorithm. *Transportation Research Part B: Methodological*, 81, 2015.

Ralf Borndörfer, Martin Grötschel, and Marc E Pfetsch. Models for Line Planning in Public Transport. In Mark Hickman, Pitu Mirchandani, and Stefan Voß, editors, *Computer-aided Systems in Public Transport*, pages 363–378, Berlin, Heidelberg, 2008. Springer Berlin Heidelberg. ISBN 978-3-540-73312-6.

CENELEC. Standardization in research and innovation projects. 2014.

David Chabanon. Track 1 Signal Systems The Next Generation Capacity issues resolved by modern train control systems - Lessons learned from Europe. 2013. URL `http://www.apta.com/mc/rail/previous/2013/program/Documents/ChabanonD_Signal-Systems-The-Next-Generation.pdf`.

CPB/CBS. Toekomstverkenning Welvaart en Leefomgeving. Nederland in 2030 en 2050: twee referentiescenario's. *Den Haag: Planbureau voor de Leefomgeving/Centraal Planbureau.*, 2015. URL `https://www.ris.uu.nl/ws/files/19342106/cpb_pbl_boek_19_wlo_2015_nederland_2030_en_2050.pdf`.

Critical Software. ERTMS and CBTC Side By Side a Comparison of State of the Art Rail Traffic Management Systems. 2014.

DAT.Mobility. OmniTRANS - DAT.Mobility, 2018. URL `http://archief.dat.nl/en/products/omnitrans/`.

Roel Dollevoet. Contact patch | 1.5 Wheel-Rail Interface | RAIL101x Courseware | edX, 2018. URL `https://courses.edx.org/courses/course-v1:DelftX+RAIL101x+1T2018/courseware/49f70ce89c154f00bc0ba3a2a5a9ac4b/faac66deeb3f4a4bb665653ead106e92/?child=first`.

Ge Dubbelman and Hollandse Hoogte. 2018-01-10-Station Rokin-14 _ Nederland, Amsterdam, 10 janua... _ Flickr, 2018. URL `https://www.flickr.com/photos/noordzuidlijn/28125879619/in/photostream/`.

Coenraad Esveld. *Modern railway track*. MRT-productions Zaltbommel, The Netherlands, 2001. ISBN 9080032433, 9789080032439.

Europeese Rekenkamer. Speciaal verslag - Eén Europees beheersysteem voor het spoorverkeer: zal de politieke keuze ooit werkelijkheid worden? (13):1977–2017, 2017.

Manuel Garritsen, Onno van het Groenewoud, Errik Buursink, Rutger Veldhuijzen van Zanten, Danny Spee, and Nick van Luit. Uitbreiding metronet Amsterdam. Technical report, 2017.

Gemeente Amsterdam. Haalbaardheidsstudie station Sixhaven. 2017.

Gemeente Den Haag and DSO/Beleid/V&I. RandstadRail Hoofdrapport concept voorlopig ontwerp Den Haag Laan van NOI - CS. 2002. URL `https://web.archive.org/web/20050110085518/http://www.bezuidenhout.nl/html/den_haag_lvnoi-cs.html`.

Gemeente Rotterdam. Hoekse Lijn, 2018. URL `https://hoekselijn.mrdh.nl/`.

T Griffin. Shared track -a new dawn ? pages 15–22, 2001.

Weihua Gu, Zahra Amini, and Michael J. Cassidy. Exploring alternative service schemes for busy transit corridors. *Transportation Research Part B: Methodological*, 93:126–145, 11 2016. ISSN 0191-2615. doi: 10.1016/J.TRB.2016.07.010. URL `https://www.sciencedirect.com/science/article/pii/S0191261516300340`.

Peter Gurník. Next Generation Train Control (NGTC): More Effective Railways through the Convergence of Main-line and Urban Train Control Systems. *Transportation Research Procedia*, 14:1855–1864, 2016. ISSN 23521465. doi: 10.1016/j.trpro.2016.05.152.

GVB. Metro, 2018. URL `https://over.gvb.nl/vervoer/metro`.

GVB and Stadsregio Amsterdam. Metronet 2019 Studie. (December 2016), 2016. URL `https://www.yumpu.com/nl/document/view/57011174/metronet-2019-studie`.

GVB Rail Services. Elektrotechnisch Bedrijfsvoering Handboek voor Railinfrastructuur Metro en Tram Amsterdam. 2015.

M Hecker and H Benedick. Strategisch Programma van Eisen nieuw metromaterieel. Informatiedocument; ten behoeve van de aanschaf van nieuw materieel voor de Noord/Zuidlijn en de vervanging van het M2/M3 materieel. (november), 2005.

Klaas Hofstra. Werkwijze Logistieke Uitwerkingen; VenD - VACO, 2016.

Klaas Hofstra, Tijs Huisman, Jeroen Michels, Alwin Pot, Frank Westgeest, and Jeroen Michels. Regels voor het functioneel ontwerp van railinfrastructuur. pages 1–17, 2016.

IEEE Vehicular Technology Society. *IEEE Standard for Communications- Based Train Control (CBTC) Performance and Functional Requirements*. Number February. 2005. ISBN 0738135038. doi: 10.1109/IEEESTD.2001.93363.

Inspectie Verkeer en Waterstaat. Onderzoeksrapport RV-06U1018. (april), 2007.

Inter Connect. FACTORS AFFECTING INTERCONNECTIVITY: THE DUAL-MODE RAILWAY SYSTEM : THE KARLSRUHE MODEL. pages 232–259, 2010.

Marc Johnson. Communications Based Train Control – Rail Engineer, 2014. URL `https://www.railengineer.uk/2014/05/08/communications-based-control/`.

Francisco López-Ramos, Esteve Codina, Ángel Marín, and Armando Guarnaschelli. Integrated approach to network design and frequency setting problem in railway rapid transit systems. *Computers & Operations Research*, 80:128–146, 4 2017. ISSN 0305-0548. doi: 10.1016/J.COR.2016.12.006. URL `https://www.sciencedirect.com/science/article/pii/S0305054816303057`.

Metropoolregio Amsterdam. MRA Ontwikkelagenda Spoor 17. 2015.

Metropoolregio Amsterdam. Ruimtelijke Economisce Actie - agenda 2016 - 2020. 2016.

Ministerie van Infrastructuur en Milieu. Lange Termijn Spooragenda. page 49, 2012.

Ministerie van Infrastructuur en Milieu. Nationale Markt- Markt en Capaciteitsanalyse 2017 (NMCA) Hoofdrapport. 2017:1–62, 2017. URL `https://www.rijksoverheid.nl/documenten/rapporten/2017/05/01/nationale-markt-en-capaciteitsanalyse-2017-nmca`.

Ministerie van Infrastructuur en Waterstaat. Betere bereikbaarheid spoor Schiphol, Amsterdam, Almere, Lelystad (OV SAAL) | Spoor | Rijksoverheid.nl. URL `https://www.rijksoverheid.nl/onderwerpen/spoor/betere-bereikbaarheid-spoor-schiphol-amsterdam-almere-lelystad-ov-saal`.

Ministerie van Infrastructuur en Waterstaat. Overstappen naar 2040, Flexibel en slim OV. 2016.

Ministerie van Verkeer en Waterstaat. Light rail op een rij, 1997.

Nederlands Normalisatie Instituut. NEN-EN-IEC 62290-1:2014 en. Railway applications – Urban guided transport management and command / control systems, Part 1: System principles and fundamental concepts. 2016.

Nederlands Normalisatie Instituut. NEN-EN 15273-1 + A1. Railway applications - Gauges - Part 1: General - Common rules for infrastructure and rolling stock. 2017.

Nederlands Normalisatie Instituut. NEN-EN 13674-1 + A1. 2018.

Network Rail. Crossrail Programme Crossrail Train Protection (Plan B) - Railway Safety Regulations 1999 Exemption Application Report Crossrail Programme. pages 1–57, 2015.

Onderzoeksraad voor Veiligheid. Ontsporingen bij RandstadRail. 2008(november), 2008.

Ontwerpbureau Noord/Zuidlijn. Handboek spoorontwerp. 1998a.

Ontwerpbureau Noord/Zuidlijn. Handboek spoorontwerp bijlagen, 1998b.

R D Pascoe and T N Eichorn. What is communication-based train control? *IEEE Vehicular Technology Magazine*, 4(4):16–21, 12 2009. ISSN 1556-6072. doi: 10.1109/MVT.2009.934665.

S. David Phraner. International Transit Studies Program, Report of the Spring 2000 Mission. Germany's Track-Sharing Experience: Mixed Use of Rail Corridors. (47), 2002.

S David Phraner, National Research Council U Board, Transit Development Corporation, and Transit Cooperative Research Program. *Joint operation of light rail transit or diesel multiple unit vehicles with railroads*. 1999. ISBN 0309066042 (pbk.) 1073-4872 ;.

V Profillidis. *Railway Management and Engineering : Fourth Edition*. Taylor & Francis Group, Farnham, UNITED KINGDOM, 2006. ISBN 9781472407788. URL `http://ebookcentral.proquest.com/lib/delft/detail.action?docID=1589692`.

ProRail. NMCA Spoor 2030 – 2040 Achtergrondrapportage. (april):1–96, 2017.

ProRail. Station Amsterdam Zuid - ProRail, 2018a. URL `https://www.prorail.nl/projecten/station-amsterdam-zuid`.

ProRail. Coördinatie van treinverkeer - Reizigers - ProRail, 2018b. URL `https://www.prorail.nl/reizigers/coordinatie-van-het-treinverkeer`.

Prorail. Netverklaring 2018. 2018(november 2017):1–246, 2018.

Railway Technology. Karlsruhe Light / Heavy Rail - Railway Technology, 2018. URL `https://www.railway-technology.com/projects/karlsruhe/`.

International Union of Railways. Loading Guidlines, Code of Practice for the Loading and Securing of Goods on Railway Wagons. 1, 2017.

Rijksoverheid. Actieagenda Schiphol. 2017.

Gemeente van Rotterdam. Ontwerpboek DO HL stations en baanelementen Concept. pages 1–50, 2014.

Ruby. Ruby Programming Language, 2018. URL `https://www.ruby-lang.org/en/`.

L R Lutje Schipholt. Integratie Hoekse lijn - metro Rotterdam : perspectief of illusie ? 1993.

C. Schmelzer. Standardization of CBTC Systems – Mixed Operation on Shared Lines in accordance with ERTMS/ETCS Standards. 2015.

S G Shirlaw. Radio and communications-based train control: Migration, interoperation and system engineering issues. In *2008 International Conference on Railway Engineering - Challenges for Railway Transportation in Information Age*, pages 1–5, 2008.

Siemens. Marmaray Project. 2014. URL `http://www.marmaray.com/html/general.html`.

SporenplanOnline. GVB Metro, a. URL `http://www.sporenplan.nl/`.

SporenplanOnline. Leiden (excl) - Amsterdam RAI, b. URL `http://www.sporenplan.nl/`.

G Theeg and S Vlasenko. *Railway Signalling & Interlocking: International Compendium*. 2009.

Alejandro Tirachini, David A. Hensher, and Sergio R. Jara-Díaz. Comparing operator and users costs of light rail, heavy rail and bus rapid transit over a radial public transport network. *Research in Transportation Economics*, 29(1):231–242, 2010. ISSN 07398859. doi: 10.1016/j.retrec.2010.07.029. URL `http://dx.doi.org/10.1016/j.retrec.2010.07.029`.

UIC. A General Introduction to the Marmaray Project - UIC Communications. *UIC eNews" Nr 372.*, 2013. URL `https://uic.org/com/uic-e-news/372/article/a-general-introduction-to-the?page=iframe_enews`.

UITP. Metro, light rail and tram systems in Europe. page 44, 2009.

Unife the European Rail Industry. Factsheet: ERTMS Levels - Different Levels To Match Customer's Needs. *ERTMS Factsheets*, (3):2–3, 2014. URL `http://www.ertms.net/wp-content/uploads/2014/09/ERTMS_Factsheet_3_ERTMS_levels.pdf`.

Duco Vaillant. Wisselen bij de Noord/Zuidlijn, 2014. URL `http://wijnemenjemee.nl/nieuws/wisselen-bij-de-noordzuidlijn`.

Merlijn Van Beurden. Stopping pattern and frequency optimization for multiple public transport services. 2017.

Marcel van Lieshout. ProRail: trek Noord-Zuidlijn door tot Schiphol via ons spoor - Economie - Voor nieuws, achtergronden en columns, 2016. URL `https://www.volkskrant.nl/economie/prorail-trek-noord-zuidlijn-door-tot-schiphol-via-ons-spoor~a4365356/`.

Vervoerregio Amsterdam. Regionaal verkeersmodel VENOM - Vervoerregio, 2016. URL `https://www.vervoerregio.nl/venom`.

Yixiang Yue, Shifeng Wang, Leishan Zhou, Lu Tong, and M. Rapik Saat. Optimizing train stopping patterns and schedules for high-speed passenger rail corridors. *Transportation Research Part C: Emerging Technologies*, 63:126–146, 2 2016. ISSN 0968-090X. doi: 10.1016/J.TRC.2015.12.007. URL `https://www.sciencedirect.com/science/article/pii/S0968090X15004234`.

A

Scientific Paper

The Effect of Metro - Train Interoperability on the Performance of the Urban Rail System of the Amsterdam Metropolitan Area.

Nicoline Dammers, Mark Duinkerken, David Koopman, Rudy Negenborn

Abstract— **The current rail infrastructure is used intensively in and around large cities, several functional network levels can be defined within the rail infrastructure. The combination of different network levels puts pressure on the available infrastructure capacity and investments are needed to increase the infrastructure capacity. The definition between different networks is fading and will become less important in the future and it can be classified in a different way. Interoperability is a term that deals with the sharing of rail infrastructure. This paper describes the possibilities of interoperability between metro and train networks. The Noord/Zuidlijn metro-line in the city of Amsterdam is used as a case study and its Key Performance Indicators were assessed both before and after interoperability was experimentally applied and tested. The interoperability that is the subject of this paper entails the continuation of the Noord/Zuidlijn metro onto the ProRail network from station Amsterdam Zuid via station Amstelveenseweg and Schiphol to Hoofddorp. Currently nowhere in the Netherlands situations occur where a metro line continues its path on the mainline rail network as described in this paper. This paper outlines how interoperability influences the performance of a public rail transit system if the technical difficulties that obstruct this interoperability can be overcome.**

Key Words: Interoperability, Urban Rail System, Accessibility, Metro, Train, Noord/Zuidlijn, Network Demand Modelling, Genetic Algorithm

I. INTRODUCTION

Growing urbanization has caused the cities in the Netherlands to burst at their seams. This growth has resulted in an increasing demand for public transport. Towards the year 2040 the public transit lines in and around urban areas will clog up [Ministerie van Infrastructuur en Milieu, 2017]. There are limited funds available for new infrastructure, smart and innovative solutions could create extra space on the rails, allowing more and faster trains to run. However, this requires a change in the way stakeholders think. An innovative approach towards public transit in the future could help with a solution to the bottlenecks caused by population growth.

A. Interoperability

Interoperability refers to: "The ability of a transport network to operate trains and infrastructures to provide, accept and use services so exchanged without any substantial change in functionality or performance" according to IEC 62290-1:2006 [Nederlands Normalisatie Instituut, 2016]. This research aims to investigate the possibilities of interoperability in the Netherlands. The two network levels that were analysed are the Dutch national railway network (exploited by ProRail and operated on by mainly the NS) on the one hand, and the metro network of the Amsterdam Urban Area (exploited by the GVB).

The costs of a metro network, both infrastructural costs as well as operational costs are lower than heavy rail costs [Tirachini et al., 2010]. If two networks could be linked, thus minimizing the initial infrastructural costs, an increase in transport capacity could be reached which might provide many advantages for the city under investigation [Griffin, 2001] [Gurník, 2016] [Phraner et al., 1999]. Interoperability could be a serious alternative to building new (expensive) infrastructure when the goal is improving the performance of a rail network. There are several examples in the world where some type of rail interoperability is achieved, Karlsruhe in Germany, Crossrail in England and the yet to be completed Hoekse Lijn in the Netherlands [Bruner and Rizzetto, 2008] [Arpaci et al., 2016] [Phraner, 2002] [Schipholt, 1993].

B. Noord/Zuidlijn

A case study will be performed on the Amsterdam urban area with the focus on the Noord/Zuidlijn. The service continuation of the Noord/Zuidlijn towards Schiphol and Hoofddorp has been the topic of discussion since the start of the build of this line. There have been studies about extending the Noord/Zuidlijn by building new infrastructure [Garritsen et al., 2017]. The CEO of ProRail, Pier Eringa even expressed that the double track between Amsterdam-Zuid and Schiphol Airport station must be used not only by trains but also by metros and other forms of light rail [van Lieshout, 2016].

C. Approach

The purpose of this study was to investigate what was necessary to achieve metro - train interoperability in Amsterdam and to investigate the effects of this interoperability on the performance of the urban rail system. The central hypothesis was that interoperability is technically feasible and that it will improve the performance of the urban rail system. The technical feasibility of interoperability was assessed and compatibility issues that would occur were mapped. Design directions that would help overcome these incompatibilities were drawn up with their respective costs and actions necessary to achieve them. This showed how much time, money and effort is needed to achieve interoperability. After that an experimental research was performed simulating different scenarios that would help asses the performance in different rail configurations. The different scenarios were tested and graded based on their Key Performance Indicators.

II. COMPATIBILITY ISSUES

The compatibility issues between the two rail systems were categorized, whether an issue would occur if a mainline train would continue on metro infrastructure (train - metro) and whether an issue would occur if a metro would continue on mainline infrastructure (metro - train). The mapped incompatibilities led to the conclusion that the issues with train - metro interoperability were insurmountable without changing the NS fleet or the GVB metro infrastructure drastically. The NS rolling stock is simply too heavy (Axle Load), and too high (Loading Gauge) to be operative on the GVB infrastructure and inside the metro tunnels. The choice was therefore made to focus on the metro - train interoperability and come up with design directions that would solve the compatibility issues present for this type of interoperability.

A. Design Directions

With lessons learned from industry examples such as the Karlsruhe Project, the Randstadrail and the Hoekse Lijn, design directions were found to achieve metro - train interoperability on the Noord/Zuidlijn in Amsterdam. Special attention was given to the compatibility issue between the safety and communication systems, Communication Based Train Control (CBTC) which is active on the Noord/Zuidlijn, and European Rail Train Monitoring System (ERTMS) which will be active in the foreseeable future on the mainline network. Opinions differ drastically when it comes to the question if interoperability between these two systems is achievable. There have been researches that investigate and argue that it is feasible [Schmelzer, 2015] [CENELEC, 2014] [Gurník, 2016]. There even is a European initiative called Shift2Rail that is dedicated to achieving this interoperability [Europeese Rekenkamer, 2017]. But many more years of research are needed before these systems can achieve interoperability.

The total investment cost to achieve interoperability will be anywhere between **€56 million** and **€65 million**, depending on whether or not full CBTC/ERTMS interoperability will be achieved.

III. EXPERIMENTAL SET-UP

Five different experiments that were analysed and modelled were drawn up, they all describe a different usage of the rail network in and around Amsterdam. The rail network around Amsterdam consists of three types (Train, Metro and Tram), of which two (Train and Metro) are of interest to this research. The experiments focussed on changes to the metro lines and the influence on the performance of the rail network. The train lines will remain unchanged, but their frequency and stopping patterns are also optimized in the optimization experiments. The goal is to investigate the performance of the network in these different scenarios.

A. Modelling Framework

The case study was performed using the modelling framework created by van Beurden [Van Beurden, 2017]. This model optimizes the frequencies and stopping patterns of a network with multiple services and a set of possible lines based on a combination of costs. The optimization of the stopping patterns and frequencies uses a genetic algorithm and the experiments calculate how the different configurations respond to the passenger demand of 2040 [CPB/CBS, 2015].

B. Experiment 1: 2019 With Planned Timetable

The first experiment had the goal to find out how well the current situation is equipped to cope with the future. It calculated the current situation meaning that the infrastructure and timetable of 2019 was used combined with the passenger demand for 2040 (Figure 1). This experiment set a base case for 2019.

C. Experiment 2: 2040 With Planned Timetable

The second experiment investigated how well the plans released by the municipality of Amsterdam for 2040 (Figure 2) will cope with the 2040 passenger demand. It used the unbundled metro network with corresponding timetable and the original train timetable. It calculated how this network deals with the 2040 passenger demand. This experiment showed the effect the current plans have on the performance of the urban rail network. This experiment set the case for 2040.

D. Experiment 3: 2040+ With Planned Timetable

The third experiment first looked at interoperability in rail systems, it extended the plans of 2040 with interoperability (2040+) between station Zuid and Hoofddorp. The timetable of the planned situation for 2040 was be used with 2040 passenger demand (Figure 3). This experiment set the case for 2040+.

E. Experiment 4: 2040 Optimization

While experiment 2 was aimed at the infrastructure of 2040 with the *planned* timetable for 2040, this experiment is aimed at optimizing that scenario. The 2040 infrastructure with underlying train network (Figure 2) was used combined with 2040 passenger demand. The experiment optimized the frequency and stopping patterns based on a combination of costs. This experiment determined whether a more optimal frequency and stopping pattern is possible for the future case.

F. Experiment 5: 2040+ Optimization

This experiment optimized the frequency and stopping patterns for the 2040 infrastructure with interoperability (2040+). Where experiment 3 was aimed at the infrastructure of 2040+ with the *planned* timetable for 2040, this experiment is aimed at optimizing that scenario. The 2040+ infrastructure with underlying train network (Figure 3) was used combined with 2040 passenger demand. The experiment optimized the frequency and stopping patterns based on a combination of costs. This experiment showed if a more optimal frequency and stopping pattern is possible for the future case with interoperability.

