Mind your passenger!
The passenger capacity of platforms at railway stations in the Netherlands

van den Heuvel, Jeroen

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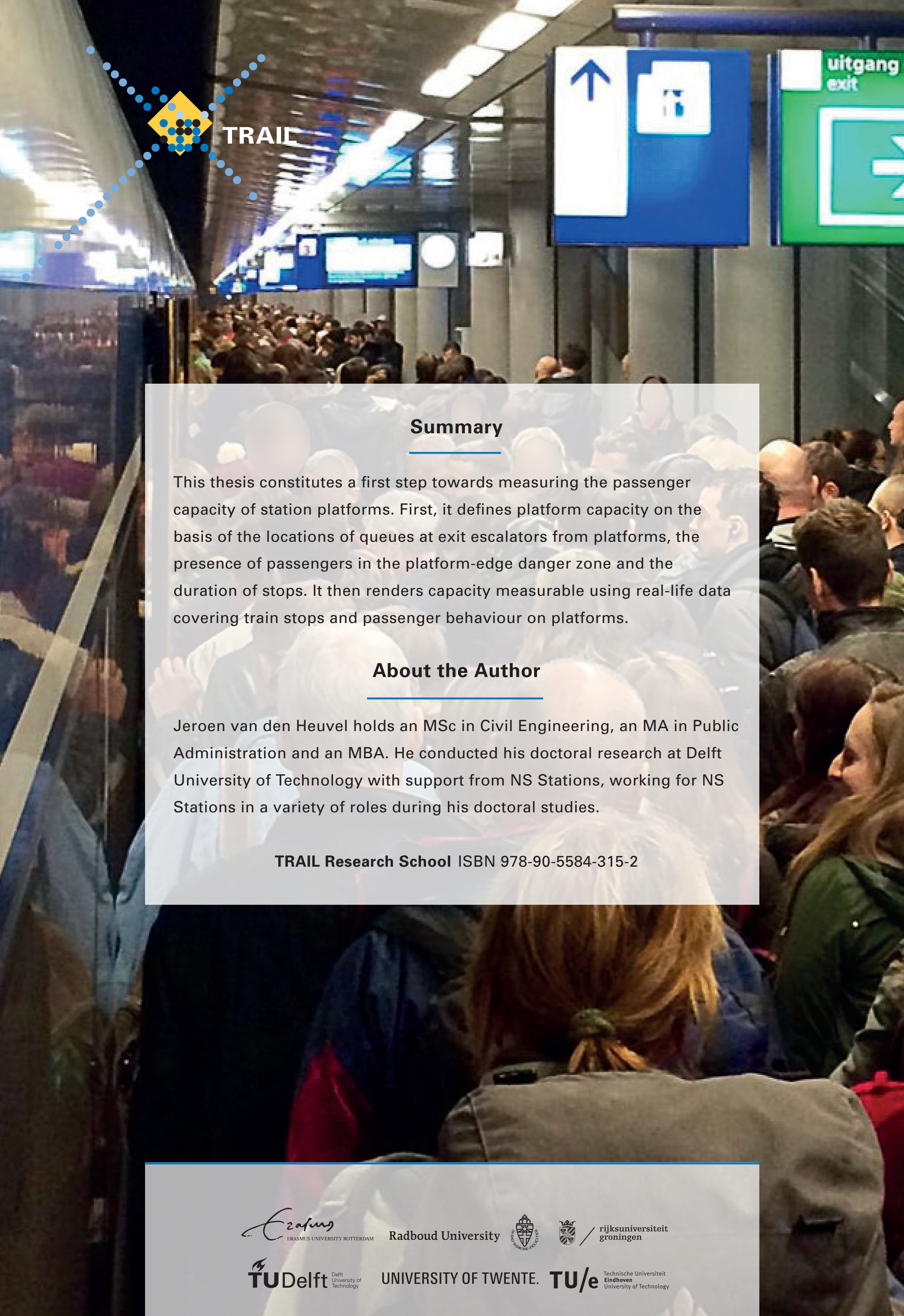

Summary

This thesis constitutes a first step towards measuring the passenger capacity of station platforms. First, it defines platform capacity on the basis of the locations of queues at exit escalators from platforms, the presence of passengers in the platform-edge danger zone and the duration of stops. It then renders capacity measurable using real-life data covering train stops and passenger behaviour on platforms.

About the Author

Jeroen van den Heuvel holds an MSc in Civil Engineering, an MA in Public Administration and an MBA. He conducted his doctoral research at Delft University of Technology with support from NS Stations, working for NS Stations in a variety of roles during his doctoral studies.

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The author wishes to thank NS Stations (the stations and property division of Netherlands Railways) for their support.

Front cover photo: Timo Kans
Back cover photo: Jeroen van den Heuvel

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The passenger capacity of platforms at railway stations in the Netherlands

Dissertation

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at Delft University of Technology
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chair of the Board for Doctorates
to be defended publicly on Thursday 27 October 2022 at 12:30 o'clock

by

Jeroen Petrus Adrianus VAN DEN HEUVEL
Master of Science in Civil Engineering,
Twente University,
Master of Arts in Public Administration and Public Policy,
Twente University,
Master of Business Administration,
Rotterdam School of Management, Erasmus University,
born in Apeldoorn, the Netherlands.

This dissertation has been approved by the promotors.

Composition of the doctoral committee:

Rector Magnificus,	chairperson
Prof. dr. ir. S.P. Hoogendoorn	Delft University of Technology, promotor
Dr. ir. W. Daamen	Delft University of Technology, promotor
Dr. ir. drs. Th.S. de Wilde	NS Stations

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"Nulla tenaci invia est via"

Acknowledgement

It is with great pleasure that I hereby present my doctoral thesis. After eight years of research and a major pandemic. I can finally answer the most frequently-asked question regarding my thesis with one word. “Now!”

COVID-19 has had a major impact on my doctorate. Back at the beginning of 2020, I was ready for my umpteenth (and final) PhD sprint. And then the pandemic turned the world upside-down. Defending a thesis about overcrowded platforms online, as platforms stood empty, was unthinkable. So I decided to wait a bit. Unfortunately, “a bit” turned into over a year and a half. The good news is that we are seeing passenger numbers recover rapidly as soon as restrictions are lifted, all over the world. So the subject of this thesis will remain highly relevant after the pandemic is over. COVID-19 has had no effect on the thesis itself. Once you finish reading my foreword, you will find no further mention of the pandemic. And that is deliberate. My actual research was already complete when the pandemic started. Any attempt to shoehorn COVID-19 into this research would do justice neither to the work done nor to the question of the effects the pandemic may have on future passenger behaviour. I have therefore chosen to leave that topic to others. There may possibly be an opportunity to reflect on the structural consequences of COVID-19 during the ceremony.

A doctorate is an individual mission, but I have been far from alone. My thesis has most certainly not been a solo effort, and I will try not to forget anyone in the paragraphs that follow. I shall start with Peter Zandvliet. In 2012, Peter was the Tickets & Service Manager at Schiphol Airport station. He phoned me in March of that year with the surprising – and worrying – news that one of the platforms was dangerously full. Only later did we understand why. The opening of the Zwolle–Lelystad Hanzelijn in December 2011 meant that there was now a concentration of heavily-loaded trains at Schiphol Airport’s narrowest platform. That phone call and diagnosis played a major role in shaping this thesis. I should also mention Susan de Vos and Jildou van der Sluis with whom I had the pleasure of working on the first NS Stations transfer policy, including the principle of “to measure is to know”, which was later fleshed out through SMART Station and ROCKT. And Adriaan Roeleveld, for his help in collecting line statistics. Without the trust of Michiel Noy I would no longer be working at NS and would never have started on this PhD. The last NS colleagues I must mention are Aad Veenman and Roger van Boxtel. Aad for expressing his confidence in me and his curiosity at the beginning of this long journey. Roger for the inspiring manner in which he launched discussion of the future overloading of the Dutch railway network, including its stations.

But many colleagues outside NS have also provided inspiration for my research. First off, there were those at ProRail, especially Hans van Gelderen, Lee Verhoeff, Ilka Vaatstra and Marcel van Ofwegen. At an international level, I should like to thank all the participants in the Station Capacity Workshops for the many guided tours and discussions, the standards, the handbooks and the knowledge. And the beer. It was a good idea to bring together experts from the various European countries so that we could see that we were basically all facing the same challenges. I should particularly like to thank Jasmin Thurau and Sebastian Ropers of the Swiss Federal Railways and Isabelle Milford of Network Rail in the UK. And finally Jeroen Gemke, Bert van Eekelen and Wilbert Staring, with whom I have regularly discussed the social context of doctoral research.

I am very much aware of the privileged position I enjoyed in carrying out this research thanks to the abundance of data to which I had access. For that privileged position I have partly to thank Jan Hoogenraad, Kees Jong, Marnix van den Broek and Victor van den Broek. Our ROCKT algorithm has turned out way better than we could ever have dared to hope! I am most grateful to the following colleagues from ASE (Switzerland) in connection with the sensors used for SMART Station: Uri Schtalheim, Michael Moos, Mirwais Tayebi, Lukas Gamper and Pascal von Burg. And colleagues from what was then Blip Systems (now Veovo, Denmark): Peter Knudsen and Kim Hermansen. Thanks are also due to the colleagues from RoyalHaskoningDHV in the Netherlands who, along with installation technicians at the various stations, got the sensors working and ensured that they continued to work: Arjan van Gelswijck, Eelco Thiellier and Niels van Gerwen. Like ROCKT, SMART Station has turned out way better than I could ever have dared to hope. I eventually decided not to use pedestrian models for my thesis. Nevertheless, Marlies Wouters and Jeroen Steenbakkers of Incontrol made it possible for me to work on related research. And that was a real learning experience. Thank you.