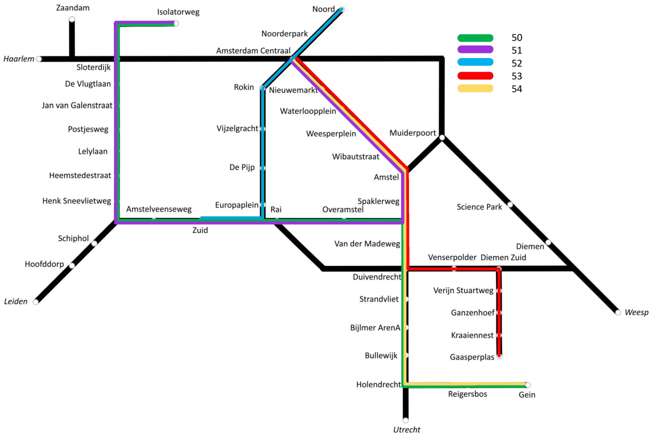


Fig. 1: Metro Configuration 2019

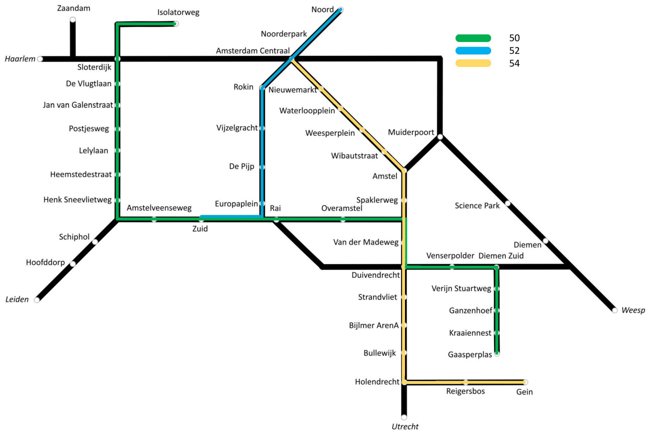


Fig. 2: Metro Configuration 2040

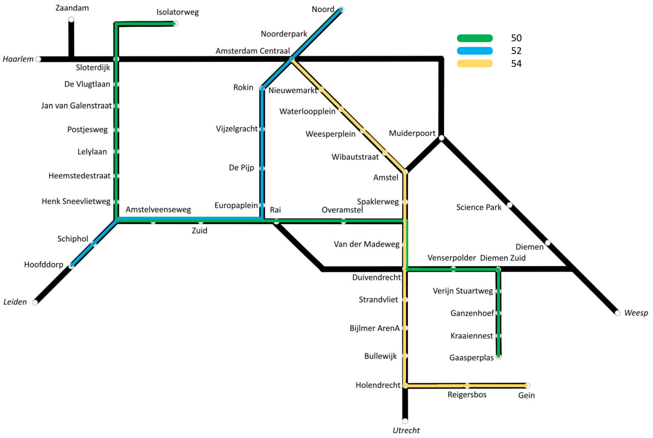


Fig. 3: Metro Configuration 2040+

G. Key Performance Indicators

The performance of the urban rail system depends on many factors. This section will describe how the performance of rail infrastructures can be measured and defined. Key performance indicators (KPIs) can help railway companies to become more attractive for their customers and more efficient in their operations. The KPIs used for this research can be seen in Table I.

TABLE I: KPIs

Performance Category	**KPI**
Accessibility	Train Kilometres Provided [km]
	Unserved Demand [# Passengers]
	Stop Use [Access/Egress Passengers & Transfer Passengers]
Passenger Satisfaction	Walking Distance [€]
	In-Vehicle Travel Time [€]
	Waiting Time [€]
	Transfers [€]
Costs	Operator Cost [€]

IV. RESULTS

This section will describe the results of the different experiments. For this section the results are structured in the same way as the predetermined KPIs.

A. Provided Train Kilometres per Peak Hour

The train kilometres are calculated as followed:

$$TrainKilometres = \sum_{l\in L} LineDistance_l * LineFrequency_l$$

with:

- $LineDistance$[km]: The total distance of line l
- $LineFrequency$: The frequency of line l

The higher the number, the better the score of that experiment on this KPI.

TABLE II: Provided Train Kilometres

Experiment	**1**	**2**	**3**	**4**	**5**
Total [km]	30150	29967	30379	34472	32169
Metro [km]	1218	1035	1035	1035	1447
Train [km]	28932	28932	28932	33437	30722

B. Unserved Demand

None of the experiments have unsatisfied demand, meaning that all of the passengers have some way of getting to their final destination. An unsatisfied demand of zero does not mean that all travellers use the rail network, this section shows the unserved demand, e.g. how many people use the urban rail network to reach their destination.

The total number of passenger trips the model uses is **481 875 passenger trips**. Table III shows how many people use what lines in one hour of morning traffic. The higher this number is, the better the performance of your system. If more people use the urban rail system this means that this system is more attractive than other means of transport, people will only choose a specific transport method over another one if it is more efficient.

TABLE III: Passengers per Experiment per Peak Hour

Experiment	**1**	**2**	**3**	**4**	**5**
Total	449.556	448.466	449.191	444.178	430.154
Train Total	370.862	372.216	359.903	362.380	346.815
Metro Total	78.694	76.250	89.288	81.798	83.339
Metro 50	9.937	31.086	31.776	31.941	31.730
Metro 51	29.220	0	0	0	0
Metro 52	23.598	26.833	40.085	24.596	35.678
Metro 53	8.275	0	0	0	0
Metro 54	7.664	18.331	17.427	25.261	15.930

C. *Stop Use*

In the National Market and Capacity Analysis (NMCA), a list of stations is listed where several serious transfer bottlenecks will occur in the future [ProRail, 2017]. For this analysis, the current plans for future renovations to increase station capacity are taken into account. In the Amsterdam urban area there are currently four stations that are seeming to become a bottleneck towards 2040, if these stations can be relieved that is an improvement of the performance of the network. These key stations are:

- Amsterdam Amstel
- Amsterdam Sloterdijk
- Amsterdam Zuid
- Schiphol Airport

For the station usage two factors will be investigated, the amount of access and egress passengers (Table IV) and the amount of transfer passengers (Table V).

TABLE IV: Access/Egress Passengers Key Stations per Peak Hour

Experiment	**1**	**2**	**3**	**4**	**5**
Amsterdam Amstel	11.131	10.468	10.107	5.460	7.912
Amsterdam Zuid	13.220	13.765	9.220	13.206	8.975
Schiphol Airport	22.782	22.798	22.703	22.096	21.690
Amsterdam Sloterdijk	22.379	20.549	21.246	20.550	21.034

TABLE V: Transfer Passengers Key Stations per Peak Hour

Experiment	**1**	**2**	**3**	**4**	**5**
Amsterdam Amstel	4.217	2.783	2.734	0	454
Amsterdam Zuid	20.737	19.437	16.364	15.808	15.283
Schiphol Airport	4.497	4.422	6.803	7.891	2.433
Amsterdam Sloterdijk	6.580	7.313	6.938	11.684	9.995

D. *Overall Costs*

For this result the costs are calculated as followed:

$$TotalCost = PassengerCost + OperatorCost$$

$$PassengerCost = WalkCost + InVehicleCost + TransferCost + UnsatisfiedDemand$$

$$OperatorCost = FixedCost + VariableCost$$

This result represent the result of the objective function of the model and it is minimized in the optimization experiments (4 and 5). Table VI show the results per experiment.

TABLE VI: Total Cost per Peak Hour [x1000]

Experiment	**1**	**2**	**3**	**4**	**5**
Total Cost [€]	2.740	2.742	2.722	2.382	2.388

1) Passenger Satisfaction: As stated above, the costs components are constructed in a certain way. The passenger costs are monetised versions of time spent on the public transport journey. Table VII shows these monetised values per experiment.

TABLE VII: Passenger Cost per Peak Hour [x1000]

Experiment	**1**	**2**	**3**	**4**	**5**
Passenger Cost [€]	2.561	2.566	2.543	2.184	2.205
Walk Costs [€]	837	841	836	808	805
In-Vehicle Costs [€]	1.112	1.122	1.112	920	930
Transfer Costs [€]	49,6	49,8	50,3	52,1	47,9
Waiting Costs [€]	562	554	545	404	422

2) Operator Cost: For the operator cost the fixed costs are linked to the amount of rolling stock and the variable costs are linked to the frequencies and line usage of these vehicles. For the experiments were interoperability is assumed (3 and 5), the investment costs that were found in chapter 4 and that were calculated back to one hour of operation are also added, Table VII shows the results.

TABLE VIII: Operator Cost per Peak Hour [x1000]

Experiment	**1**	**2**	**3**	**4**	**5**
Operator Cost [€]	179	175	179	198	182
Fixed Costs [€]	82,3	79,8	81,5	86,9	80,8
Variable Costs [€]	97,0	95,6	97,0	111	101
Investment Costs [€]	0	0	0,642	0	0,642

V. DISCUSSION

A. *General*

1) Experiment 1: 2019 With Planned Timetable: Experiment 1 set the base case base with which all of the other experiments will be compared. In experiment 1, the unserved demand is the lowest with more people using the urban rail network as their means of transport than any other of the experiments.

2) Experiment 2: 2040 With Planned Timetable: Experiment 2 showed how the plans of the municipality of Amsterdam would affect the urban rail network around Amsterdam. This experiment shows the highest amount of passengers choosing to travel by train. Out of all of the experiments it has the lowest operator costs, which can be traced back to the decrease in metro lines.

3) Experiment 3: 2040+ With Planned Timetable: Experiment 3 used the configuration of experiment 2 with added interoperability between metros and trains between station Zuid and Hoofddorp. In this experiment the metro lines get use most intensive out of all the experiments, a major increase in the use of line 52 can be seen with almost twice as much people using this line when compared to the other experiments.

4) Experiment 4: 2040 Optimization: In experiment 4, in which the timetable of experiment 2 was optimized, it can be seen that the metro configuration does not change substantially when compared to its base case, the frequencies are the same as in the original configuration but the capacities decrease from 1000 per metro to 500 a metro. The system optimizes in a way that results in the elimination of 5 train lines when compared to experiment 2. The train lines that remain mostly increase in frequencies thus being able to serve more people. The train lines that remain do skip stations resulting in less transfer possibilities. The experiment has the lowest overall cost as a result of the optimization, this translates to a decrease in passenger costs but an increase in operator costs.

5) Experiment 5: 2040+ Optimization: In experiment 5, in which the timetable of experiment 3 was optimized, it is interesting to see that the interoperability between metros and trains between station Zuid and Hoofddorp was not part of the result. Apparently this solution proved to be to expensive when compared to other results and was eliminated from the solution set early on in the optimization. The optimization resulted in a timetable similar to that of experiment 4, but less stations were skipped. The initial result of experiment 5 was complemented with the extension of the Noord/Zuidlijn to Schiphol and Hoofddorp. This extension resulted in lower overall costs thus being an optimization of the initial result.

B. Train Kilometres Provided

For experiments 1, 2 and 3, the train kilometres are the same for all of the mainline trains as the same timetable is used. For the metro lines experiment 1 has the lowest value (as a result of the unbundling) and experiment 3 has the highest value(due to the extension to the Noord/Zuidlijn).

In the experiment where the 2040 scenario was used and optimized (experiment 4), it is interesting to see that the metro kilometres remained the same as the frequencies of those lines did not change in the optimized version. The train kilometres however did increase, this is interesting because the amount of lines decreased with five lines. However the train lines that remained, increase in frequency eventually resulting in a higher amount of train kilometres.

A similar but less extreme result as in experiment 4 can be seen in experiment 5 with an increase in the metro kilometres by the interoperability and an increase in the train kilometres provided.

The changes in provided train kilometres are visualised in Figure 4.

Fig. 4: Train Kilometres Provided

C. Unserved Demand

In experiments 1, 2 and 3, the total amount of passengers is roughly the same, but there is a shift in the modal split (Figure 6), especially between experiments 1 and 3. In experiment 3 less people use the train and more people use the metro. Experiment 3 has the highest metro use out of all the experiments.

In the optimization experiments (4 and 5) there is a decrease in the total amount of passengers. This is interesting because more train kilometres are provided but apparently less passengers use these extra train kilometres.

Figures 5 and 6 show the line use of the total rail system.

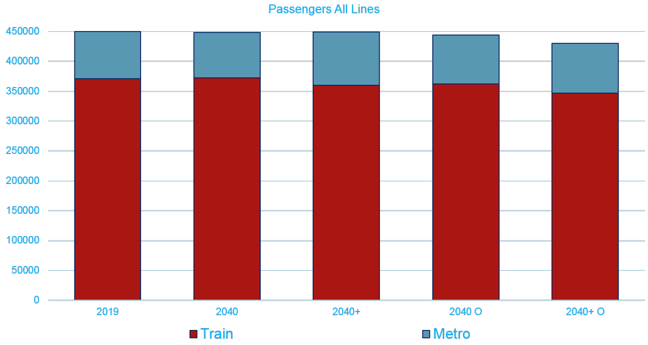


Fig. 5: Total Passengers

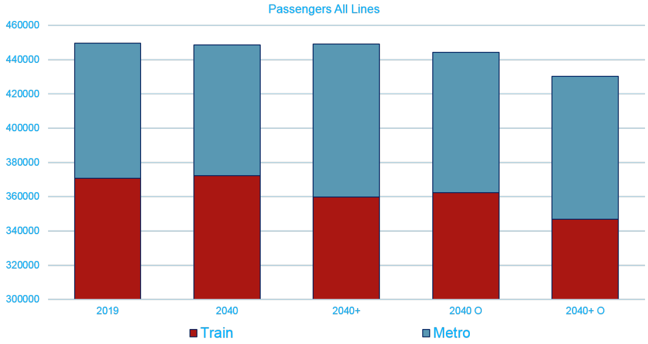


Fig. 6: Total Passengers (Zoomed View)

Figure 7 shows the line use of the metro subsystem, for the metro line use, interoperability (as used in experiments 3 and 5) contributes to the overall metro line use, especially on the extended line 52.

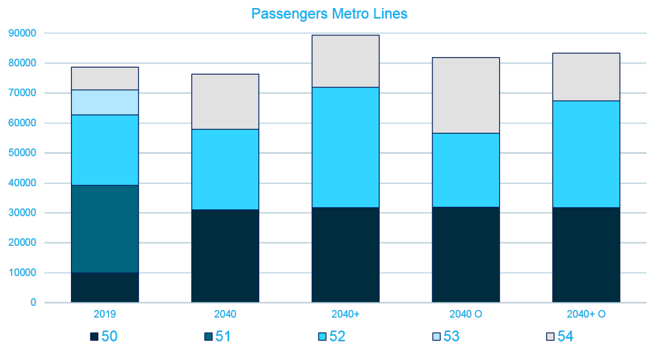


Fig. 7: Passengers Metro Lines

D. Stop Use

Figures 8 and 9 show the difference in both access/egress passengers as well ass the difference in transfer passengers for the four key stations as mentioned before. The graphs are followed by some more in-depth discussion on stations where significant changes to the base case scenario occurred are discussed, this discussion consists of a comparison to the base case scenario (experiment 1).

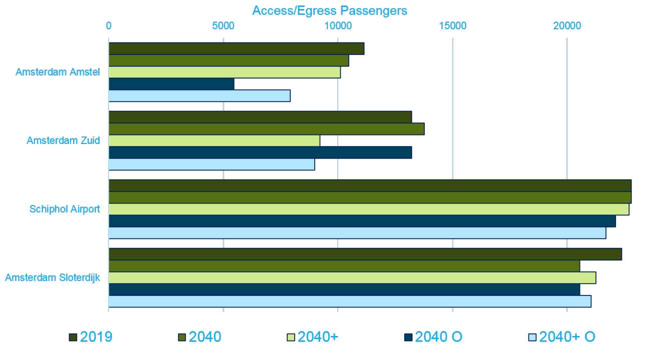


Fig. 8: Stop Use Access and Egress Passengers

Fig. 9: Stop Use Transfer Passengers

1) Experiment 2: The difference between experiment 2 and the base case is the unbundling of the metro network of Amsterdam.

The differences in access and egress passengers between experiment 1 and experiment 2 are not significant. The only minor negative is the increase in passengers at Amsterdam Centraal, this is one of the stations that already is quite busy and where it would be an improvement if less people used it as their access or egress station. But overall, the changes are not significant. Station Duivendrecht also is used more as a first/last stop.

For the transfer passengers, Amsterdam Zuid has a slight relieve and Van der Madenweg gets busier with transfer passengers. Because of the unbundling of the network the amount of transfer stations between the lines decrease and the increase in transfers here makes sense as this is the station where transfers between line 50 and line 53 are possible.

2) Experiment 3: The difference between experiment 3 and the base case is, in addition to the unbundling of the metro network, the extension of line 52 to Schiphol and Hoofddorp.

For this experiment the stop use as an access/egress stop, a switch is noticeable from station Zuid (-4000 passengers/hour) to station Amstelveenseweg (+3984 passengers/hour). The stations along line 52 get more crowded in general while the stations along line 54 get less crowded.

For transfers, station van der Madeweg still has a significant increase in transfer passengers and the switch between station Zuid and station Amstelveenseweg can also be seen here. There are also more transfers at Schiphol and Hoofddorp as a result of the extension of line 52. At Schiphol this might present an issue as this is already quite a crowded station.

3) Experiment 4: The difference between experiment 4 and the base case is, in addition to the unbundling of the metro network, a change in the train network around Amsterdam. Some train lines have been eliminated and the remaining trains often have an increased frequency.

For the difference in access and egress passengers results in an increase in Amsterdam Centraal Station that is most noticable (+5571 passengers/hour) and a decrease at Amstel Station (-5671 passengers/hour). This decrease in Amstel is a result of the fact that no more trains will stop at Amstel station in this optimized timetable.

Because no more trains stop at Amstel there are no more transfers possible at that station resulting in no transfer passengers. The transfer passengers shift to the train stations at the perimeter of the city, such as station Sloterdijk and station Bijlmer ArenA. The increase to van der Madeweg is still present in this scenario as is the shift from station Zuid to station Schiphol, in this experiment however, this is not a result of the continuation of a metro line, but as a result of less trains stopping at station Zuid than in the base case.

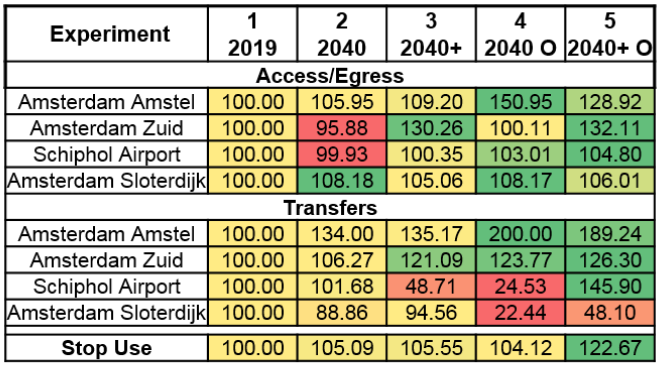
4) Experiment 5: The difference between experiment 5 and the base case is, in addition to the unbundling of the metro network, a change in the train network around Amsterdam. Some trains have been cancelled and the remaining trains often have an increased frequency. The Noord/Zuidlijn was extended to Schiphol and Hoofddorp.

In experiment 5, a lot happens for access and egress stations. For the metro lines stations along line 54 get used less whereas stations along line 52 get busier. The trade-off in passengers between Zuid (-4245 passengers/hour) and Amstelveenseweg (+3638 passengers/hour) as a result of the extension of line 52 is noticeable. A decrease in access/egress passengers is seen at stations Sloterdijk and Schiphol.

The shift in transfer passengers is high at Schiphol where almost a halving in the number of transfer passengers can be seen. These transfer passengers probably switch to Hoofddorp and Amstelveenseweg. Furthermore an increase is seen at station Sloterdijk and a decrease at stations Zuid and Amstel.

5) Performance Stop Use: The performance rating for the stop use will be based on how much the found solution relieves the bottleneck stations: Amsterdam Amstel, Amsterdam Zuid, Schiphol Airport and Amsterdam Sloterdijk. A decrease in both transfers as well as access/egress passengers would be an improvement to the performance of the system. Table IX shows how the performance values on stop use is created. Here a result higher than 100 means that this experiment scores higher on this KPI than the base case scenario, a score lower than 100 means that it scores worse. The colours correspond with the level of performance.

TABLE IX: Performance Rating Stop Use



Experiment	**1** **2019**	**2** **2040**	**3** **2040+**	**4** **2040 O**	**5** **2040+ O**
Access/Egress					
Amsterdam Amstel	100.00	105.95	109.20	150.95	128.92
Amsterdam Zuid	100.00	95.88	130.26	100.11	132.11
Schiphol Airport	100.00	99.93	100.35	103.01	104.80
Amsterdam Sloterdijk	100.00	108.18	105.06	108.17	106.01
Transfers					
Amsterdam Amstel	100.00	134.00	135.17	200.00	189.24
Amsterdam Zuid	100.00	106.27	121.09	123.77	126.30
Schiphol Airport	100.00	101.68	48.71	24.53	145.90
Amsterdam Sloterdijk	100.00	88.86	94.56	22.44	48.10
Stop Use	100.00	105.09	105.55	104.12	122.67

E. Overall Costs

The result of the cost function gives an indication of both passenger and operator cost. With the passenger cost being a representation of the passenger satisfaction. Here a lower result means lower costs thus better performance. In experiments 4 and 5, an optimization model was used with the goal to minimize the overall costs, so it makes sense that in these experiments the overall cost are lower than in the experiments where the original timetable was used (1, 2 and 3).

Figures 10, 11 and 12 show the different components that make up the costs. Overall experiment 4 has the lowest cost and experiment 2 the highest, this is visualised in Figure 10.

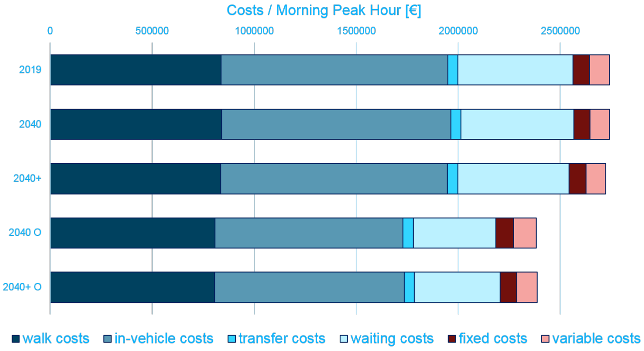


Fig. 10: Cost Component Comparison

1) Passenger Satisfaction: From the passengers side the performance of experiment 4 is the highest and experiment 2 is the lowest. In experiment 4, travellers spend the least time in vehicles and the least time on waiting, they do however have to transfer the most. This can be traced back to the fat that in the 2040 optimization experiment, the solution contained fewer train lines than the base case scenario. So the remaining train lines have higher frequencies but passengers do have to transfer more often. In experiment 5, where the optimized timetable is complimented with interoperability, passengers have to spend the least time on walking and they also have to transfer the least. The monetised passenger satisfaction results are shown in Figure 11 with lower costs equalling better performance.