I am grateful to the Transport & Planning team at Delft University of Technology for their hospitality and support. I rarely came to Delft over the years, and when I did my visits were often brief, but I got a lot out of the time we did spend together. I should especially like to thank Dorine Duives, Erica Kinkel, Mario Campanella and Niels van Oort for the many inspiring conversations we had during this project. Thanks are also due to Danique Ton and Aral Voskamp for their brilliant dissertations on topics covered in my thesis. And to Flurin Hänseler for the opportunity to combine our skills in developing a new pedestrian model for measuring crowding on platforms and trains using OV-chipkaart data. This was one of the intellectual high points of the process and really kept me on my toes.

This doctorate has its roots deep in my personal life. My parents always made sure I could do anything I wanted as regards education and development. This enabled me to develop my talents to the maximum. As far as I know, I am the first in our family to study for a doctorate, and I am extremely proud of that. Martine Keizer and Marian de Wal have also played an important role – probably more so than they realized. They were the emotional anchors I very much needed at times, to cope with the intense pressure and fatigue. That is even truer of my wife, Carrie de Wilde. The process of obtaining a doctorate was nothing remotely like the intensive MBA course I followed in 2008 and 2009 (I did promise, after all!). Even so, I spent virtually every free day at home together working on my thesis. For eight years. And she let me get on with it, and continued to support me. My young neighbour Timo Kans made an unexpected but striking contribution: it was he who built the LEGO platform you see on the cover of this thesis.

Finally, I wish to thank the colleagues who supported the PhD process. First of all, my assistants Lars Mosch and Rik Schakenbos. When I asked them to take on this role, they knew they were going to have to work for it. You rarely get something for nothing. And they passed the test with flying colours, reading and commenting on the entire thesis. They will therefore be well qualified to support me during the ceremony! Sebastiaan de Wilde took on just about every role one can imagine: friend, coach, colleague and supervisor. He kept his promise “we started together, we’ll finish together” and this has been a truly great journey – together. Shall we we stop counting titles and letters now? Finally, Winnie Daamen and Serge Hoogendoorn. The principle of “starting together and finishing together” applies to them too. It wasn’t easy at first, but our cooperation developed into something enjoyable, inspiring and productive. Whenever my own thoughts were going round in circles, I could always depend on them for a rapid response. I’m looking forward to the post-PhDiners. Thanks a lot!

As I had decided to publish this thesis in both Dutch and English, I wrote the original in Dutch. The official English translation is by Steve Rawcliffe – thank you for going through my manuscript so carefully, and for the excellent translation.

Jeroen van den Heuvel
December 2021

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Summary

This thesis addresses the passenger capacity of railway station platforms in the Netherlands. It was prompted by reports of "full" platforms.

Examination of developments in rail traffic and stations reveals that in 2019 the number of passengers per station reached its highest level since the Second World War. Passenger numbers through the larger stations have risen considerably since the 1990s. The passenger load on the busiest platforms rose by 50% between 2014 and 2019, and the number of platforms with high peak loads doubled over the same period.

In the past, it was often possible to extend platforms by rebuilding stations or modifying existing sidings. However, the urban development of recent decades has left little space adjacent to stations, making it difficult to enlarge platforms. These trends are expected to continue, resulting in even busier platforms.

In the Netherlands, consideration of platform crowding focuses on passenger safety. Experience with main-line and metro systems in other countries indicates that the presence of large numbers of passengers on a platform can keep trains at the platform for longer than scheduled, making it difficult to maintain a stable timetable. Delays or cancellations owing to timetable instability can cause hazards (or additional hazards) for passengers on the platform, by increasing crowding still further. Safety, punctuality and line capacity are hence relevant to the research presented here.

Defining passenger capacity

Little existing research was found on the passenger capacity of railway station platforms. Such research as does exist indicates that using a platform to its maximum physical capacity, or "system capacity", is dangerous and causes accidents.

No records were found of deaths resulting from crowding-related platform accidents in the Netherlands. Research in other countries paints a similar picture. Station and platform operators throughout the world take steps to prevent accidents, which means that the occurrence or non-occurrence of accidents is not a good indicator of whether or not platform capacity has been reached. As the system capacity of platforms is unknown, it is not possible to derive the safe working capacity from it.

John Fruin, the father of the level-of-service (LOS) concept, drew attention to this as early as the 1970s. His LOS concept forms the basis for many standards covering different types of pedestrian infrastructure. Many operators of main-line and metro stations, including those in the Netherlands, also base their standards on Fruin. However, the LOS concept is too general to form the basis for precise platform-capacity limits.

In practice, station operators determine platform capacity on the basis of standards. However, an unambiguous, generally-accepted definition of service capacity and corresponding criteria are lacking. Furthermore, there has been virtually no empirical research in this area.

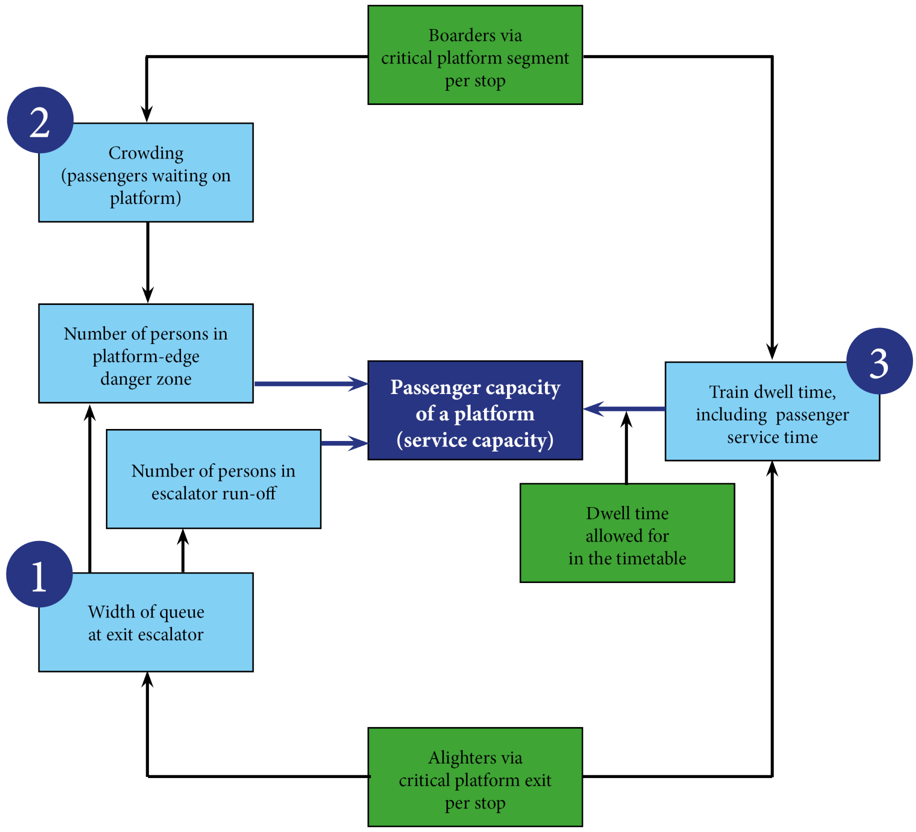


Figure 1: Relationships between the limits on the passenger capacity of a platform

The present thesis constitutes a first step towards making service capacity measurable. This "passenger capacity" is defined in terms of three limits (see Figure 2):

1. Arriving passengers queueing for an exit escalator following the arrival of their train stand in or walk through areas that are undesirable from a safety point of view.

2. Boarders wait in or walk along the buffer zone (the "danger zone") along the platform edge prior to the arrival of their train.

3. Train dwell times are longer than allowed for in the timetable owing to the number of alighting and boarding passengers.

These three capacity limits have been rendered measurable by means of three thematic studies based on empirical train-stop datasets. The data sources were developed within NS Stations in parallel with the research for this thesis, under the supervision of the author. The thematic studies used trajectory data for over 31,000 stops. These were captured by SMART Station sensors on platforms at Utrecht Centraal and Amsterdam Zuid stations. The datasets prepared for this thesis are being published with it and are hence available for further research. This study also used ROCKT data from 14.5 million stops made by NS trains over one timetable year. For each stop, the dataset gives the number of alighters and boarders and the scheduled and actual dwell times. Data regarding train traffic on the network was also used, as were open historical weather data from the *Koninklijk Nederlands Meteorologisch Instituut* (KNMI, the Royal Dutch Meteorological Institute).

Thematic study 1: Queues at escalators

The first thematic study examines queues at the escalators via which alighting passengers leave the platform. This study shows the number of persons in a queue to be a good predictor of its size. By contrast, each stop results in a queue of different width, even if the stops themselves are comparable. But here too, there is a pattern. The probability of a queue being broader (e.g. in the direction of the platform edge) increases with the number of persons in the queue.

This thematic study also highlights the relationship between queue width and use of the platform-edge buffer zone by passengers. Passengers in the queue itself were not observed to make regular use of the buffer zone. However, a queue of 20 or more persons forms an obstacle for persons attempting to pass it, causing them to walk along the buffer zone. This study also showed that a queue of 15 or more persons will encroach upon the run-off from the adjacent arriving escalator unless a divider is installed between the two escalators.

Thematic study 2: Use of platform-edge zone

The second thematic study examines the phenomenon of passengers walking along or waiting in the platform-edge buffer zone prior to the arrival of a train. A quantitative relationship has been established between the level of crowding on the platform and the number of persons in this zone, also known as the “danger zone”. As crowding on the platform increases, so does the length of time spent in the buffer zone. This confirms the expectation that more passengers stand in the buffer zone for longer periods when the platform becomes more crowded.