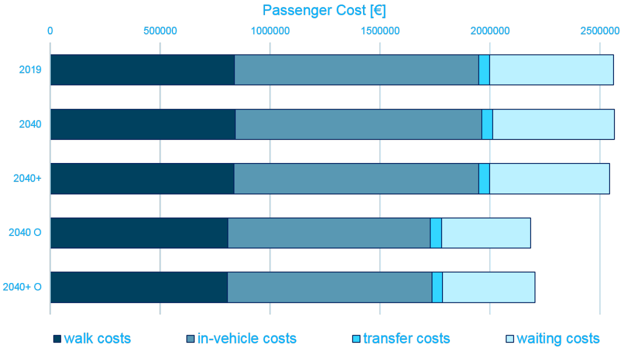


Fig. 11: Passenger Cost Component Comparison

2) Operator Cost: From an operator point of view, experiment 1 has the best result and experiment 4 the worst. For the operator costs, the investment costs needed for interoperability are included in experiments 3 and 5. Both the fixed and the variable cost are the highest in experiment 4, this is due to the high frequencies of the trains in the system and the most amount of train kilometres provided out of all the experiments. The operator cost results are shown in Figure 12.

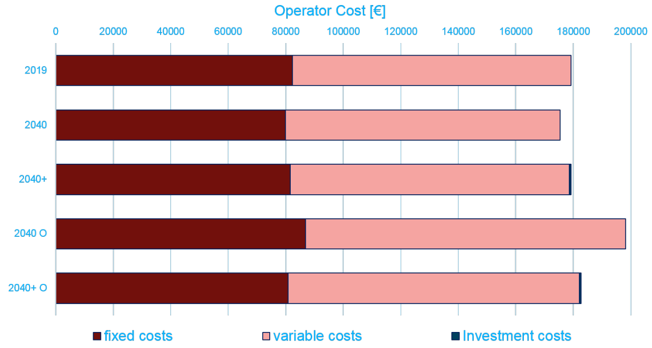


Fig. 12: Operator Cost Component Comparison

VI. CONCLUSIONS

The aim of this research was to answer the following question: *What is the effect of interoperability on the performance of the urban rail network of the Amsterdam metropolitan area?*

The effect of the different experiments on the performance of the rail network will be assessed by comparing them (percentage) to the base case scenario (experiment 1). A higher performance than the base case will result in a score higher than 100%, a lower performance in a lower score. The performance of rail systems is complex to measure, so for the table below the choice was made to use equal count for each of the KPIs. The table already is a simplified representation of the true **influence** of the different scenarios on the performance and this type of representation was chosen to truly show the complexity and diversity of rail systems. The decision that are taken under consideration in a multi-actor system are about more than just costs. When all of the experiments are graded all of the performances are added up and the average is taken. The effect of the different experiments on the different KPIs can be seen in Table X. The colours correspond with the level of performance.

TABLE X: Performance Rating

Experiment	1	2	3	4	5
	2019	2040	2040+	2040 O	2040+ O
Train Kilometres Provided	100.00	99.39	100.76	114.33	106.70
Unserved Demand	100.00	99.76	99.92	98.80	95.68
Stop Use	100.00	105.09	105.55	104.12	122.67
Walking Distance	100.00	99.55	100.14	103.49	103.76
In-Vehicle Travel Time	100.00	99.12	100.04	117.26	116.39
Waiting Time	100.00	101.54	103.08	128.18	125.06
Transfers	100.00	99.52	98.47	94.91	103.29
Operator Cost	100.00	102.15	100.06	89.48	98.07
Performance	100.00	100.76	101.00	106.32	108.95

To assess the effect of interoperability, experiments 3 and 5 are the ones to look at, as these are the experiments where the Noord/Zuidlijn continues its path to Schiphol and Hoofddorp. Here experiment 3 uses an original timetable and experiment 5 uses an optimized timetable. When compared to the 2019 scenario, both of these experiments show an improved performance.

When graded from best performance to worst performance the experiments are rated in the following way [1]:

1) ***Experiment 5: 2040+ Optimized***
2) *Experiment 4: 2040 Optimized*
3) **Experiment 3: 2040+**
4) Experiment 2: 2040
5) Experiment 1: 2019

The base case (2019) is does not have optimal performance and improvements are feasible, the current plans released by the municipality of Amsterdam (2040) are an improvement to the base case performance but are still not optimal. When interoperability is added to these plans (2040+) an even better performance is achieved. And when interoperability is combined with an optimized timetable, the biggest improvement to the performance can be achieved.

All of the optimization experiments score higher than the base case scenario, this means that part of the improvement in performance lies in the optimization of the timetable.

The interoperability has the biggest positive influence on stop use and the passenger waiting time. Overall, the interoperability has a positive effect on the performance of the urban rail network of the Amsterdam metropolitan area.

When the different configurations were tested with the public transport demand for 2040, it became evident that there are configurations possible in which the performance of the urban rail system can be improved when compared to the current configuration. The improvements in performance are achieved in twofold:

- An optimized timetable (frequencies and stopping patterns)
- Interoperability between metros and the train infrastructure

Figure 13 shows the differences in performance visually, the green experiments are those without an optimized timetable, the blue experiments are those with an optimized timetable. The lightest green (2040+) and lightest blue (2040+ O) are the experiments with interoperability.

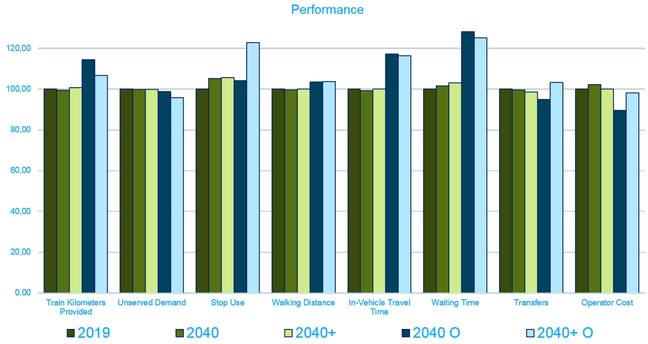


Fig. 13: Performance Comparison

Overall interoperability between metro and train systems improves the performance of the urban rail network of the Amsterdam metropolitan area.

---

[1] Experiments with added **interoperability** are in bold, experiments with *optimized timetable* in italic.

A. *Acknowledgements*

This paper was created with the help of the experts at Royal HaskoningDHV and the TU Delft, it is based on the work by [Dammers, 2018]. For the modelling part of this research, the thesis by [Van Beurden, 2017]

REFERENCES

[Arpaci et al., 2016] Arpaci, M., Eichhorn, M., and others (2016). Case study: Coexistence of CBTC and etcs on crossrail project in London. *CORE 2016: Maintaining the Momentum*, page 20.

[Bruner and Rizzetto, 2008] Bruner, M. and Rizzetto, L. (2008). Dynamic simulation of tram-train vehicles on railway track. *WIT Transactions on the Built Environment*, 101:491–501.

[CENELEC, 2014] CENELEC (2014). Standardization in research and innovation projects.

[CPB/CBS, 2015] CPB/CBS (2015). Toekomstverkenning Welvaart en Leefomgeving. Nederland in 2030 en 2050: twee referentiescenarios. *Den Haag: Planbureau voor de Leefomgeving/Centraal Planbureau.*

[Dammers, 2018] Dammers, N. (2018). Interoperability in rail systems. The influence of interoperability on the performance of an urban rail system. Technical report, TU Delft.

[Europeese Rekenkamer, 2017] Europeese Rekenkamer (2017). Speciaal verslag - Eén Europees beheersysteem voor het spoorverkeer: zal de politieke keuze ooit werkelijkheid worden? (13):1977–2017.

[Garritsen et al., 2017] Garritsen, M., van het Groenewoud, O., Buursink, E., Veldhuijzen van Zanten, R., Spee, D., and van Luit, N. (2017). Uitbreiding metronet Amsterdam. Technical report.

[Griffin, 2001] Griffin, T. (2001). Shared track -a new dawn ? pages 15–22.

[Gurník, 2016] Gurník, P. (2016). Next Generation Train Control (NGTC): More Effective Railways through the Convergence of Main-line and Urban Train Control Systems. *Transportation Research Procedia*, 14:1855–1864.

[Ministerie van Infrastructuur en Milieu, 2017] Ministerie van Infrastructuur en Milieu (2017). Nationale Markt- Markt en Capaciteitsanalyse 2017 (NMCA) Hoofdrapport. 2017:1–62.

[Nederlands Normalisatie Instituut, 2016] Nederlands Normalisatie Instituut (2016). NEN-EN-IEC 62290-1:2014 en. Railway applications Urban guided transport management and command / control systems, Part 1: System principles and fundamental concepts.

[Phraner, 2002] Phraner, S. D. (2002). International Transit Studies Program, Report of the Spring 2000 Mission. Germany's Track-Sharing Experience: Mixed Use of Rail Corridors. (47).

[Phraner et al., 1999] Phraner, S. D., Board, N. R. C. U., Corporation, T. D., and Program, T. C. R. (1999). *Joint operation of light rail transit or diesel multiple unit vehicles with railroads*.

[ProRail, 2017] ProRail (2017). NMCA Spoor 2030 2040 Achtergrondrapportage. (april):1–96.

[Schipholt, 1993] Schipholt, L. R. L. (1993). Integratie Hoekse lijn - metro Rotterdam : perspectief of illusie ?

[Schmelzer, 2015] Schmelzer, C. (2015). Standardization of CBTC Systems Mixed Operation on Shared Lines in accordance with ERTMS/ETCS Standards.

[Tirachini et al., 2010] Tirachini, A., Hensher, D. A., and Jara-Díaz, S. R. (2010). Comparing operator and users costs of light rail, heavy rail and bus rapid transit over a radial public transport network. *Research in Transportation Economics*, 29(1):231–242.

[Van Beurden, 2017] Van Beurden, M. (2017). Stopping pattern and frequency optimization for multiple public transport services.

[van Lieshout, 2016] van Lieshout, M. (2016). ProRail: trek Noord-Zuidlijn door tot Schiphol via ons spoor - Economie - Voor nieuws, achtergronden en columns.

B

Complete System Analysis

This Appendix contains the complete system analysis performed on the train and urban rail system. The highlights of this analysis were discussed in Chapter 3.

B.1. Train Railway System

For the train system, the Dutch national railway system will be analysed, which consists of the ProRail network when looking at infrastructural aspects, and the trains of the Nederlandse Spoorwegen (NS) when the subject is the rolling stock.

B.1.1. Infrastructure

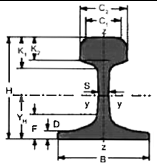
Track Gauge

Track gauge: the nominal rail gauge throughout the entire network is 1435 mm, in accordance with EN 13848-1 (minimum 1430mm, maximum 1450mm).

Rail Profile

The most common used rail profile on the Dutch railway network is: 54 E1 (NP46 and UIC 60 can also be found), Table B.1 shows the corresponding dimensions.

Table B.1: Rail Dimensions 54 E1 (Esveld, 2001)

	H Rail Height [mm]	B Base Width [mm]	C_1 Head Width [mm]	C_2 Head Width [mm]	S Web [mm]	K_1 Total Head Height [mm]	K_2 Head Height [mm]
54 E1	159,00	140,00	70,00	72,20	16,00	49,40	36,30
Continuation	F Base Height [mm]	D Base Thickness [mm]	A Cross Section $[mm^2]$	G Weight [kg/m]	Y_h Neutral Axis [mm]	J_x Moment of Inertia $[cm^4]$	W_x Section Modulus Head $[cm^3]$
Continuation	31,50	11,50	7687	60,34	80,90	3055	335,50

Axle Load

The allowable axle loads are shown Appendix C, Figure C.1. ProRail has the following to say about axle loads on their network (Prorail, 2018):

- Load class C2 is permitted throughout the network.
- On large parts of the network, including all route sections that are part of the international freight corridors, loading class D4 is permitted under the special transport conditions.
- The rail vehicle must not be loaded heavier than the highest value allowed for that vehicle.

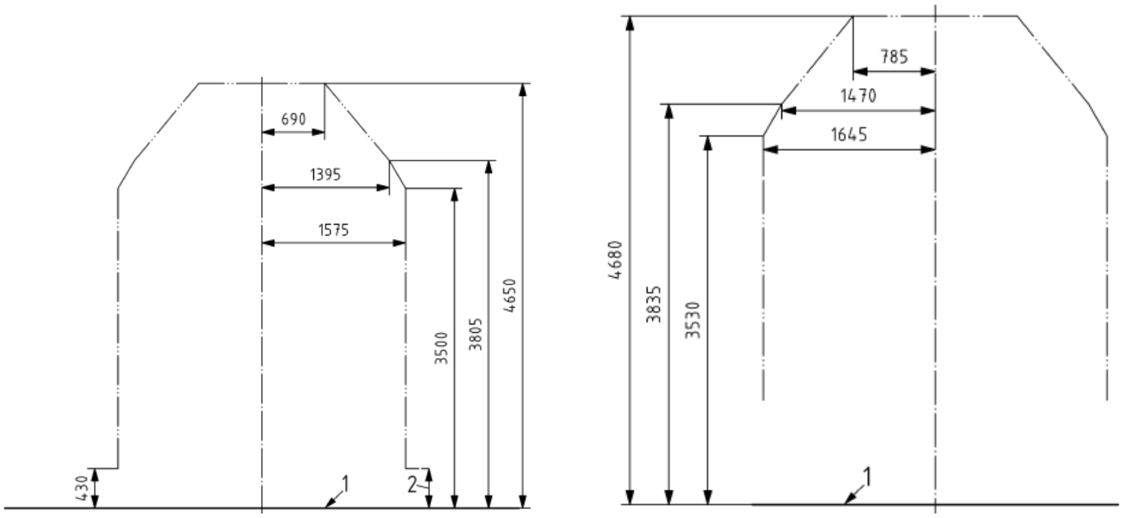
Load Gauge

ProRail says the following about the load gauge on their network(Prorail, 2018):

- Railway vehicles (including cargo) whose reference profile complies with G2 are permitted on all railways managed by ProRail.
- Railway vehicles (including cargo) whose reference profile complies with GC are permitted on the routes identified as GC or NL-2 in Appendix C, Figure C.2.
- Railway vehicles (including cargo) whose reference profile complies with NL-1 are permitted on the routes identified as NL-1 or NL-2 in Appendix C, Figure C.2.
- Railway vehicles (including cargo) whose reference profile complies with NL-2 are permitted on the routes marked as NL-2 in Appendix C, Figure C.2.

- Railway vehicles (including cargo) whose reference profile does not fit within it reference profile of the route section to be travelled are regarded as Exceptional Transport.
- Rail vehicles used on border-line rail sections must also comply with the profile requirements of the adjacent rails.

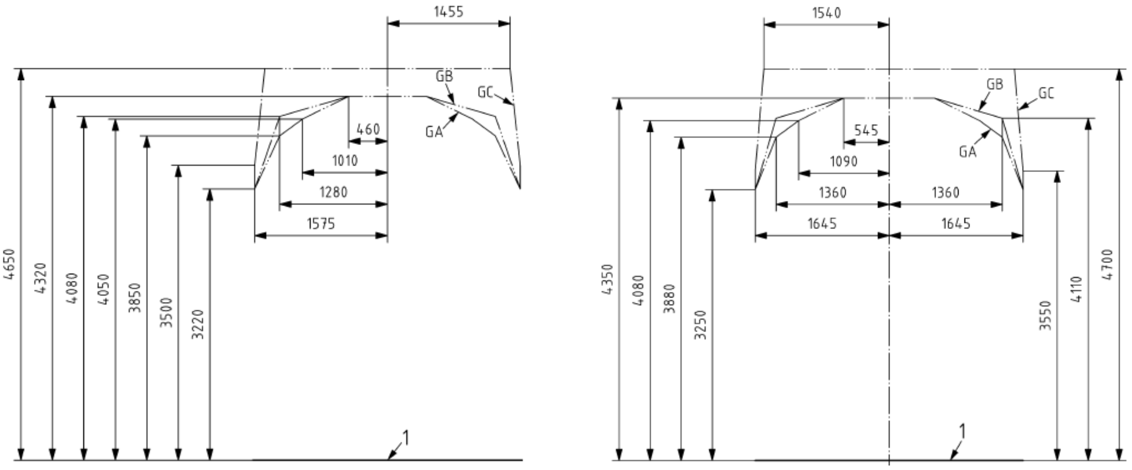
The four different load gauges described in this list are: G2, GC, NL-1 and NL-2 for G2 and GC there are static as well as kinematic gauges, for NL-1 and NL-2 there are only kinematic gauges.



(a) G2 Static

(b) G2 Kinetic

Figure B.1: Reference profile of static and kinematic gauges G2 (Nederlands Normalisatie Instituut, 2017)



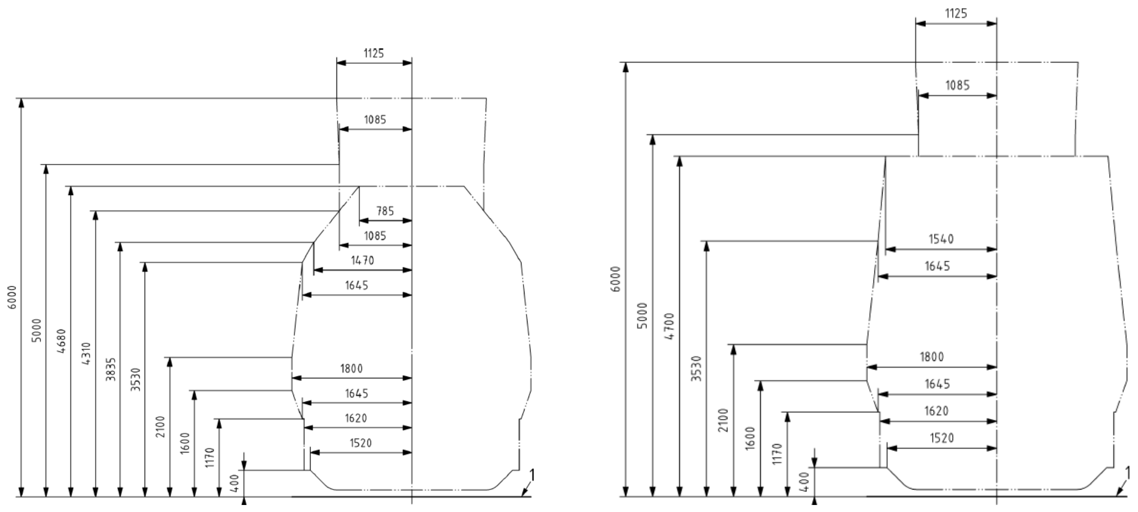
(a) GC Static

(b) GC Kinetic

Figure B.2: Reference profile of static and kinematic gauges GC(Nederlands Normalisatie Instituut, 2017)

The associated rules for G2 and GC are the following:

- $l_{nom} = 1,435$m: the nominal track gauge
- $l_{max} = 1,465$m: the maximum track gauge
- $L = 1.5$m: the standard distance between the centrelines of the rails of the same track.



(a) NL1 Kinetic

(b) NL2 Kinetic

Figure B.3: Reference profile of kinematic gauges NL1 and NL2 (Nederlands Normalisatie Instituut, 2017)

The associated rules for NL1 and NL2 are the following:

- $l_{nom} = 1,435$m: the nominal track gauge
- $l_{max} = 1,450$m: the maximum track gauge
- $L = 1.5$m: the standard distance between the centrelines of the rails of the same track.

Radius of Curvature

For railways in the Netherlands, the curve radius has a minimum of 190 meters on track sections where the maximum speed is 40 km/h, when a higher maximum speed is allowed the minimum radius is 400 meters. At platforms, ProRail applies a horizontal curve radius that generally is not smaller than R=1000m. Curve radii smaller than 250m occur in incidental cases owing to spatial restrictions(Prorail, 2018).

Power Supply

In Appendix C, Figure C.3, information can be found about the different power supplies in the Dutch railway network. The information includes(Prorail, 2018):

- The route sections fitted out with an overhead line for electrical tractive power supply
- The contact line voltage and any maximum current collection per route section in accordance with EN 50367
- The provisions at transition points to other contact line voltages.

The standard height of the overhead contact line in relation to the top edge of the rail is +5.50m. A different height may apply at the location of structural works, although the overhead contact line remains beyond the loading gauge locally applicable.

Stations and Nodes

The track plan of the Dutch Railway system is mapped out extensively with information on stations, number of platforms, types of railroad turnouts and more. Appendix D, Figure D.1, shows a part of such a plan for the route between Amsterdam Zuid and Schiphol.

ProRail has started an 'Adjust platform height accessibility programme aimed at bringing all platforms in the Netherlands to the standard height (based on European regulations and national agreements regarding rail accessibility).

An adjusted platform meets the following standards(Prorail, 2018):

- The platform height is at a height of 760mm +top of rail, with a tolerance in the management phase of -35/+30mm.
- The nominal distance between the edge of the platform to the centre of the track is 1700mm, with a maximum of 1735mm.

The following applies to platforms that have not yet been adjusted:

- Platform heights may range from a minimum of 500mm to a maximum of 1000mm +top of rail.
- Situations exist where the distance from the edge of the platform to the centre of the track ranges from a minimum of 1650mm to a maximum of 1900mm.

The different platform length present on the ProRail network can be found in Appendix C, Figure C.5 and range from 90-340 meters.

Turnouts and Crossings
On the ProRail network the rules for the infrastructure design state the following about the turnouts and crossings present with corresponding maximum speeds. The fraction indicates the angle that the turnout makes (tangent of the turnout angle). (Hofstra et al., 2016):
Standard Turnout

- 40 km/hr: 1:9
- 60 km/hr: 1:12
- 80 km/hr: 1:15
- 80 km/hr: 1:18
- 140 km/hr: 1:29

Symmetric Turnouts

- 50 km/hr: 1:9
- 100 km/hr: 1:15
- 125 km/hr: 1:20

Slip Switch (Double/ Single) Slip Switches are preferably not used. In route sections with a section speed higher than 80 km/h these type of turnouts are not allowed at all.

- 40 km/hr: 1:9

Crossings Cross-turnouts are preferably not be applied when the track distance is less than 5.5 meter. The use of two switches is then preferred to a crossing. In track sections, with a track section speed higher than 80 km/h, crossings are not allowed at all.
Around stations the situation might be different as speeds are very low, more information about the turnouts and crossings around stations can be found in the corresponding trace plans.

Track Sections (network-configuration)
Figure C.4 in Appendix C shows the network configuration of the Dutch railway system. The Figure shows where there are single, double or multiple tracks with corresponding distances between the nodes. Figure C.6. shows the corresponding maximum travel speeds.

B.1.2. Safety and Communication Systems

The Dutch railways are fitted with signalling systems, as well as safety and communications systems to ensure the safe and controlled flow of traffic. All route sections and tracks that are designed for speeds greater than 40 km/h are equipped with a signalling system that monitors the relationship between the position of points, track occupation and signalling. Additional safety systems use automatic train control to monitor the maximum speed and correct signal performance(Prorail, 2018). Figure B.4 shows an overview of the safety measures present in railway systems.

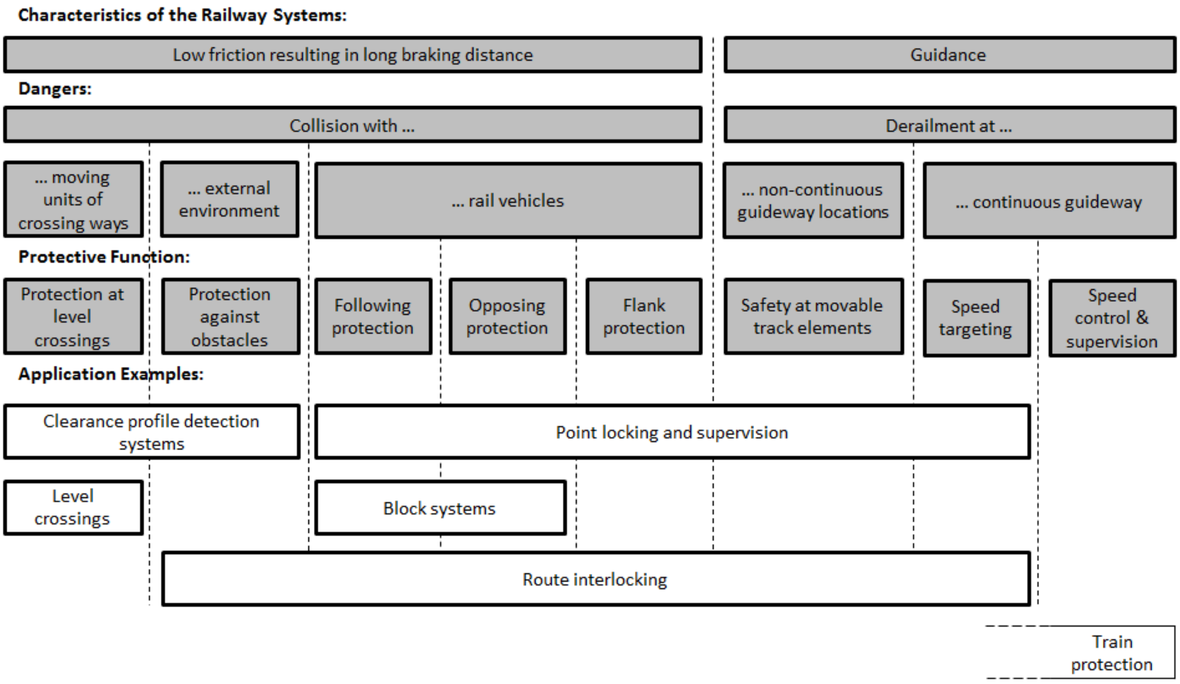


Figure B.4: Dangers and Safety Measures in Railway Operation (Issues Relevant to Signalling Only) (Theeg and Vlasenko, 2009)

Train Control System

A railway vehicles speed control is not just monitored by the driver, there is a train control system that kicks into action in the event of human failure. For the types of automatic train control (ATC) system per route section: see Figure C.7 ProRail is, as part of the ERTMS program, working on the plan development of the Rail map ERTMS. This means that 36 sections of the Dutch Railway network currently equipped with ATB will be replaced by ERTMS, this can be seen in Table B.2. This means for this research that ERTMS is the the control system that will be further discussed. The European Train Control System (ECTS) is the core signalling and train control component of the European Rail Traffic Management System (ERTMS). The system calculates and communicates the safe maximum speed and the maximum distance that the train is allowed to travel for each train with the driver. If one of these permitted values is exceeded, an on-board system takes control. ECTS enables the standardization of different national train control systems and it is the basis for interoperability between the on-board and line-side equipment.

ERTMS

All around Europe (and the world), different signalling and traffic regulation systems are being used. To enable more interoperability on the European rail network, the European Rail Traffic Management System (ERTMS) was created. The ERTMS can be applied on three different levels ranging from track to train communications (Level 1) to continuous communications between the train and the radio block centre (Level 2) to a more conceptual moving block technology (Level 3) (Unife the European Rail Industry, 2014). On the next pages the three levels will be discussed in more detail.

ERTMS Level 1, point-to-point train safety system with fixed blocks, and conventional train detection, can be added to lines that are already equipped with line-side signals and train detectors. The tracks and train communicate via balises (transponders) that are located on the track-side next to the line-side signals at required intervals. These are connected to the train control centre. The information that is received via these balises is communicated to the ECTS (European Train Control System) to calculate the maximum speed of the train and the next braking point if needed, taking into account the train braking characteristics and the track description data. This information is communicated to the driver via a screen in the cabin. The speed of the train is continuously monitored. This level has the advantage of enabling interoperability (between suppliers and countries) and safety, since the train will automatically brake if exceeding the maximum speed allowed under the movement authority.

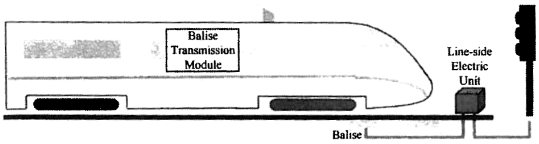


Figure B.5: ERTMS Level 1 (Profillidis, 2006)

ERTMS Level 2, cabin signalling based on radio-communication, conventional train detection, fixed blocks, does not need the line-side signals that ERTMS Level 1 needs. The movements are communicated directly from a Radio Block Centre (RBC) to the on-board unit using GSM-R (a radio communication system). The balises are only used to transmit “fixed messages” such as location, gradient, speed limit, etc. A continuous stream of data informs the driver of line specific data and signals status on the route ahead, allowing the train to reach its maximum or optimal speed but still maintaining a safe braking distance factor. This level has the same advantages of level 1 plus it enables reductions in maintenance costs because no line-side signals are needed. The line capacity can also be increased by enabling higher operational speeds and offering reduced headways.

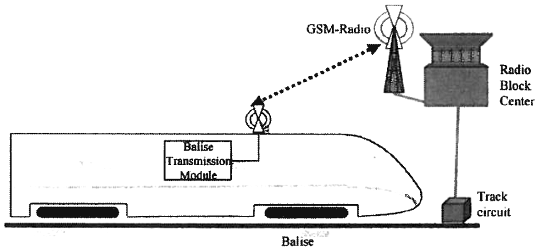


Figure B.6: ERTMS Level 2 (Profillidis, 2006)

ERTMS Level 3, cabin signalling based on radio-communication, the train reports its own position, fixed or moving blocks, introduces a “moving block” technology. This technology enables accurate and continuous position data that is supplied to the control centre directly by the train, rather than by track based detection equipment. As the train continuously monitors its own position, there is no need for “fixed blocks” – rather the train itself will be considered as a moving block. So this level enables the desk operator to follow the trains in real-time on the tracks and can increase the capacity of a line.

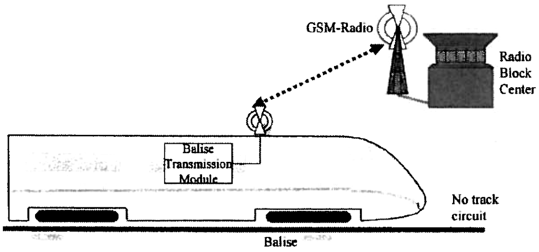


Figure B.7: ERTMS Level 3 (Profillidis, 2006)

Table B.2: Implementation of ERTMS on Dutch Network (Prorail, 2018)

North		South	
Section	Year	Section	Year
Haarlem e.o.	2024	Kijfhoek - Roosendaal	2024
Leiden - Den Haag	2025	Roosendaal - ’s-Hertogenbosch	2025
Leiden - Hoofddorp - Duivendrecht	2026	Meteren - Eindhoven	2026
OV SAAL	2027	Utrecht - Meteren	2027
Asd Centraal	2029	Utrecht	2028
Hilversum - Utrecht/Amersfoort	2028	Eindhoven - Venlo	2027
Utrecht - Amersfoort	2029	Utrecht Arnhem	2029
Amersfoort - Zwolle	2030	Arnhem - Zevenaar	2030
Zwolle	2031	Arnhem - Nijmegen	2030
Zwolle - Meppel	2032	Rotterdam	2031
Rotterdam - Utrecht	2033	Den Haag - Rotterdam	2031
Den Haag - Gouda	2034	Vlissingen - Roosendaal	2032
Leiden - Gouda e.o.	2035	Venlo Roermond	2033
Alkmaar - Amsterdam	2035	Roermond - Sittard	2033
Meppel - Groningen	2035	Nijmegen - Venlo	2034
Meppel - Leeuwarden	2036	Merwede Lingelijn	2035
Amersfoort - Barneveld	2037		
Barneveld - Deventer	2037		
Deventer - German Border	2037		
Barneveld - Ede Wageningen	2038		

Signalling Systems

The main purpose of this signalling is safety, but this type of safety also ensures the traffic regularity. Signalling enables capacity optimization. Light signalling happens continuously and automatically. Light signalling is active when two trains run on the same track and determines whether any other train is present at some point of the track(Profillidis, 2006). Figure B.8 shows how light signalling works on the ProRail network, Table B.3 shows which different signalling systems are installed on the Dutch railway network.

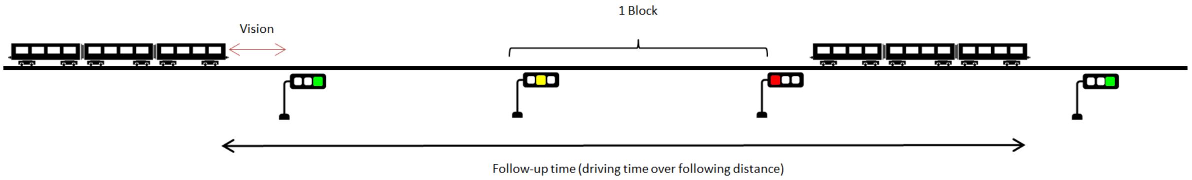


Figure B.8: Light Signalling

Table B.3: Type of signalling system per route section (Prorail, 2018)

Route section	Applicable signalling system
Hoofddorp – Rotterdam Centraal (forming part of the HSL-Zuid)	Single signalling system ERTMS Level 2 version 2.3.0 corridor with cabin signalling via ETCS. The fall-back signalling system is ERTMS Level 1.
Rotterdam Lombardijen – Hazeldonk border (forming part of the HSL-Zuid)	
Maasvlakte – Barendrecht Vork (forming part of the Betuweroute)	Single signalling system ERTMS Level 1 version 2.3.0.d. Light signalling system.
Barendrecht Vork – Kijfhoek Zuid (forming part of the Betuweroute)	Dual signalling: - ERTMS Level 1 version 2.3.0.d. - ATB and light signalling system. Trains equipped with only ATB, and trains with ERTMS/ETCS can run simultaneously.
Kijfhoek-Zuid – Zevenaar Betuweroute connection (forming part of the Betuweroute)	Single signalling system ERTMS Level 2 version 2.3.0d with cabin signalling via ETCS.
Zevenaar-Oost – Zevenaar border	Single signalling system ERTMS Level 2 version 2.3.0d with cabin signalling via ETCS.
Amsterdam Duivendrecht – Utrecht (Amsterdam-Utrecht)	Dual signalling: - ERTMS Level 2 version 2.3.0d with cabin signalling via ETCS. - Light signals, supported by cabin signalling via ATB.
Lelystad stabling yard connection – Hattemerbroek connection (Hanzelijn)	
Enschede – Enschede border	Local operation of signals by train personnel using an infrared remote control system.
Winterswijk – Doetinchem	
Groningen – Leeuwarden	
Other route sections	Light signals, supported by cabin signalling via ATB or ETCS.

Traffic Control Systems

ProRail is responsible for the coordination of train traffic for all parties that use the Dutch railways on a daily basis.

ProRail ensures that trains can run according to the timetable. This daily process is largely automated: turnouts, signals and bridges are automatically operated. When conflicts occur or exceptions to the regular timetable are made, the national traffic control of ProRail takes action, which restores the trains as quickly as possible. The national traffic control of ProRail operates from the Operational Control Centre Rail (OCCR) in Utrecht, the joint control centre of ProRail, several transporters and contractors. The OCCR has an emergency centre that in direct contact with police, fire brigade and other emergency services in case of calamities. (ProRail, 2018b)

Communication systems

The Dutch railways, managed by ProRail, are fitted out with GSM-R, an internationally standardised digital radio-communication system. GSM-R is suitable for data communication between ETCS systems and voice communication between the driver and traffic control.

Train Detection Systems

It is important that the integrity of a train as a whole on a track section is ensured. This section describes the train detection systems that verify that. Detection systems can be classified according to different criteria (Theeg and Vlasenko, 2009): Axles or wheels of the rail vehicle, the body of the rail vehicle, other passive parts of the rail vehicle (e.g. the pantograph) or by particular active communication devices on the train.

On the Dutch Railway network several train detection systems are active to have enough information about track occupation. Which train detection systems are in use on which route section is stated in Appendix C, Figure C.8. The two most used will be discussed below.

A way of detecting if there is a train on a particular section of the track is by using a track circuit. In this detection system, a current flows from a battery through the rails, if an approaching train reaches the section the axles short circuit the current, if this happens a signal that was green, turns red.

In contrast to the track circuit, the axle counting system uses indirect detection. The track section is clear if the same number of axles entered at the beginning have left the track section at the end. If this condition is not fulfilled, the track section will be considered occupied (Theeg and Vlasenko, 2009).

Interlocking is a key function of a safety system ensuring the safe technical movement of trains. The interlocking system receives information about track occupation and the position of movable track elements, evaluates this information and allows movements via signals (Theeg and Vlasenko, 2009).

Railway vehicles must at all times be compatible with the train detection systems installed on the route sections on which the vehicles are run, which in any event includes compatibility as regards shorting and circuit behaviour (train-track).

B.1.3. Rolling Stock

For this section, the characteristics of the trains that use the ProRail network that could benefit from track sharing with the Amsterdam metro will be investigated.

The rolling stock currently used by the NS (or in close collaboration with the NS) can be seen in Table B.4, the different characteristics can be found in Tables B.5-7.

Table B.4: Rolling Stock Active on ProRail Network

Sprinters	**Intercitys**	**International Transport and High Speed Trains**
SLT (4 or 6 Carriages)	VIRM (4 or 6 Carriages)	Thalys
FLIRT (3 or 4 Carriages)	DDZ (4 or 6 Carriages)	Intercity Direct (ICD)
SNG (3 or 4 Carriages)	ICM (3 or 4 Carriages)	Intercity Express (ICE)
	ICNG (5 or 8 carriages)	IC Brussels
		IC Berlin

Table B.5: Geometric Characteristics NS Material (blanks are unknown)

Train	**Length**	**Width**	**Height**	**Floor Height**	**Loading Gauge**	**Doors**	**Wheel Diameter**
SLT 4	69,36 m	2,84 m	4,21 m	1055 mm (high) 850 mm (low)	G1	12	850 mm
SLT 6	100,54 m	2,84 m	4,21 m	1055 mm(high) 850 mm (low)	G1	20	850 mm
FLIRT 3	63,20 m	2,82 m	4,12 m	1180 mm(high) 808 mm (balcony) 780 mm (low)	G1	6	693 mm (min) 760 mm (max)
FLIRT 4	80,70 m	2,82 m	4,12 m	1180 mm(high) 808 mm (balcony) 780 mm (low)	G2	8	693 mm (min) 760 mm (max)
SNG 3	59,56 m	2,88 m	4,3 m	760 mm	-	6	-
SNG 4	75,76 m	2,88 m	4,3 m	760 mm	-	8	-
VIRM 4	108,56 m	3,02 m	4,67 m	2444 mm (high) 1163 mm (balcony) 356 mm (low)	-	8	-
VIRM 6	162 m	3,02 m	4,67 m	2444 mm (high) 1163 mm (balcony) 356 mm (low)	-	12	-
DDZ 4	101,08 m	2,78 m	4,60 m	2434 mm (high) 1183 mm (balcony) 352 mm (low)	G1 (minus footboards and middle of the carriages)	8	840 mm (min) 920 mm (nominal)
DDZ 6	153,88 m	2,78 m	4,60 m	2434 mm (high) 1183 mm (balcony) 352 mm (low)	G1 (minus footboards and middle of the carriages)	12	840 mm (min) 920 mm (nominal)
ICM 3	80,6 m	-	4,65 m	1230 mm	G1 (minus footboards)	8	950 mm (powered wheels) 920 mm (non-powered wheels)
ICM 4	107,10 m	-	4,65 m	1230 mm	G1 (minus footboards)	6	950 mm (powered wheels) 920 mm (non-powered wheels)
ICNG 5	110 m	-	-	800 mm	-	-	-
ICNG 8	165 m	-	-	800 mm	-	-	-

Table B.6: Mechanic and Dynamic Characteristics NS Material (blanks are unknown)

Train	Weight	Power	Maximum Speed	Operating Speed
SLT 4	128,3 ton	1500 kW	160 km/h	140 km/h
SLT 6	175 ton	2000 kW	160 km/h	140 km/h
FLIRT 3	116 ton	2000 kW	160 km/h	140 km/h
FLIRT 4	137 ton	2000 kW	160 km/h	140 km/h
SNG 3	110 ton	2880 kW	160 km/h	140 km/h
SNG 4	138 ton	2880 kW	160 km/h	140 km/h
VIRM 4	262 ton	1608 kW	160 km/h	140 km/h
VIRM 6	391 ton	2412 kW	160 km/h	140 km/h
DDZ 4	225.4 ton	2400 kW	140 km/h	140 km/h
DDZ 6	369,5 ton	2400 kW	140 km/h	140 km/h
ICM 3	143,8 ton	1260 kW	160 km/h	140 km/h
ICM 4	192 ton	1890 kW	160 km/h	140 km/h
ICNG 5	-	-	200 km/h	200 km/h
ICNG 8	-	-	200 km/h	200 km/h

Table B.7: Operational Characteristics NS Material (blanks are unknown)

Train	Axle Load	Train Control System	Train Detection System
SLT 4	C2	STM ATB-EG and ETCS L2	Compatible with all train detection systems
SLT 6	C2	STM ATB-EG and ETCS L2	Compatible with all train detection systems
FLIRT 3	C2	ATB EG and ATB NG	Compatible with all train detection systems
FLIRT 4	C2	ATB EG and ATB NG	Compatible with all train detection systems
SNG 3	-	ATB EG and ETCS	Compatible with all train detection systems
SNG 4	-	ATB EG and ETCS	Compatible with all train detection systems
VIRM 4	-	ATB-EG	Compatible with all train detection systems
VIRM 6	-	ATB-EG	Compatible with all train detection systems
DDZ 4	13,9 ton - 16,9 ton and 2,3 ton/m - 2,8 ton/m A	ATB	Compatible with all train detection systems, no authorization on route sections with tonal frequency tracks
DDZ 6	13,9 ton - 15,3 ton and 2,1 ton/m - 2,6 ton/m A	ATB	Compatible with all train detection systems, no authorization on route sections with tonal frequency tracks
ICM 3	17,4 ton and 1,9 ton/m B1	ATB-EG	Compatible with all train detection systems
ICM 4	17,4 ton and 2,2 ton/m B1	ATB-EG	Compatible with all train detection systems
ICNG 5	-	ETCS, ATB-EG	Compatible with all train detection systems
ICNG 8	-	ETCS, ATB-EG	Compatible with all train detection systems

(Electrical) Traction System

All of the trains operated by the NS have a 1500 V DC voltage, supplied by an overhead line.

B.1.4. Stakeholders

ProRail

ProRail is responsible for the railway network in the Netherlands: construction, maintenance, management and safety. ProRail divides the available space on the track, arranges all train traffic, builds and manages stations and creates new tracks. They also maintain the existing tracks, points, signals and level crossings.

Other Stakeholders

There are multiple carriers that have an access agreement with ProRail and use the track, of which the biggest is the NS, but more parties in passenger traffic, freight traffic and other (non-)railway undertakings are stakeholders in the national network. It is clear that the more stakeholders involved, the more difficult introducing a new player can be. All of the traffic companies want to have the best possible use of the network. If a new player gets involved that is interested in occupying the network for a certain amount of time, it might cause conflict with stakeholders already involved.

B.1.5. Network

For trains, there are minimal stopping times at each station that are shown in Table B.8. These stopping times are purely based on technical vehicle characteristics.

Table B.8: Station Stopping Times(Hofstra et al., 2016)

Train Type	**Min. Stopping Time**
High-Speed line	2 min
Intercity	0,9 min
Sprinter	0,7 min

The minimum station time stated above are scheduled at small stations. At larger stations more time is needed for (de)boarding and transferring passengers, therefore 1 minute of buffering is added. This buffer time can also be used to absorb delays. Table B.9 indicates at which stations the minute buffer is added.

Table B.9: Tables with Altered Stationing Times (Hofstra et al., 2016)

Stations with 1 minute buffer time during stationing		
Alkmaar	Den Haag HS	Leiden C
Amersfoort	Deventer	Nijmegen
Amsterdam C	Dorrecht	Roosendaal
Amsterdam Zuid	Eindhoven	Rotterdam C
Arnhem	Groningen	Tilburg
Breda	Haarlem	Utrecht C
Den Bosch	Hoorn	Zwolle

A standard time of 2 minutes applies to cross-platform connections, for a cross-platform connection between two Intercity trains 3 minutes is used, for non cross-platform connection a standard of 6 minutes is applied.

The times allowed to reverse passenger trains, a time between 10 and 15 minutes is sought. If necessary, a shorter turnaround time of at least 4 minutes can be used. On the main rail network this can only be done if there is a switch operator, on regional lines it can also be done without the switch operator.

In collaboration with RHDV, ProRail drafted additional requirements to the stopping times stated above. These requirements enable reliable planning of the timetable and are based on simulations. The driving time to be planned consists of a technically minimal time plus driving tolerance. The stations where the stopping time will alternate from the stopping times stated before are shown in Tables B.10 and A.11, the Thalys will have even longer stopping times as can be seen.