This study also shows that a certain percentage of passengers use the buffer zone even at low densities. The present research revealed no explanation for this. However, previous research has shown that passengers may have a number of reasons for this behaviour. Several researchers have pointed to passengers perceiving the risks associated with the platform edge as low. Research conducted in Switzerland has found that passing slower-moving passengers and avoiding standing passengers may also prompt people to use the buffer zone. Research conducted in the United Kingdom identified wishing to board the train as quickly as possible after it arrives as a reason for being in the buffer zone. This in turn is motivated by a desire to obtain a seat on the train when it arrives.

How the platform is divided into segments along its length proved to have a decisive effect on the research results. A segment length of 5 m was chosen for this study. Treating the entire platform as a single segment, or using a segment length of 10 m, does not produce valid results. Using long segments masks the uneven distribution of passengers along the platform. This hides the relationship between (local) density and the number of persons in the buffer zone.

Finally, the standard buffer-zone width chosen by the station operator was found to have a major influence on the percentage of passengers in that zone at a given density. That relationship is not linear. With buffer zones of 0.8 m or wider, at higher densities the density in the buffer zone approaches that observed across the rest of the platform. In practice, this means that a buffer zone of 0.8 m (including marking) is of no benefit to passengers at higher densities.

Thematic study 3: Dwell time

The third thematic study examines the effect of the number of alighters and boarders on dwell time. This study showed that it is possible to derive passenger service time from total dwell time using existing statistical models and data regarding the number of passengers. Analysis of data for the 2018 timetable year showed that at several stations passenger service time was the reason (or one of the reasons) for actual dwell times exceeding those provided for in the timetable. The stations affected were Amsterdam Bijlmer ArenA, Tilburg, Rotterdam Alexander, Amsterdam Zuid and Schiphol Airport. In the case of the last two stations, extended passenger service times regularly resulted in trains departing late.

This study also showed that passenger behaviour has no significant influence on dwell time. Weather conditions did affect dwell times at a limited number of stations. At all stations, passenger infrastructure and operating characteristics were the important factors determining passenger service time. In this context, “passenger infrastructure” means platform and train characteristics, plus train door capacity. “Operating characteristics” are all aspects related to the stop, excluding the passenger service process. Examples include the departure process executed by the conductor.

General conclusions and implications

This thesis shows that the platform capacity of a platform can be derived from:

1. a standard for the width of the platform-edge buffer zone
2. a standard for the maximum queue at a platform exit
3. timetabled train dwell times.

These parameters also make it possible to measure passenger capacity. It has been established that one or more passenger capacity limits were exceeded during the period covered by this study at Amsterdam Zuid, Utrecht Centraal and Schiphol Airport. In addition to the platforms studied at those stations, a number of other platforms with similar high peak loads were identified. Further study is required to establish whether passenger capacity is also being exceeded on those platforms.

The results of this research indicate that the passenger capacity of a platform depends on several factors. First, there are the structural factors, such as platform width, the locations and capacity of platform entrances and the timetable. But passenger capacity is also the result of interactions between less obvious factors. These include the presence of a divider between escalators moving in opposite directions, or the type of train (in terms of rolling stock and length) serving busy stations while running to a timetable that requires short dwell times. The choices made by station operators and individual passengers also play an important role in determining the passenger capacity of a platform. These choices include buffer-zone width (station operators) and whether or not to stand in or walk along that zone (passengers). Knowledge regarding this aspect of passenger behaviour is especially lacking. Obtaining a clearer understanding of this important factor will require research that focuses on passenger preferences, the factors affecting their decisions and the options that may exist for influencing their behaviour.

Samenvatting

Dit proefschrift gaat over de reizigerscapaciteit van perrons van treinstations in Nederland. De aanleiding zijn signalen over ”volle perrons”.

Uit de vervoer- en stationsontwikkeling blijkt dat het treinvervoer per station in 2019 op het hoogste niveau sinds de Tweede Wereldoorlog lag. Sinds de jaren ’90 zijn de reizigersaantallen op de grootste stations sterk gegroeid. In de periode 2014-2019 zijn de reizigersbelastingen van de drukste perronsporen met de helft gestegen, en is het aantal perronsporen met een hoge piekbelasting verdubbeld.

In het verleden waren perronuitbreidingen vaak mogelijk door nieuwbouw van het station of het saneren van oude spooremplacementen. Tegenwoordig is echter minder ruimte beschikbaar omdat de stationsgebieden de afgelopen decennia zijn volgebouwd als gevolg van stedelijke ontwikkeling. Dit bemoeilijkt het uitbreiden van de perrons van treinstations. De verwachting is dat de bovengenoemde trends doorzetten. Hierdoor zal de drukte op perrons verder toenemen.