Table B.10: Stations With Alternative Stopping Times (Hofstra, 2016)

Station	Direction	Stopping Time
Culemborg	Both	0,9 Minutes
Koog-Zaandijk	Wormerveer	0,9 Minutes
Krommenie-Assendelft	Wormerveer	0,9 Minutes
Muiderpoort	Amstel	0,9 Minutes
Oudenbosch	Both	1,1 Minutes
Veenendaal West	Veenendaal C	0,9 Minutes
Zevenbergen	Lage Zwaluwe	0,9 Minutes
Zoetermeer Oost	Zoetermeer	0,9 Minutes

Table B.11: Stations With Longer Stopping Times (Hofstra, 2016)

1 Minute	1,5 Minutes	2 Minutes	Exeptions
Almelo	Alkmaar	Amersfoort	
Alphen a/d Rijn	Almere C	Amsterdam C	Thalys (5 Minutes)
Amsterdam Bijlmer ArenA	Breda	Amsterdam Zuid	
Amsterdam Sloterdijk	Den Haag HS	Arnhem C	
Apeldoorn	Deventer	Eindhoven	
Assen	Dordrecht	’s-Hertogenbosch	
Bergen op Zoom	Haarlem	Roosendaal	
Breukelen	Hoorn	Rotterdam C	Thalys (4 Minutes)
Delft	Leiden C	Schiphol	Thalys (3 Minutes)
Ede-Wageningen	Nijmegen	Utrecht C	
Geldermalsen	Roermond	Zwolle	
Goes	Sittard		
Gouda	Tilburg		
Heerenveen	Venlo		
Heerhugowaard	Zutphen		
Heerlen			
Hengelo			
Hilversum			
Lelystad C			
Maastricht			
Oss			
Roermond			
Uitgeest			
Weesp			
Woerden			
Zaandam			

The time tabling for the Dutch rail has a base that is called the Basic Hour Pattern (Basis Uur Patroon), a timetable that repeats every 60 minutes. To this base the extra trains in rush hour are added, in the evening, at night and in the weekend other deviations might occur. This Basic Hour Pattern can be translated to all of the arrivals and departures on one specific station. Table B.12 shows all of the trains that have a stop at Schiphol Airport. Note that no freight transport uses the Schiphol corridor so these are currently the only trains using that specific track section.

Table B.12: Trains Stopping at Schiphol Airport

Series	Train Type	Route	Frequency/hr
700	Intercity	Den Haag Centraal– Schiphol Airport – Amsterdam Zuid – Lelystad Centrum – Zwolle – Groningen	1
900	Intercity direct	Amsterdam Centraal – Schiphol Airport – Rotterdam Centraal – Breda	2
1000	Intercity direct	Amsterdam Centraal – Schiphol Airport – Rotterdam Centraal	2
1400	Intercity	Utrecht Centraal – Amsterdam Centraal – Schiphol Airport – Den Haag HS – Rotterdam Centraal	1
1600	Intercity	Schiphol Airport – Amsterdam Zuid – Amersfoort – Deventer – Hengelo – Enschede	1
1800	Intercity	Den Haag Centraal – Schiphol Airport – Amsterdam Zuid – Lelystad Centrum – Zwolle – Meppel – Leeuwarden	1
2400	Intercity	Lelystad Centrum – Amsterdam Zuid – Schiphol Airport – Leiden Centraal – Den Haag HS – Rotterdam Centraal – Dordrecht	2
3100	Intercity	Schiphol Airport – Utrecht Centraal – Ede-Wageningen – Arnhem Centraal – Nijmegen	2
3300	Sprinter	Leiden Centraal – Hoofddorp – Schiphol Airport – Zaandam – Purmerend – Hoorn Kersenboogerd	2
3500	Intercity	Schiphol Airport – Utrecht Centraal – ’s-Hertogenbosch – Eindhoven – Helmond – Venlo	2
4300	Sprinter	Hoofddorp – Schiphol Airport – Amsterdam Zuid – Weesp – Almere Centrum – Almere Oostvaarders	2
4600	Sprinter	Den Haag Centraal – Leiden Centraal – Schiphol Airport – Amsterdam Sloterdijk – Amsterdam Centraal	2
5700	Sprinter	Utrecht Centraal – Hilversum – Weesp – Amsterdam Zuid – Schiphol Airport – Hoofddorp	2
5800	Sprinter	Hoofddorp – Schiphol Airport – Amsterdam Sloterdijk – Amsterdam Centraal	2
9200 IC 35	Intercity (NS International)	Amsterdam Centraal – Schiphol Airport – Rotterdam Centraal – Breda – Antwerpen Centraal – Mechelen – Brussel-Centraal – Brussel-Zuid/Midi	1
Thalys 9300	Thalys (NS International)	Amsterdam Centraal – Schiphol Airport – Rotterdam Centraal – Antwerpen Centraal – Brussel-Zuid – Paris Nord	1
Thalys 9900	Thalys (NS International)	Amsterdam Centraal – Schiphol Airport – Rotterdam Centraal – Antwerpen Centraal Onwards to Bourg-Saint-Maurice	1/week
11600	Intercity	Schiphol Airport – Amsterdam Zuid – Duivendrecht – Hilversum – Amersfoort – Amersfoort Schothorst	1

B.2. Urban Rail Transit System

Because there are so many different terminologies for the urban rail network, and because there are no national standards for metro systems, it is difficult to generalize on the characteristics of a metro network. So the choice is made to focus one one specific city for this section. And within that city, the focus will be on one specific line. The city in this case is Amsterdam and the line will be the Noord/Zuidlijn.

B.2.1. Infrastructure

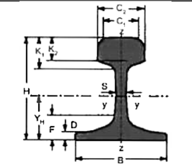
Track Gauge

The track gauge on the Noord/Zuidlijn (and other metro networks in the Netherlands) is 1435 mm. Which is the same as the national railway network.

Rail Profile

The rail profile that is used on the Noord/Zuidlijn is 49 E1, see Table B.13 for the dimensions of this rail profile.

Table B.13: Rail Dimensions 49 E1 (Esveld, 2001)

	H Rail Height [mm]	B Base Width [mm]	C_1 Head Width [mm]	C_2 Head Width [mm]	S Web [mm]	K_1 Total Head Height [mm]	K_2 Head Height [mm]
49 E1	149,00	125,00	67,00	70,00	14,00	51,50	39,80
Continuation	F Base Height [mm]	D Base Thickness [mm]	A Cross Section [mm^2]	G Weight [kg/m]	Y_h Neutral Axis [mm]	J_x Moment of Inertia [cm^4]	W_x Section Modulus Head [cm^3]
Continuation	29,00	12,00	6948	54,54	75,00	2073	262,00

Axle Load

The maximum axle load cannot exceed 12 ton or 2 ton/m, if this is translated to the standard a load class of A would suffice.

Load Gauge

For metropolitan railways, the kinematic load gauge requires special attention as they run through tunnels for the majority of the time. Each metro-line has its own rules and regulations concerning the load gauge. Figure B.9 shows the dynamic and static load gauge of a metro.

Radius of Curvature

The Noord/Zuidlijn had the following guidelines for the design of the track (Ontwerpbureau Noord/Zuidlijn, 1998b) :

$$h = 11,8 * \frac{V^2}{R} - 30mm$$

with:

h = Cant [mm]

V = Speed [m/s]

R = Radius of Curvature [m]

The GVB has a preference to determine the cant size and radius of curvature as followed:

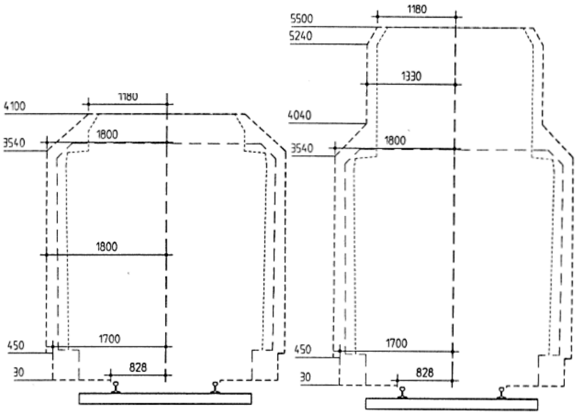


Figure B.9: Loading Gauge GVB Metros in tunnels (left) and in open air (right) (Ontwerpbureau Noord/Zuidlijn, 1998b)

R < 500m for cant deficiency of around 100 mm

500 m ≤R < 1000 m for h=20 mm

1000m ≤R for h=0 mm

Power Supply

Usually, a metro network is supplied with power via a third rail (750 V) , the metro network of Amsterdam has different power supplies throughout the network as a result of some level crossings. The different power supplies for each vehicle (line-specific) will be discussed in the section rolling stock (B.2.3). If there is an overhead line, the desired height of this line in relation to the top edge of the rail is + 5,50 m. At structural works this height is 4,0 m. + top of the rail. Figure B.10 shows the cross-section of how electrification via a third rail works.

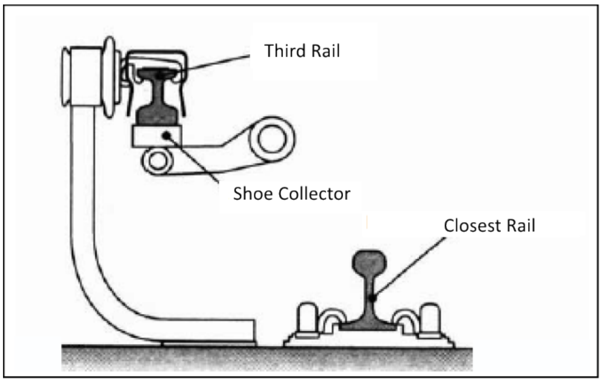


Figure B.10: Cross-section Rail and Third Rail (GVB Rail Services, 2015)

Stations and Nodes

The specifications for the platform dimensions for the Noord/Zuidlijn are determined in the document ”Handboek Spoorontwerp”(Ontwerpbureau Noord/Zuidlijn, 1998a). The platform height throughout the entire Amsterdam metro is 1040 mm + top of rail. For the distance between the edge of platform to the centre of the track the values vary based on the cant, the radius of curvature and the type of platform (concave or convex). For a concave platform and rolling stock with a width of 3 m, the distance is between 1580 and 1623 mm. For a convex platform this value is between 1563 and 1582 mm. For a straight platform with no cant (the desired situation), the distance between the platform edge and the centre of the track is 1580 mm. An example of what a metro platform looks like in Amsterdam can be seen in Figure 3.13. Platforms along the metro network of Amsterdam have a minimum length of 130 m (123 m on the Noord/Zuidlijn) (Ontwerpbureau Noord/Zuidlijn, 1998a)

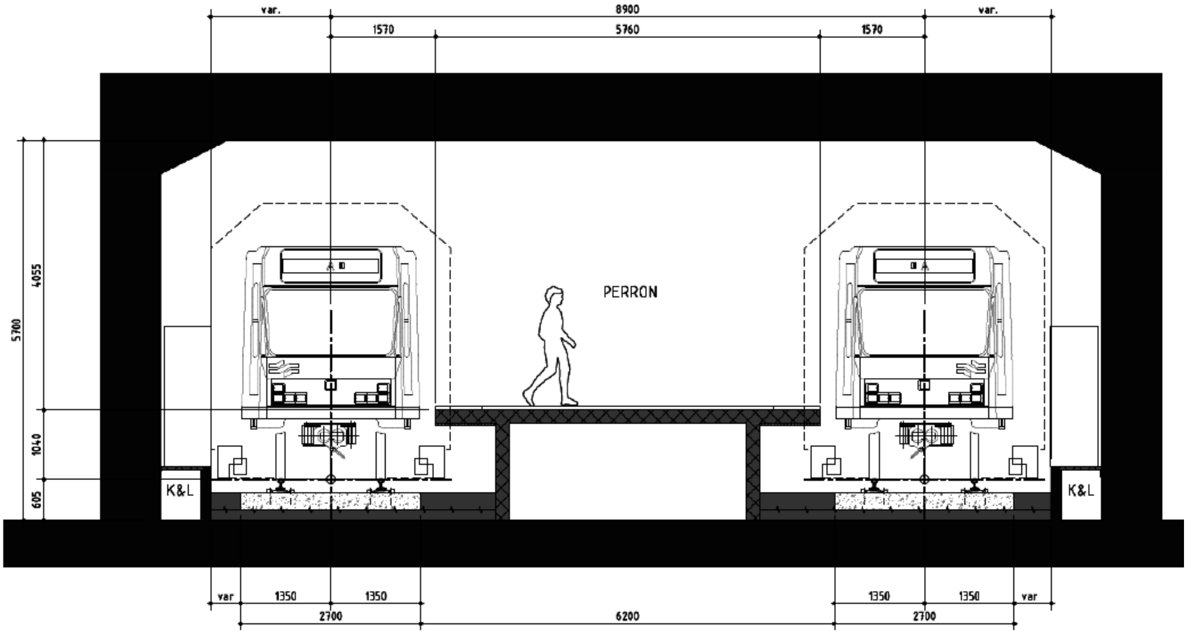


Figure B.11: Platform Layout GVB Metro (Gemeente Amsterdam, 2017)

Crossings and turnouts
The specifications for the Noord/Zuidlijn (Ontwerpbureau Noord/Zuidlijn, 1998a) state the following (Hofstra et al., 2016):
Standard Turnout

- 25 km/hr: 1:6 , R=100 m
- 40 km/hr: 1:7 , R=190 m
- 40 km/hr: 1:9 , R=190 m
- 50 km/hr: 1:9 , R=300 m
- 70 km/hr: 1:14 , R = 760 m

(Double/Single) Slip Switch

- 40 km/hr: 1:9 , R=190 m
- 25 km/hr: 1:6 , R=100 m

Crossings (allowed speeds unknown):

- 1:4
- 1:2

Track Sections (network-configuration)
The metro-network of Amsterdam consists of the following:

- 117 km (single)track
- 225 turnouts
- 52 stations
- 295.000 boarding passengers

Figure D.3 (in Appendix D) shows the network configuration for the metro system of Amsterdam. The Figure shows how the tracks are laid and what stops there are.

B.2.2. Safety and Communication Systems

Before the new rolling stock for the Noord/Zuidlijn was ordered, a strategic program of requirements was drafted to ensure that the new material was up to all of the standards(Hecker and Benedick, 2005).

This program of requirements expressed the ambition to have fully automatic driving metros in Amsterdam in the future. The new vehicles for the Noord/Zuidlijn had to be equipped with at least ATP and ATO. ATP stands for Automatic Train Protection, ATO for Automatic Train Operation and ATC for Automatic Train Control. The ATO system should at least have the functions automatic driving and brakes, station stop and door control. In the future, conversion to automatic operation is possible, but small changes to the rolling stock (the driver's cab for instance) need to be made.

The metros that were chosen for the Noord/Zuidlijn are the *Urbalis* metro by the manufacturer Alstom. The following sections describe the safety and communication systems present in this metro(system).

Train Control System

The function of a train control system is to prevent collisions between trains and ensure safe movement of a train from one track to another. For the entire Amsterdam metro system, (including the Noord/Zuidlijn) Communication Based Train Control (CBTC) will be implemented. The goal of CBTC is safe train separation whilst minimizing the amount of way-side and track side equipment. The system uses the telecommunications between vehicle and track for traffic management and infrastructure control. This type of system makes sure the exact position of a train is known more accurately than with the traditional signaling systems which results in shorter headways, more efficiency and safety whilst managing the railway traffic. The CBTC system used in the Noord/Zuidlijn includes:

- Cab Signaling
- Automatic Train Control System
- Automatic Train Operation

Signalling Systems

The train determines its own location, remembers it and communicates it to other trains. The system uses moving blocks to enable the shorter headways. Moving blocks are equivalent to giving the following CBTC train a movement authority up to the exact rear-end location of the lead CBTC train. As the lead CBTC train moves forward, given the movement authority, the following CBTC train is advanced in each communication cycle by and from the zone controller (Pascoe and Eichorn, 2009). A CBTC system is a ”continuous, automatic train control system utilizing high-resolution train location determination, independent from track circuits; continuous, high-capacity, bidirectional train-to-wayside data communications; and train-borne and wayside processors capable of implementing Automatic Train Protection (ATP) functions, as well as optional Automatic Train Operation (ATO) and Automatic Train Supervision (ATS) functions.”, as defined in the IEEE 1474 standard (IEEE Vehicular Technology Society, 2005). Attempts to standardise the functionality and technology have had mixed success. Results so far include:

- IEEE 1474.1 – Functional and Performance Requirements
- IEEE 1474.2 – User Interfaces
- IEEE 1471.3 – Recommended Practice for System Design
- IEEE 1474.4 – Recommended Practice for Functional Testing.

Traffic Control Systems

Traffic control for the Noord/Zuidlijn will be done with the use of the ICONIS Integrated Control Center (Alstom, 2011). This system gives infrastructure managers and their agents complete control over the network operations. The platform can integrate ATS (Automatic Train Supervision), SCADA (Supervisory Control And Data Acquisition), Infotainment (Passenger Information), Security as well as optional functions. The traffic controllers get constant supervisory information on all trains and stations. The ICONIS system can work with fixed block or moving block operations and all train control systems worldwide (Alstom, 2011).

ICONIS can interface with both BTC and ERTMS systems, as well as with the various maintenance support systems of the interlocking and control systems.

Communication Systems

The communication system for the Noord/Zuidlijn includes a radio system along the infrastructure of the entire metro network track that will be communicate with the vehicles. This radio system operate based on the WiFi standard and will operate in the license-free 5 GHz band.

Train Detection System

Train detection is incorporated with moving block based CBTC system. If a mix of vehicles (CBTC and non-CBTC) use the same track, axle counters could be incorporated to use for train detection of non CBTC trains (Pascoe and Eichorn, 2009).

B.2.3. Rolling Stock

Table B.14 shows the main characteristics of the different metro vehicles used by the GVB on the urban rail network of Amsterdam. For this section, the metros that will be used on the Noord/Zuidlijn (M5) will be investigated more in-depth.

Table B.14: Specs of the Amsterdam Metro Vehicles (GVB, 2018)

Metro-Type	**Metropolis (M5)**	**CAF (M4)**	**Sneltram (S1 and S2)**
Length	116,2 m	30 m	30 m
Width	3,00 m	2.65 m	2.65 m
Weight	190 ton	48 ton	48 ton
Max Speed	70 km/u	70 km/h	70 km/h
Power	4x 4 x 200 kW	6 x 70 kW	6 x 77 kW
Power Supply	750 V	750 V	600/750 V
Seated Capacity	178	66	64
Standing Capacity	782	184	169

The Metropolis M5 is a metro vehicle produced by the company Alstom. This metro was purchased for the Noord/Zuidlijn but it can operate on all of the metro lines of the Amsterdam metro network. The website of the supplier of the metros, Alstom provided the different characteristics that can be found in Tables B.15-17.

Table B.15: Geometric Characteristics M5

Length	116,2 m
Width	3005 mm
Height	3770 mm
Floor Height	1100 mm
Loading Gauge	-
Doors	24
Wheel Diameter	840 mm (new), 760 mm (worn)

Table B.16: Mechanic and Dynamic Characteristics M5

Weight	190 ton
Power	16 x 200 kW
Maximum Speed	90 km/h
Operating Speed	80 km/h

Table B.17: Operational Characteristics M5

Axle Load	12 ton (A)
Train Control System	CBTC
Train Detection System	CBTC, Axle Counters

(Electrical) Traction System
The different electrification systems on the metro network of Amsterdam are:

- **Oostlijn (Gaasperplaslijn (53), Geinlijn (54))**: Third rail 750 Volt
- **Amstelveenselijn (51)** This is a tram/metro combination with: Third rail 750 Volt between the central station and station Zuid. Between station Zuid and Westwijk the electrification system is with an overhead line 600 Volt
- **Ringlijn (M50)**: Third rail 750 Volt
- **Noord/Zuidlijn (M52)**: Third rail 750 Volt

B.2.4. Stakeholders

For the metro network of Amsterdam, the organizational structure differs from the national railway network. The lead for this immense project is the Municipality of Amsterdam, more specifically the departments Metro and Tram and Metro- and Tramnetwork. These departments are assisted by several contractors and engineering firms for the build.

It is clear that many parties are and were involved with the Noord/Zuidlijn, the eventual exploitation (which has started on 22nd of July 2018) will be in the hands of the GVB.

B.2.5. Network

This section will describe the different network characteristics of the different lines of the Amsterdam metro.

Line 50 has 20 stations and an average speed of 36km/h, line 51 has 29 stations and an average speed of 30 km/h, line 53 has 14 stations and an average speed of 34 km/h, line 54 has 15 stations and an average speed of 33.2 km/h. All of the lines mentioned above have the same frequency table as can be seen in Table B.18.

Table B.18: Frequencies lines 50, 51, 53, 54

Rush Hour	Rush Hour Vacation	Off Peak	Off Peak Vacation	Evening	Evening Vacation	Saturday and Sunday	Saturday and Sunday Vacation
8/hour	6/hour	6-8/hour	4/hour	4-6/hour	4/hour	4-6/hour	4/hour

Because the Noord/Zuidlijn is not in operation yet, the timetabling is not entirely sure yet. For the first couple of months of operation, the timetable will be less frequently than planned due to safety issues. But what is known about the frequency can be seen in Table B.19.

Table B.19: Frequencies Noord/Zuidlijn

Rush Hour	Rush Hour Vacation	Off Peak	Off Peak Vacation	Evening	Evening Vacation	Saturday and Sunday	Saturday and Sunday Vacation
12/hour	12/hour	12/hour	8/hour	12/hour	8/hour	12/hour	8/hour

A rule of thumb of 20 seconds applies to the stopping time at stations for metros of the Amsterdam metropolitan region (Garritsen et al., 2017).

C

Maps Dutch Railway System

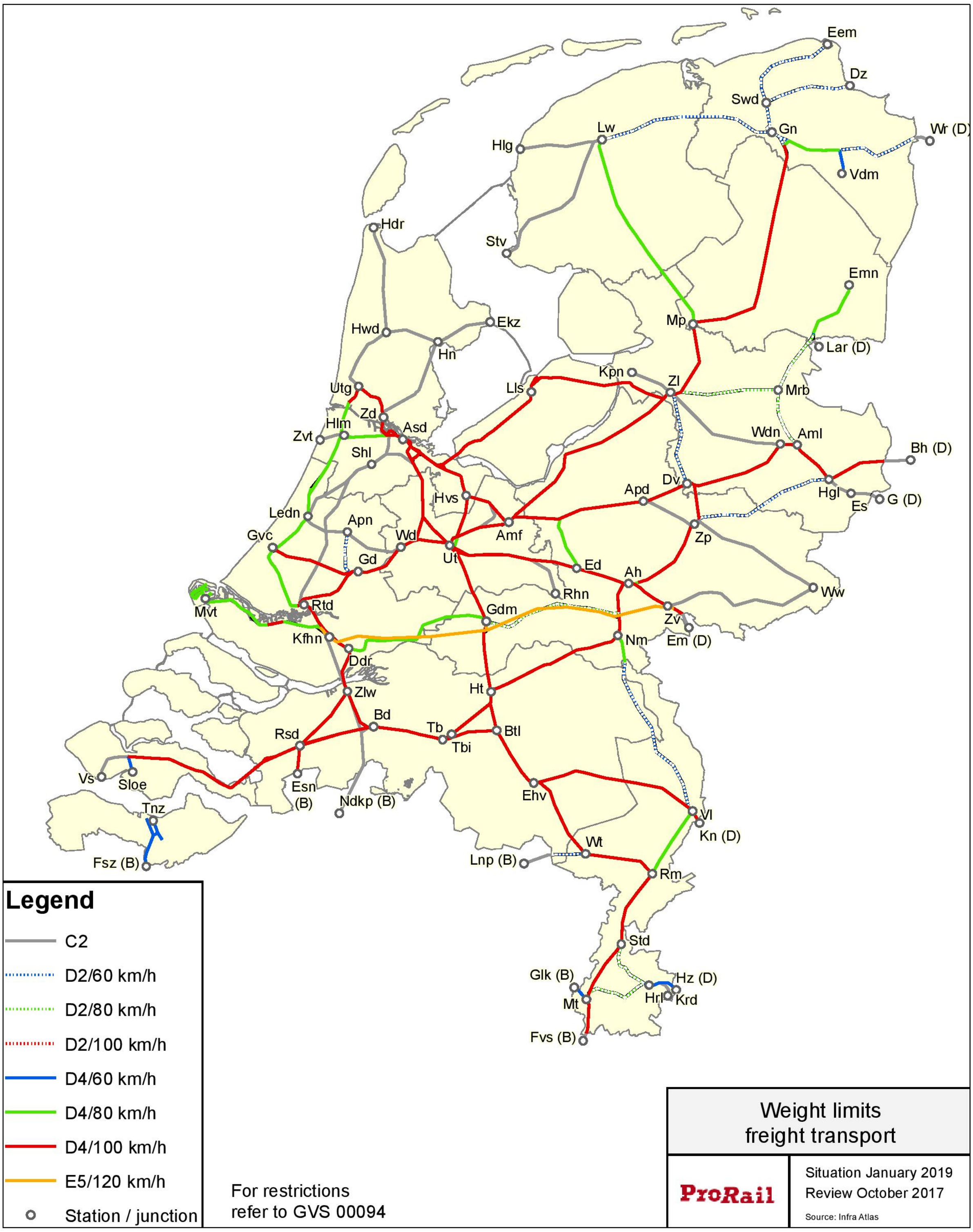


Figure C.1: Axle Loads Dutch Railway System (Prorail, 2018)

Figure C.2: Loading Gauges Dutch Railway System (Prorail, 2018)

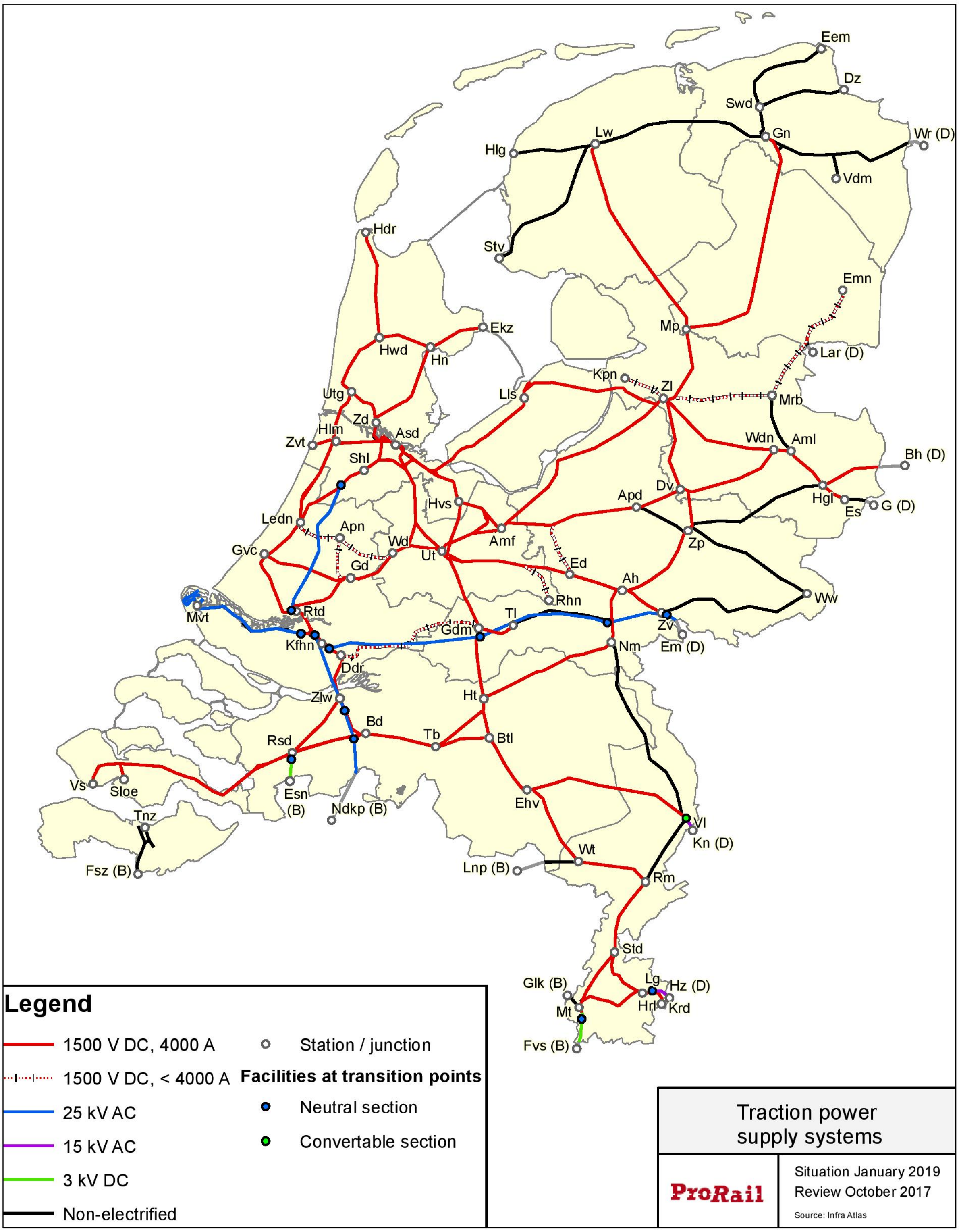


Figure C.3: Power Supply on the Dutch Railway System (Prorail, 2018)

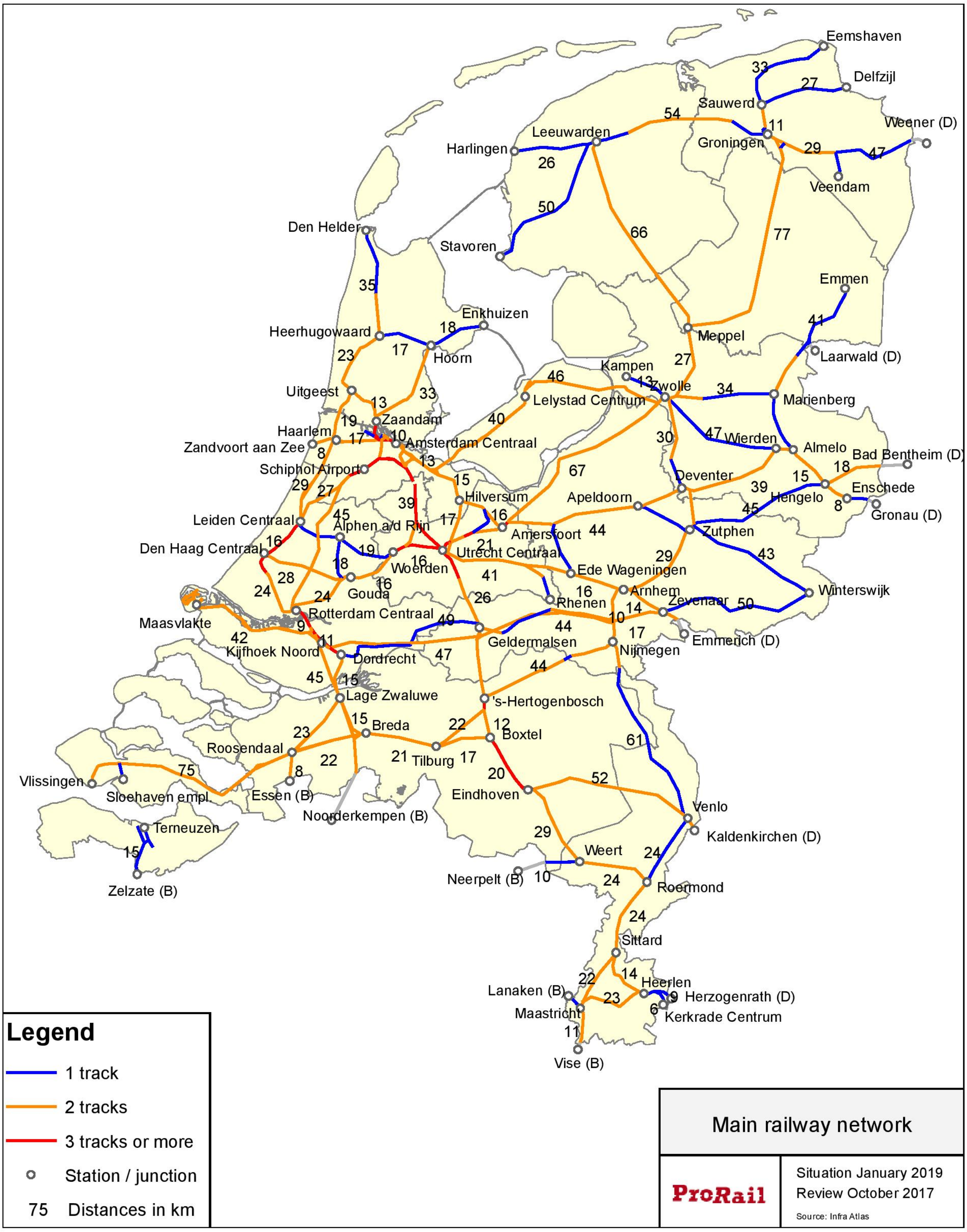


Figure C.4: Main Railway Network(Prorail, 2018)

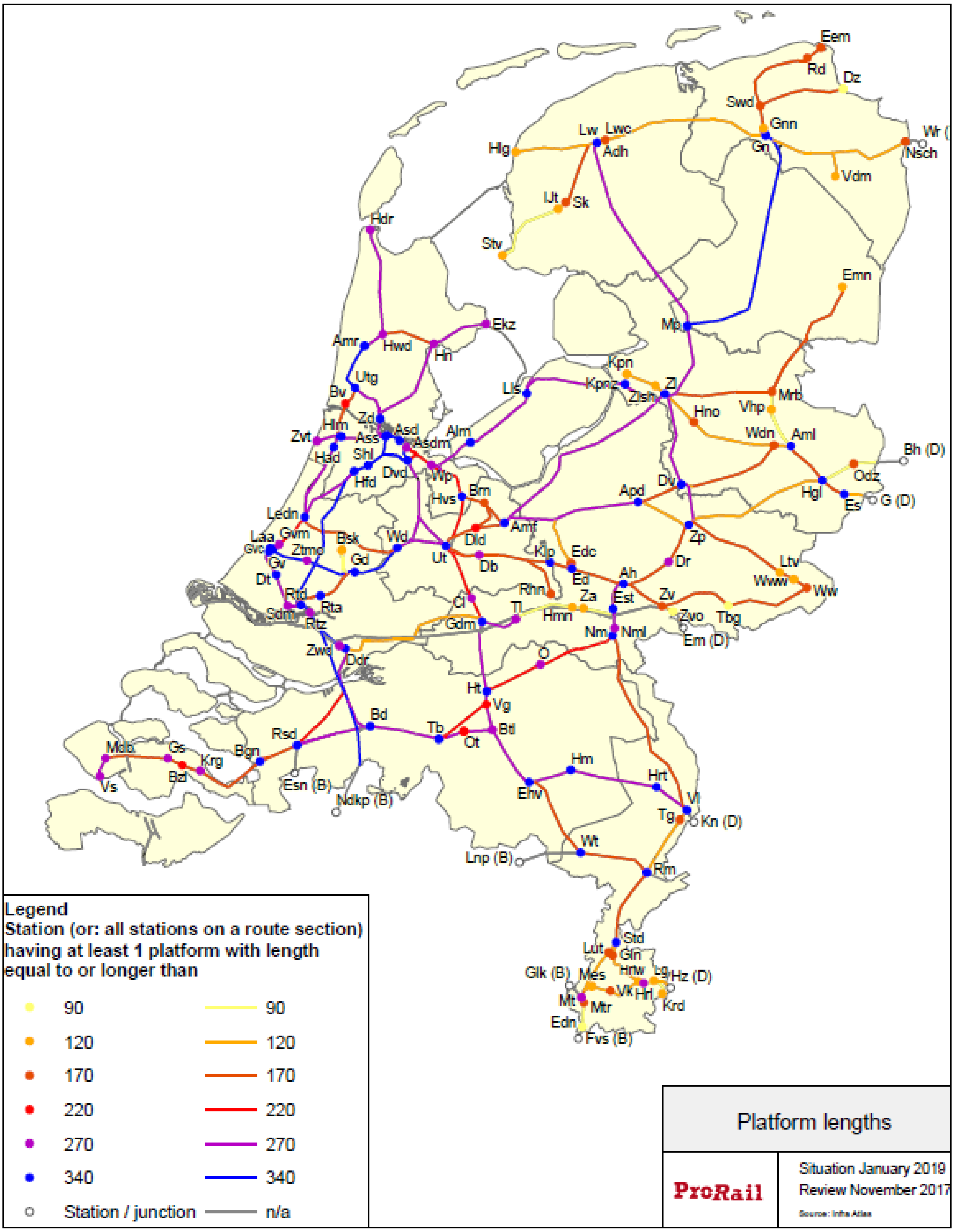


Figure C.5: Network Configuration Dutch Railway System (Prorail, 2018)

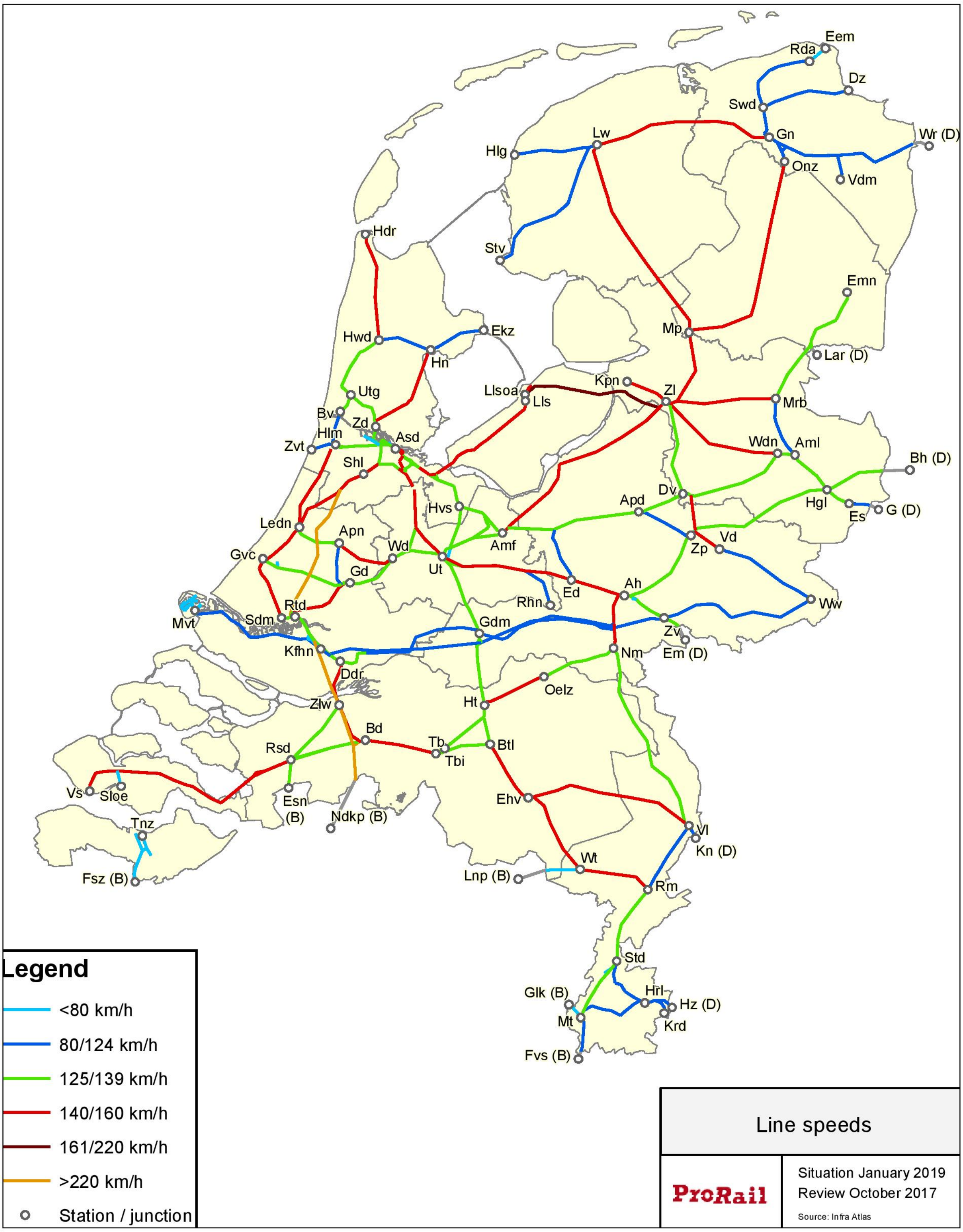


Figure C.6: Line Speeds Dutch Railway System (Prorail, 2018)

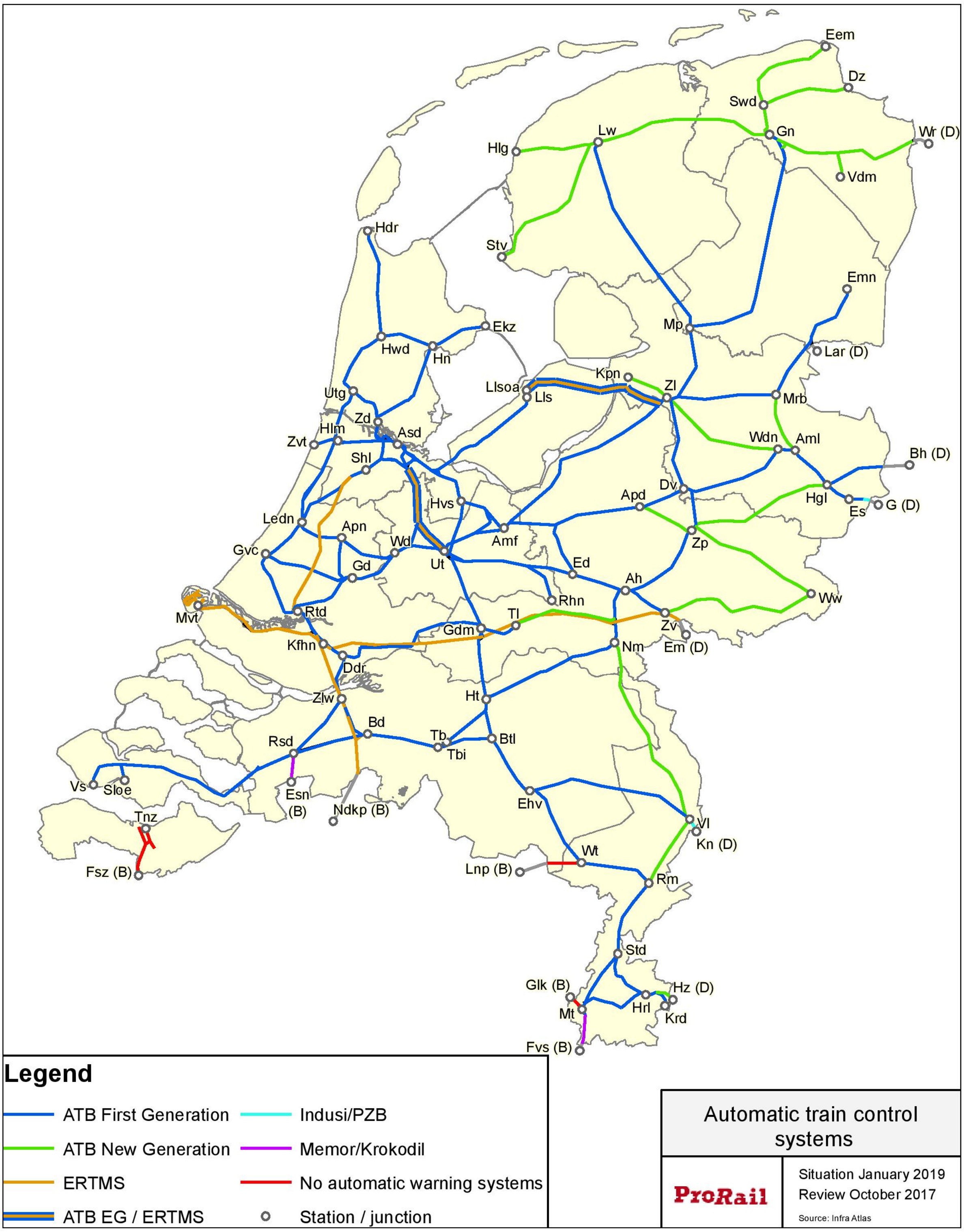


Figure C.7: Automatic Train Control Systems (Prorail, 2018)