In Nederland gaat de aandacht vooral uit naar de veiligheid van reizigers op het perron. Ervaringen in andere landen met trein- en metrosystemen laten zien dat bij grote aantallen reizigers op een perron ook problemen kunnen ontstaan door te lange stationnementen van treinen. Te lange stationnementen maken het uitvoeren van een stabiele dienstregeling moeilijker. Vertraging of uitval van treinen door een instabiele dienstregeling kan weer zorgen voor (additionele) veiligheidsrisico’s voor reizigers op het perron als gevolg van extra drukte. Veiligheid, punctualiteit op en capaciteit van het spoor zijn daarom relevante aspecten voor dit onderzoek.

Reizigerscapaciteit gedefinieerd

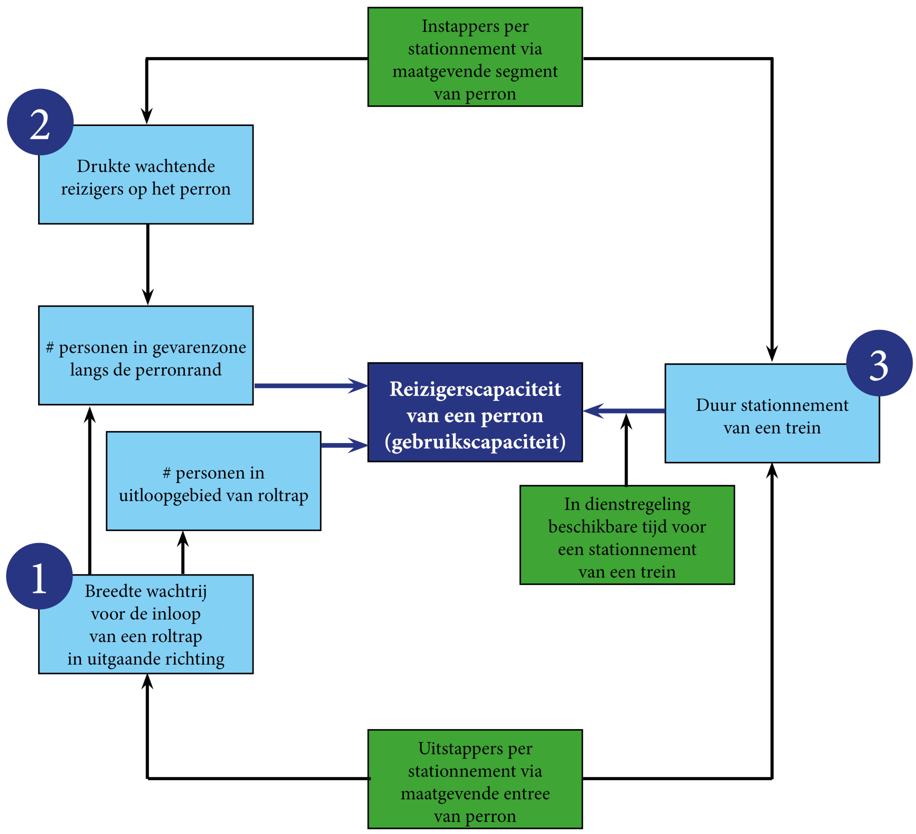
Er is weinig onderzoek over de reizigerscapaciteit van perrons van stations gevonden. Uit het wel beschikbare onderzoek blijkt dat een maximale benutting van de perroncapaciteit (”systeemcapaciteit”) resulteert in veiligheidsrisico’s en ongevallen.

Voor Nederland zijn geen geregistreerde perronongevallen gevonden die naar drukte herleidbaar zijn. Onderzoek in andere landen laat een vergelijkbaar beeld zien. Overal ter wereld nemen beheerders van perrons en stations maatregelen om ongevallen te voorkomen. Ongevallen zijn daarmee geen goede indicator voor het bereiken van de capaciteit van treinperrons. Omdat de systeemcapaciteit niet bekend is kan de veilige capaciteit hier niet van worden afgeleid.

Als grondlegger van het *Level-Of-Service*-concept (LOS) wees John Fruin hier in de jaren ’70 van de vorige eeuw al op. Zijn LOS-concept ligt in de praktijk vaak ten grondslag aan de gebruiksnormen voor uiteenlopende soorten voetgangersinfrastruc-

tuur. Ook veel beheerders van trein- en metrostations, waaronder in Nederland, hebben hun normen op het werk van Fruin gebaseerd. Het LOS-concept is echter te algemeen voor het bepalen van een harde gebruiksgrens voor een treinperron.

In de praktijk bepalen stationsbeheerders de perroncapaciteit met behulp van normen. Van deze "gebruikscapaciteit" is geen eenduidige, algemeen geaccepteerde definitie met operationalisatie beschikbaar. Ook is nauwelijks empirisch onderzoek naar dit onderwerp beschikbaar.