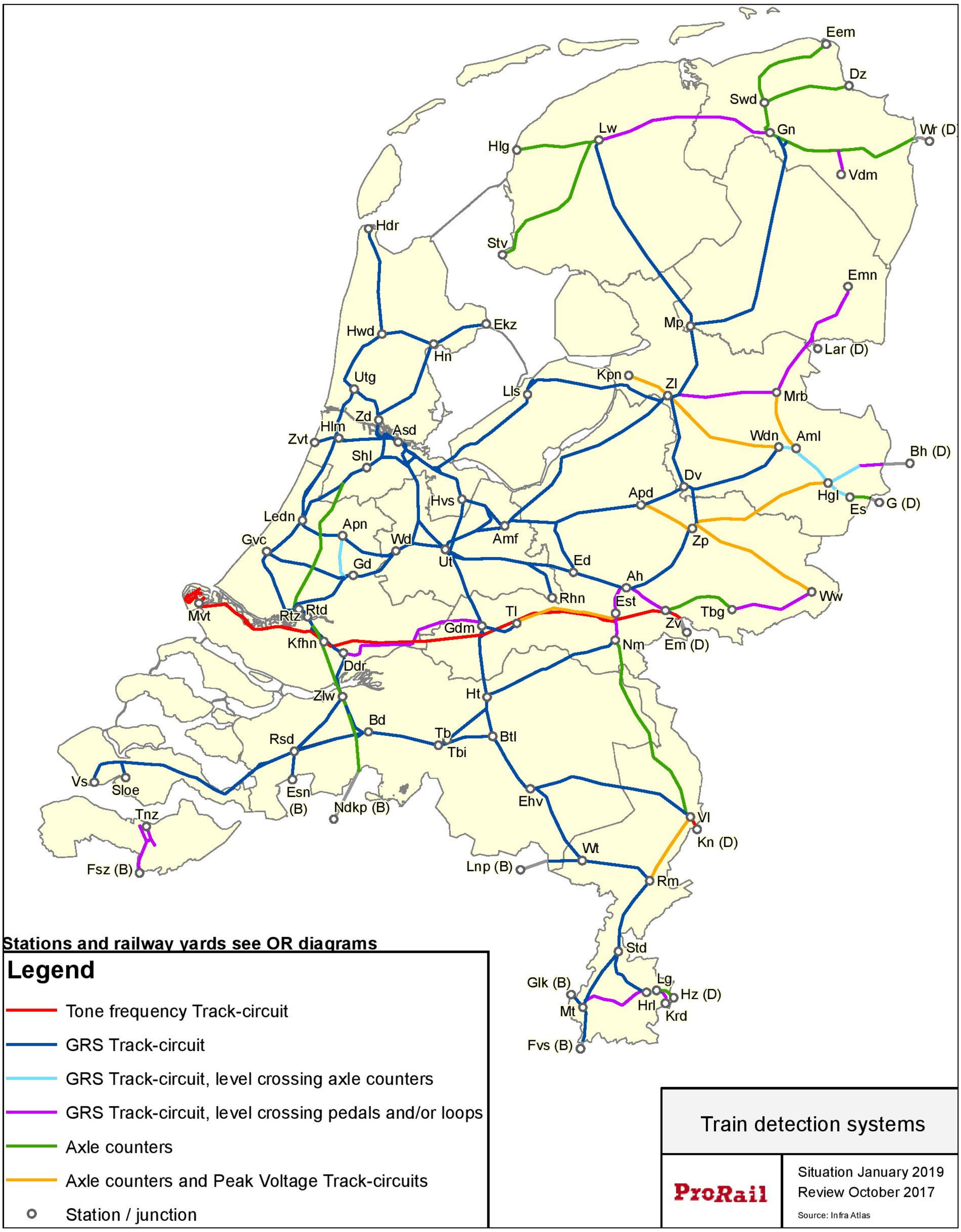
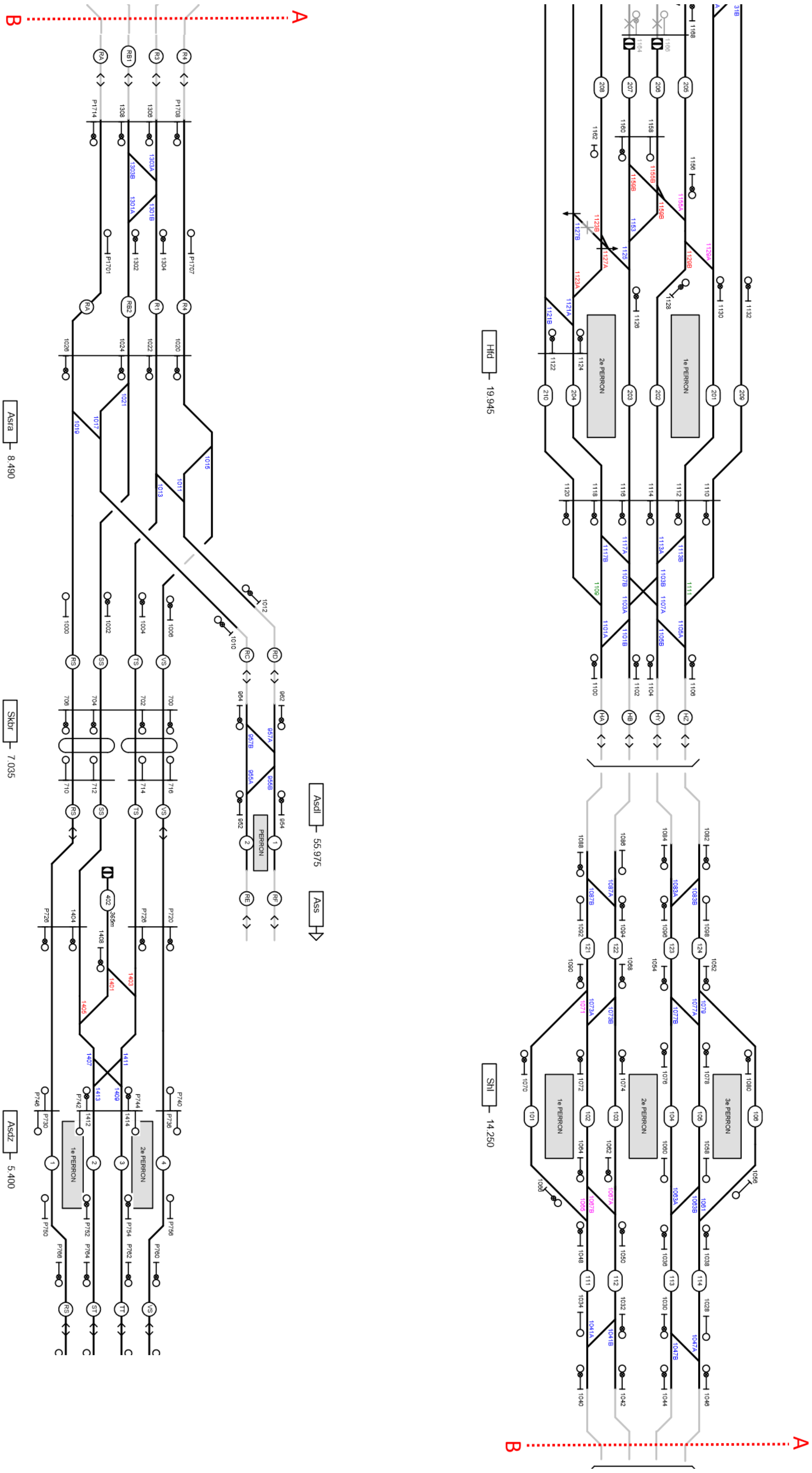


Figure C.8: Train Detection Systems (Prorail, 2018)

D

Trace Plans



(a)

(b)

Figure D.1: Track between Amsterdam Zuid and Hoofddorp(SporenplanOnline, b)

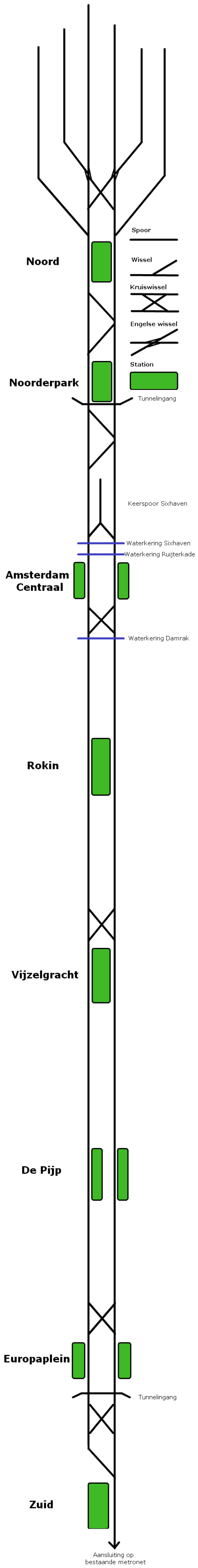
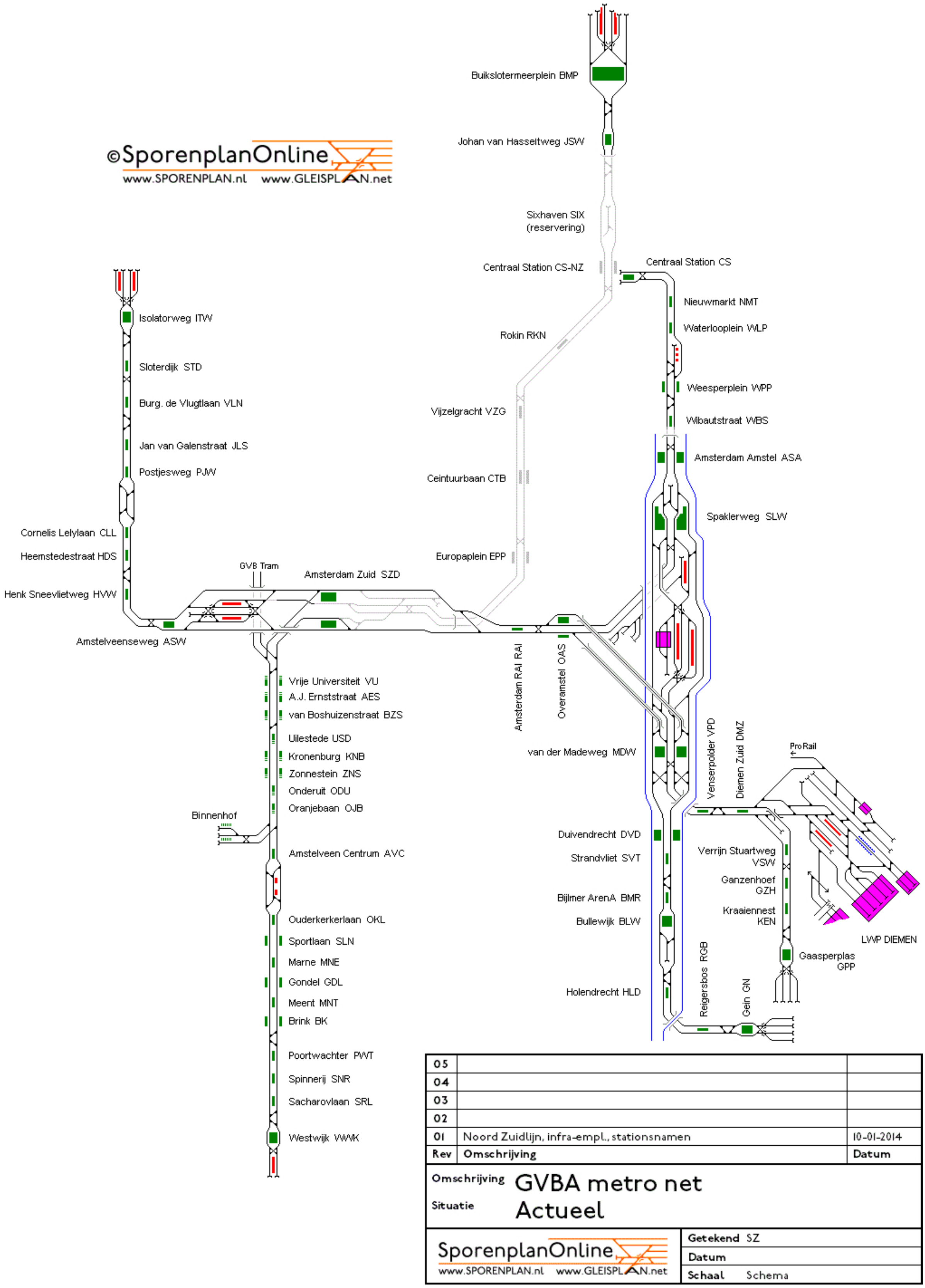


Figure D.2: Trace Plan With Turnouts Noord/Zuidlijn (Vaillant, 2014)



05		
04		
03		
02		
01	Noord Zuidlijn, infra-empl., stationsnamen	10-01-2014
Rev	**Omschrijving**	**Datum**

Omschrijving GVBA metro net
Situatie Actueel

Getekend SZ
Datum
Schaal Schema

Figure D.3: Metro System Amsterdam (SporenplanOnline, a)

E

Model Comparison

Paper	**Decision variable(s)**	**Passenger assignment**	**Capacity constraints**	**Demand satisfaction constraints**	**Assessment criteria**	**Multiple services considered**	**Optimization method**	**Application to network**
Ceder and Wilson, 1986	Route set, frequencies	None	Fleet size	100% satisfaction	Passenger and operator costs	No	No	Fictional network
van Nes, 2002	Stop spacing, line spacing, speed, frequency	None	None	Not applicable (no capacity constraints)	Total costs, social welfare	Yes, hierarchical	Analytical	Fictional networks
Fan and Machemehl, 2004	Route set, frequencies	Static	Vehicle capacity, fleet size	No, but penalty for unsatisfied demand	Passenger, operator and unsatisfied demand cost	No	Genetic Algorithm, Local Search, Simulated Annealing, Random Search, Tabu Search, Exhaustive Search	Fictional example network
Goossens *et al*. (2006)	Lines, stopping pattern	Static	Carriage capacity, number of carriages	100% satisfaction	Operational costs	Yes, no limit	Combinatorial optimization	Dutch train network
Borndörfer *et al.* (2008)	Route set, frequencies	Static	Link capacity	100% satisfaction	Passenger and operator costs	No	No	No
Lin and Ku, 2014	Stopping pattern	Board first arriving train	Train capacity	100% satisfaction	Profit company	Yes, no limit	Genetic Algorithm	Taiwan Railway Administration
Schmid, 2014	Route set, frequencies	Static	Fleet size, bus capacity per link	100% satisfaction	Ride and transfer time	No	Hybrid large neighbourhood search	Fictional network
Arbex *et al.*, 2015	Route set, frequencies	Static	Bus capacity	Only if within 2 transfers	Passenger and operator costs	No	Genetic Algorithm	Mandl's (1980) benchmark network
Yue *et al.*, 2016	Stopping pattern, timetable, stopping time	None	Station capacity	100% for each OD pair	"Profit", decreases with stopping time and number of stops	Yes, three different types	Column Generation	Beijing – Shanghai High Speed Rail
López-Ramos *et al.*, 2016	Route set, frequency	Static	Infrastructure budget, fleet size, vehicle capacity, link capacity	100%, but not all stations need to be served	Passenger and operator costs	Yes, local and express	Lexicographic Goal Programming	Rapid transit Seville and Santiago de Chile
Gu *et al.* 2016	Stop density, frequency, number of routes	Static	Vehicle capacity, minimum frequency	100%	Passenger and operator costs	Yes, all stop, skip-stop, express	Gradient descent method	Idealized line
Van Beurden, 2017	Stopping pattern, frequency	Static, zones	Node capacity, link capacity, vehicle capacity	100%, but not all stations need to be served	Passenger and operator costs	Yes	Genetic Algorithm	Fictional network & Amsterdam train and metro