Figuur 2: Samenhang tussen de grenzen van de reizigerscapaciteit van een treinperron

Dit proefschrift zet een eerste stap in het meetbaar maken van de gebruikscapaciteit. Deze "reizigerscapaciteit" is geoperationaliseerd aan de hand van drie grenzen (figuur 2):

1. wachtrijen van uitstappers rond een uitgaande roltrap komen na aankomst van een trein op plekken terecht die vanuit het perspectief van de veiligheid onwenselijk zijn,

2. instappers wachten of lopen voorafgaand aan de aankomst van hun trein in de bufferzone langs de perronrand ("gevarenzone"),

3. stationnementen van treinen duren ten opzichte van de dienstregeling te lang door het aantal reizigers dat uit- en instapt.

De drie capaciteitsgrenzen zijn meetbaar gemaakt aan de hand van drie themaonderzoeken waarbij empirische datasets van stationnementen van treinen zijn gebruikt. De databronnen zijn parallel aan dit onderzoek bij NS Stations onder leiding van de auteur ontwikkeld. Bij de themaonderzoeken is gebruik gemaakt van trajectoriedata van ruim 31.000 stationnementen uit SMART Station sensoren op perrons van de stations Utrecht Centraal en Amsterdam Zuid. De voor dit proefschrift geprepareerde datasets worden met dit proefschrift gepubliceerd en zijn daarmee beschikbaar voor vervolgonderzoek. Ook is gebruik gemaakt van ROCKT-data van de 14,5 miljoen stationnementen door treinen van NS gedurende een dienstregelingsjaar. De dataset bevat per stationnement de aantallen uit- en ingestapte reizigers en de geplande en gerealiseerde duur van het stationnement. Daarnaast is gebruik gemaakt van data over het treinverkeer op het spoor en van (open) historische weerdata van het Koninklijk Nederlands Meteorologisch Instituut.

Themaonderzoek 1: wachtrijen bij een roltrap

Het eerste themaonderzoek gaat over wachtrijen bij roltrappen waarmee uitgestapte reizigers het perron verlaten. Uit dit onderzoek blijkt dat het aantal personen in de wachtrij de omvang van een wachtrij goed verklaart. De breedte van een wachtrij blijkt daarentegen bij ieder stationnement verschillend te zijn, ook al zijn de stationnementen onderling vergelijkbaar. Toch is ook hier een patroon zichtbaar. De kans op bredere wachtrijen (bijvoorbeeld richting de rand van het perron) neemt toe naarmate het aantal personen in de wachtrij toeneemt.

Tevens wijst dit themaonderzoek op het verband tussen de breedte van de wachtrij en het gebruik van de bufferzone langs de perronrand door reizigers. Er is niet waargenomen dat reizigers in de wachtrij zelf systematisch in de bufferzone langs de perronrand terecht komen. Maar wachtrijen vanaf 20 personen werken wel als obstakel voor reizigers die de wachtrij willen passeren. Hierdoor wijken deze personen richting de perronrand uit en lopen ze door de bufferzone langs de perronrand. Ook laat dit onderzoek zien dat wachtrijen vanaf 15 personen in het uitloopgebied van de inkomende roltrap terecht komen, tenzij een stromenscheider tussen uitgaande en inkomende roltrap aanwezig is.

Themaonderzoek 2: verblijf bij de perronrand

Het tweede themaonderzoek gaat over het lopen of wachten in de bufferzone langs perronrand voorafgaand aan de aankomst van een trein. Er is een kwantitatief verband gevonden tussen de drukte op het perron en het aantal personen in de bufferzone langs de perronrand (”gevarenzone”). Bij toenemende drukte op het perron neemt ook de verblijfsduur in de bufferzone toe. Dit bevestigt de verwachting dat meer reizigers langdurig in de bufferzone langs de perronrand staan wanneer de drukte op het perron toeneemt.

Uit dit onderzoek blijkt verder dat ook bij lage dichtheden een deel van de reizigers van de bufferzone gebruik maakt. Een verklaring hiervoor kan op basis van dit onderzoek niet worden gegeven. Uit eerder onderzoek blijkt dat reizigers hiervoor meerdere redenen kunnen hebben. Zo wijzen meerdere onderzoekers erop dat reizigers een lage perceptie van de veiligheidsrisico's bij de perronrand hebben. Verder wijst onderzoek uit Zwitserland op de wens tot het inhalen van langzaam lopende reizigers of het ontwijken van wachtende reizigers. Onderzoek uit het Verenigd Koninkrijk legt een verband met de behoefte van reizigers zo snel mogelijk in te kunnen stappen zodra de trein is gearriveerd. Dit met het oog op het kunnen vinden van een zitplaats in de trein.

Verder blijkt de segmentering van het perron over de lengte bepalend te zijn voor de onderzoeksresultaten. Bij dit onderzoek is gekozen voor een segmentlengte van 5 meter. Het behandelen van perron als één geheel of het toepassen van segmenten met een lengte van 10 meter geeft geen valide resultaten. Door lange segmenten blijft een ongelijke spreiding van reizigers in de lengterichting van het perron bij lange segmenten onopgemerkt. Dit maskeert het verband tussen de (lokale) dichtheid en het aantal personen in de bufferzone langs de perronrand.