F

Stop Use

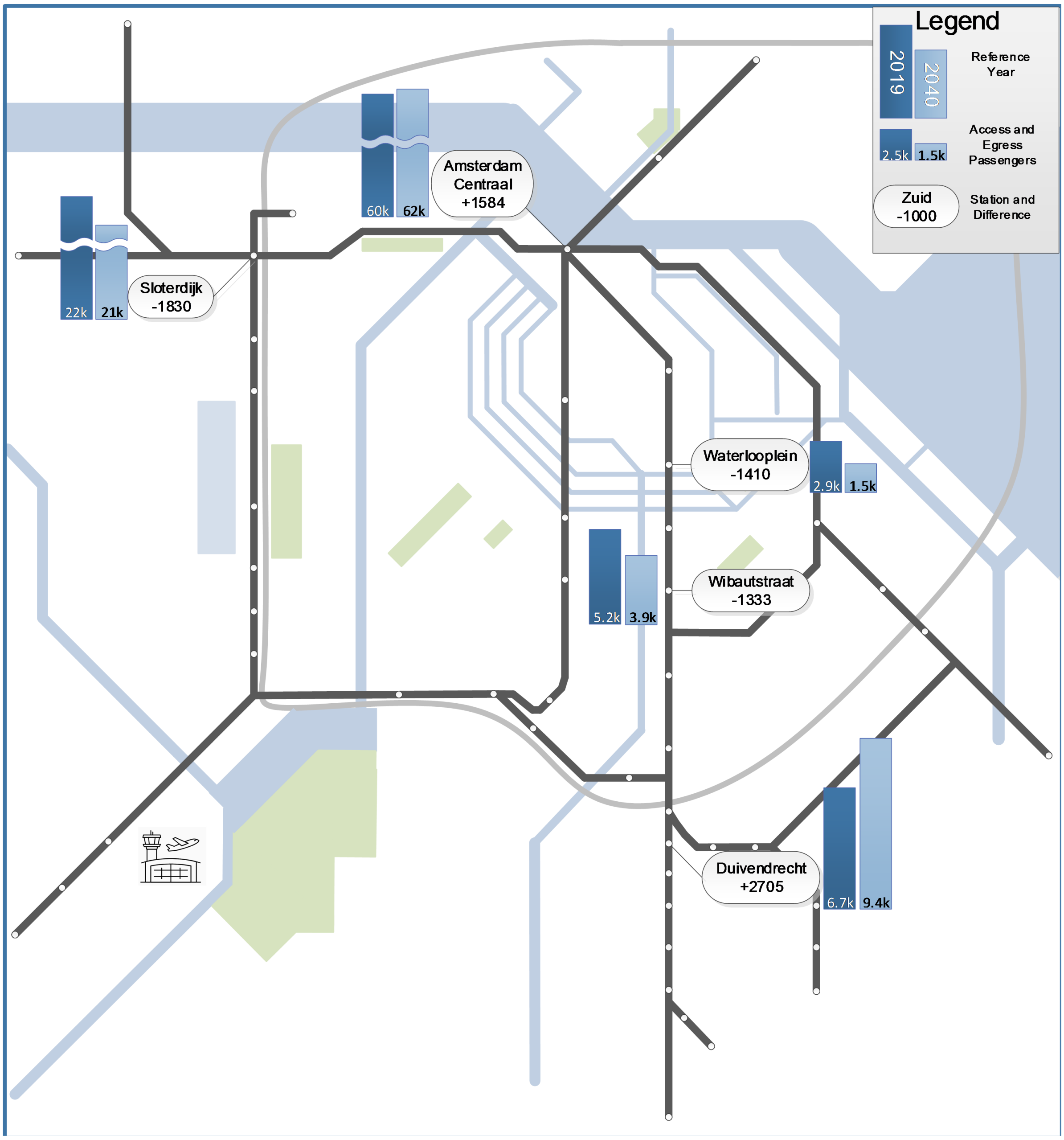


Figure F.1: Experiment 1 versus Experiment 2, Access/Egress

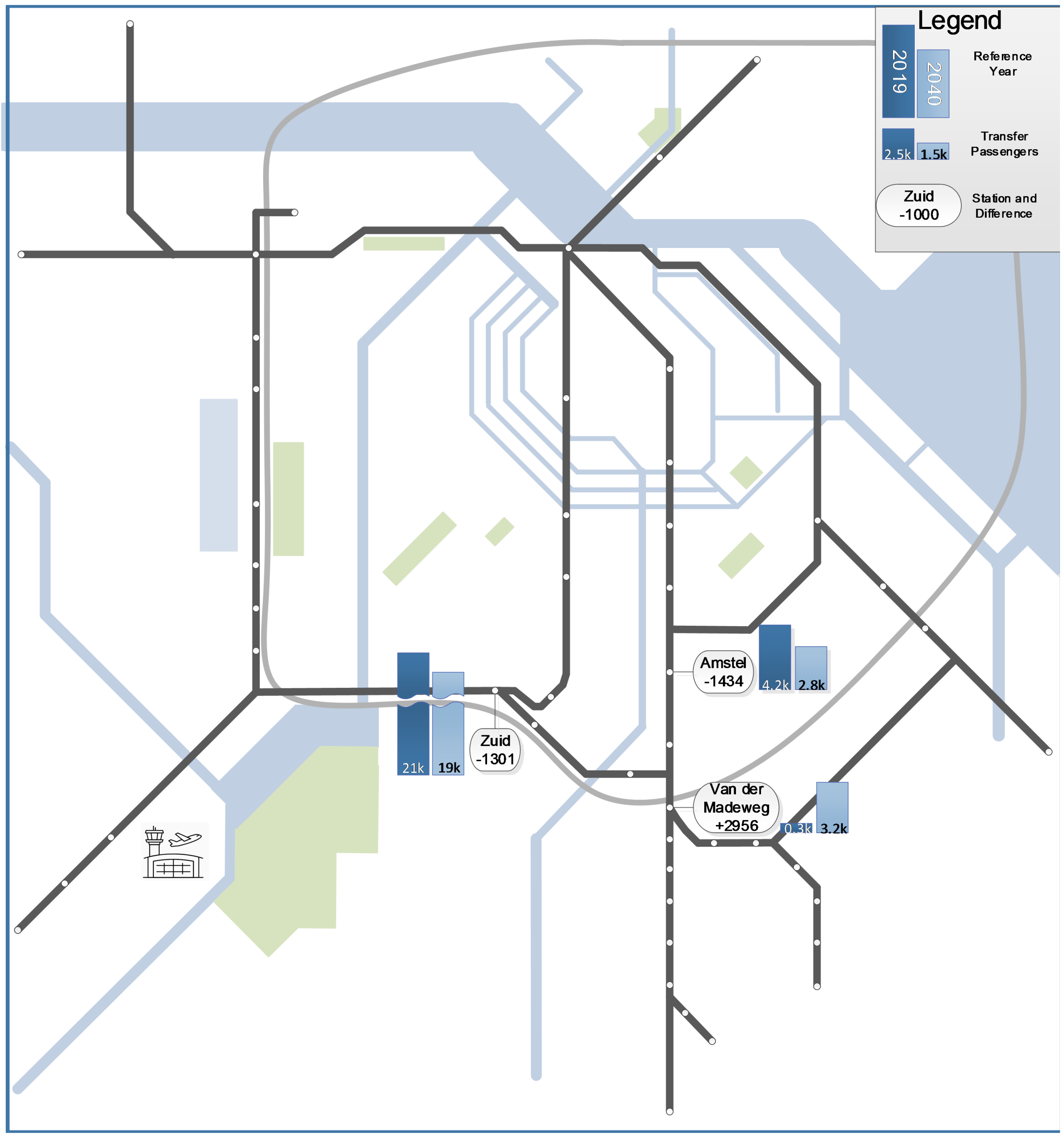


Figure F.2: Experiment 1 versus Experiment 2, Transfers

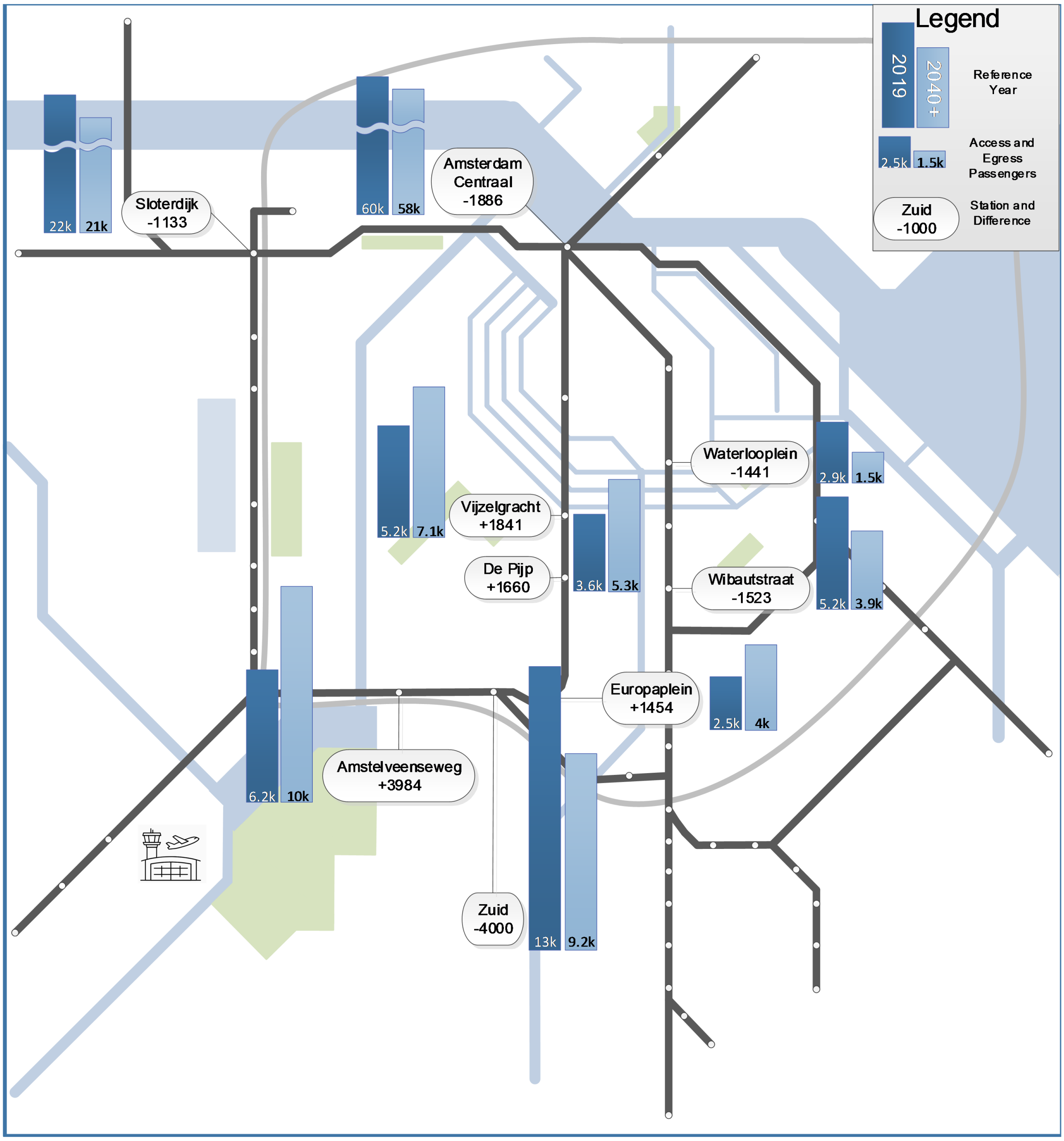


Figure F.3: Experiment 1 versus Experiment 3, Access/Egress

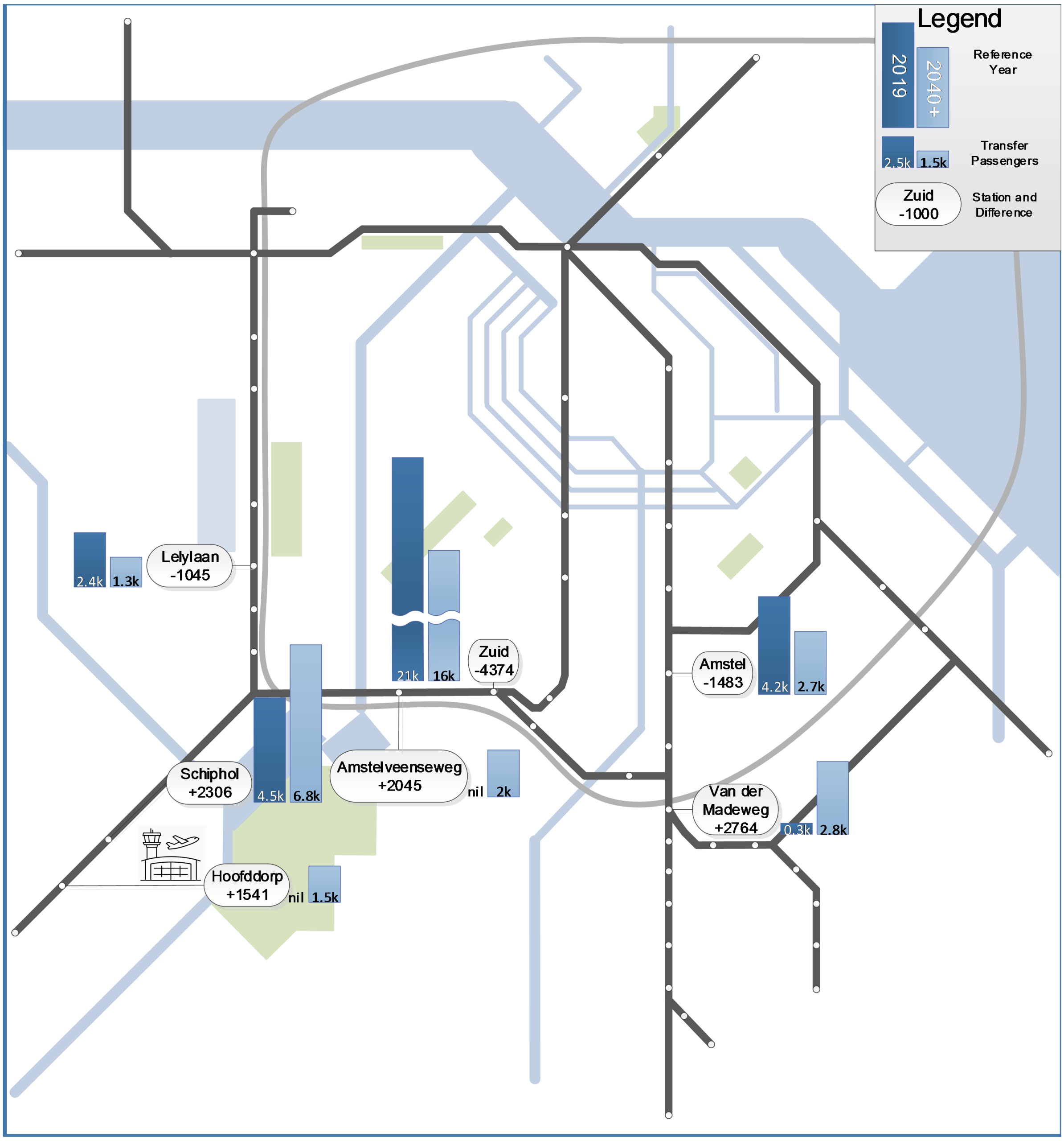


Figure F.4: Experiment 1 versus Experiment 3, Transfers

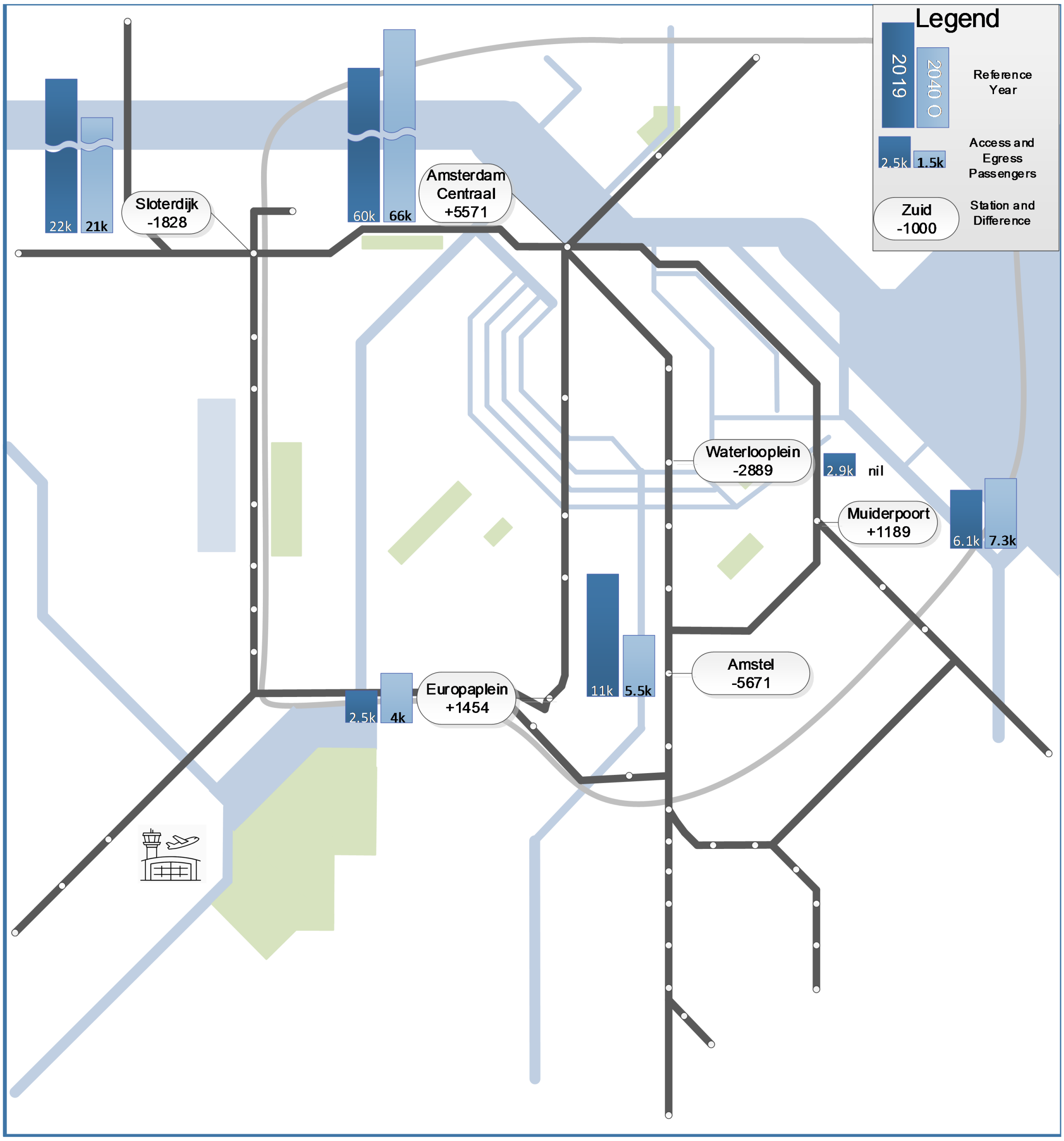


Figure F.5: Experiment 1 versus Experiment 4, Access/Egress

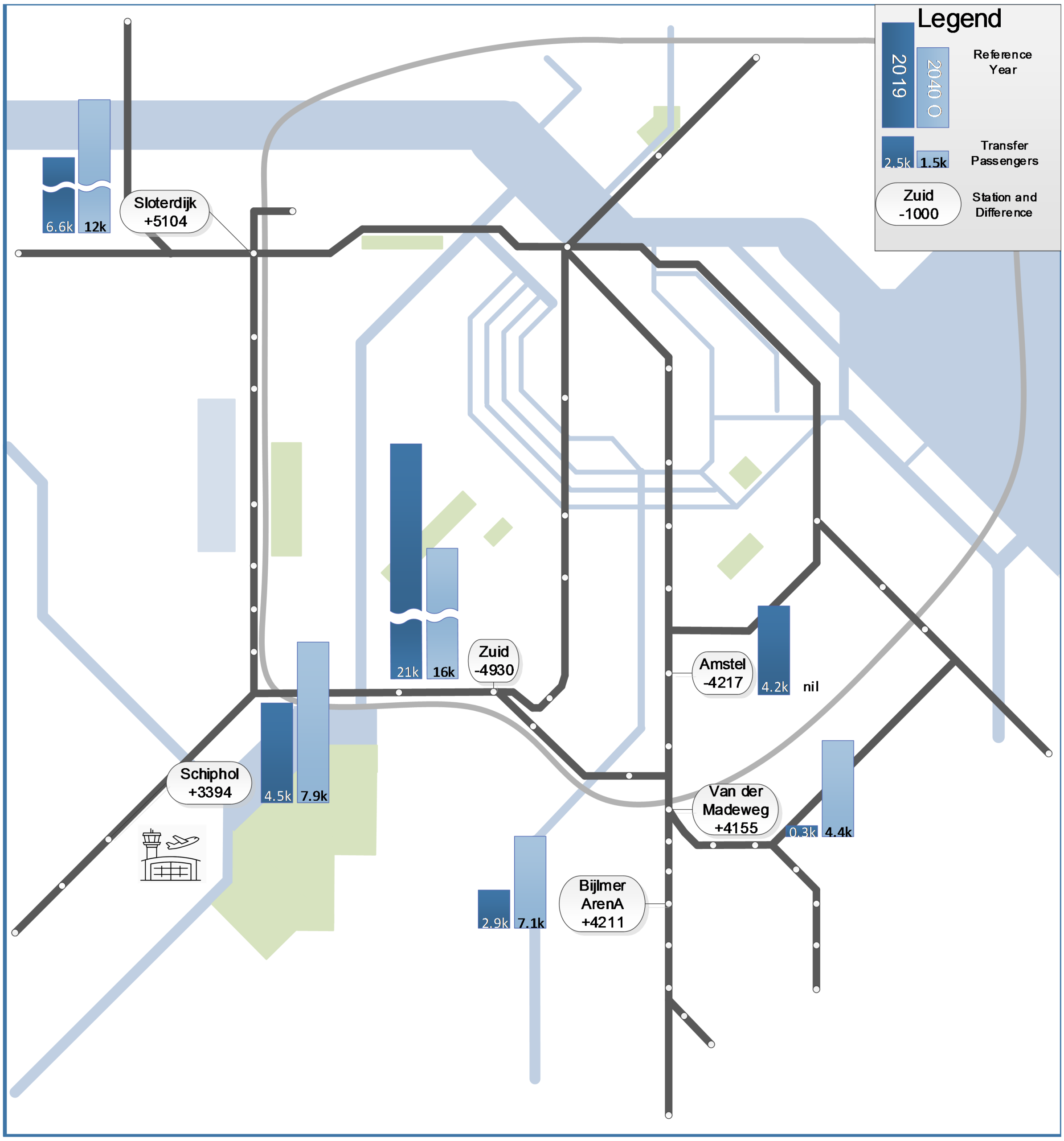


Figure F.6: Experiment 1 versus Experiment 4, Transfers

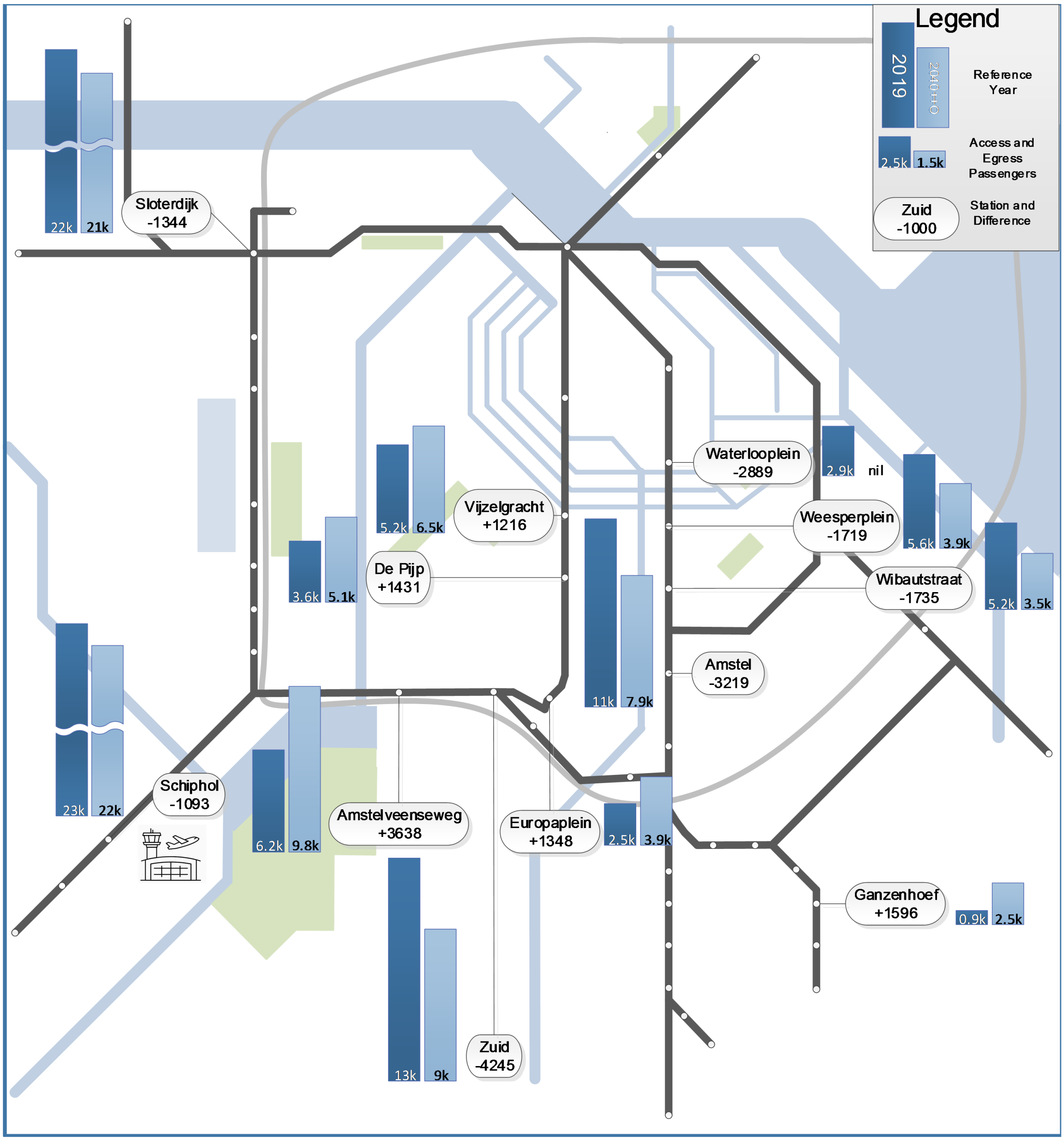


Figure F.7: Experiment 1 versus Experiment 5, Access/Egress

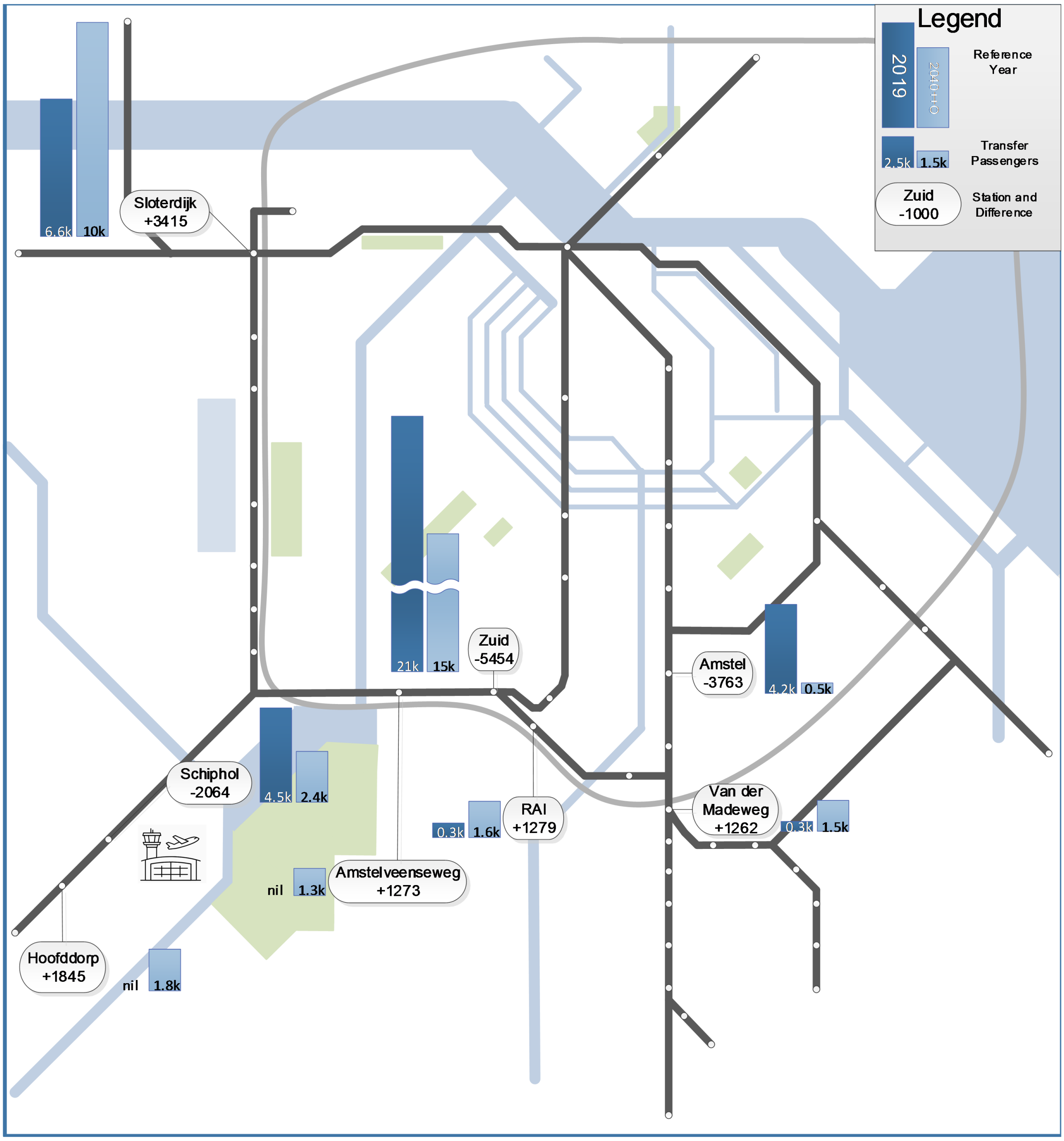


Figure F.8: Experiment 1 versus Experiment 5, Transfers