Tenslotte blijkt de door stationsbeheerders genormeerde breedte van de bufferzone langs de perronrand van grote invloed te zijn op het aandeel reizigers dat bij een bepaalde dichtheid in de bufferzone verblijft. Dit verband is niet lineair. Bij bufferzones van meer dan 0,8 meter breed lijkt de personendichtheid in de bufferzone bij hogere dichtheden steeds meer op de dichtheid op het overige perrondeel (in de breedterichting). In de praktijk betekent dit dat een bufferzone langs de perronrand (inclusief veiligheidsmarkering) met een breedte van 0,8 meter bij hogere dichtheden zijn waarde voor reizigers verliest.

Themaonderzoek 3: stationnementstijd

Het derde themaonderzoek gaat over het verband tussen de stationnementstijden en het aantal uit- en instappende reizigers. Dit onderzoek laat zien dat de tijd voor het reizigersuitwisselproces van de totale stationnementstijd kan worden afgeleid met behulp van bestaande (statische) modellen en data over het aantal reizigers. Uit de analyses van de data voor dienstregelingsjaar 2018 blijkt dat het reizigersuitwisselproces op meerdere stations (mede-)oorzaak was van te lange stationnementstijden ten opzichte van de dienstregeling. Het gaat hierbij om de stations Amsterdam Bijlmer ArenA, Tilburg, Rotterdam Alexander, Amsterdam Zuid en Schiphol Airport. Bij de laatste twee stations heeft het te lange reizigersuitwisselproces ook geresulteerd in een systematisch te laat vertrek van de treinen.

Uit dit onderzoek blijkt verder dat reizigersgedrag geen relevante invloed op de stationnementstijden heeft. Voor een beperkt aantal stations geldt dat wel voor de weersomstandigheden. De invloeden van de reizigersinfrastructuur en de operationele kenmerken zijn voor alle stations de belangrijke factoren voor de duur van het reizigersuitwisselproces tijdens een stationnement. Met reizigersinfrastructuur worden de kenmerken van het perron, de trein en de deurcapaciteit van de trein bedoeld. Operationele kenmerken zijn alle aspecten die een relatie met het stationnementsproces hebben, maar niet met het reizigersuitwisselproces (bijvoorbeeld het vertrekproces door de conducteur).

Algemene conclusies en implicaties

Dit proefschrift toont dat de reizigerscapaciteit van treinperrons kan worden afgeleid van:

1. een norm voor de breedte van de bufferzone langs de perronrand;
2. een norm voor de maximale wachtrij voor een perronuitgang;
3. de geplande stationnementstijden van de treinen.

Aan de hand van deze parameters kan de reizigerscapaciteit ook worden gemeten. Voor de stations Amsterdam Zuid, Utrecht Centraal en Schiphol Airport is geconstateerd dat één of meerdere grenzen van de reizigerscapaciteit gedurende de onderzoeksperiode zijn overschreden. Naast deze perrons is ook een aantal andere perrons geïdentificeerd met een vergelijkbare, hoge piekbelasting. Nader onderzoek moet uitwijzen of hier ook de reizigerscapaciteit wordt overschreden.

De uitkomsten van dit onderzoek impliceren dat de reizigerscapaciteit van perrons van veel factoren afhankelijk is. In de eerste plaats zijn dit structurerende elementen, zoals de perronbreedte, de situering en capaciteit van de perronentrees, en de dienstregeling van de treinen. Naast deze elementen is de reizigerscapaciteit ook het resultaat van een samenspel van minder voor de hand liggende factoren. Denk hierbij aan de aanwezigheid van een stromenscheider tussen twee roltrappen die in tegengestelde richting werken, of het type trein - soort trein en treinlengte - dat bij de uitvoering van de dienstregeling op lijnen langs drukke stations met krappe stationnementen wordt ingezet. Ook de keuzes van stationsbeheerders en individuele reizigers zijn belangrijk voor de uiteindelijke reizigerscapaciteit van een perron. Denk hierbij aan respectievelijk de breedte van de bufferzone langs de perronrand en het wel of niet gebruiken van deze zone. Vooral over dit gedrag van reizigers is weinig bekend. Voor grip op deze belangrijke factor is gericht onderzoek nodig naar de voorkeuren en afwegingen van reizigers, en de mogelijkheden voor gedragsbeïnvloeding.

Chapter 1

Introduction

This thesis addresses the passenger capacity of station platforms. The present chapter provides an introduction to the topic. It begins with a description of the background, based on media reports and railway policy (Section 1.1). The problem addressed by this study is then presented, on the basis of that background (Section 1.2) and delimited (Section 1.3). This is followed by a description of the contribution that this thesis makes to research and to operating practice (Section 1.4). The introduction ends with a reading guide, including a graphical overview of the structure of the thesis (Section 1.5).

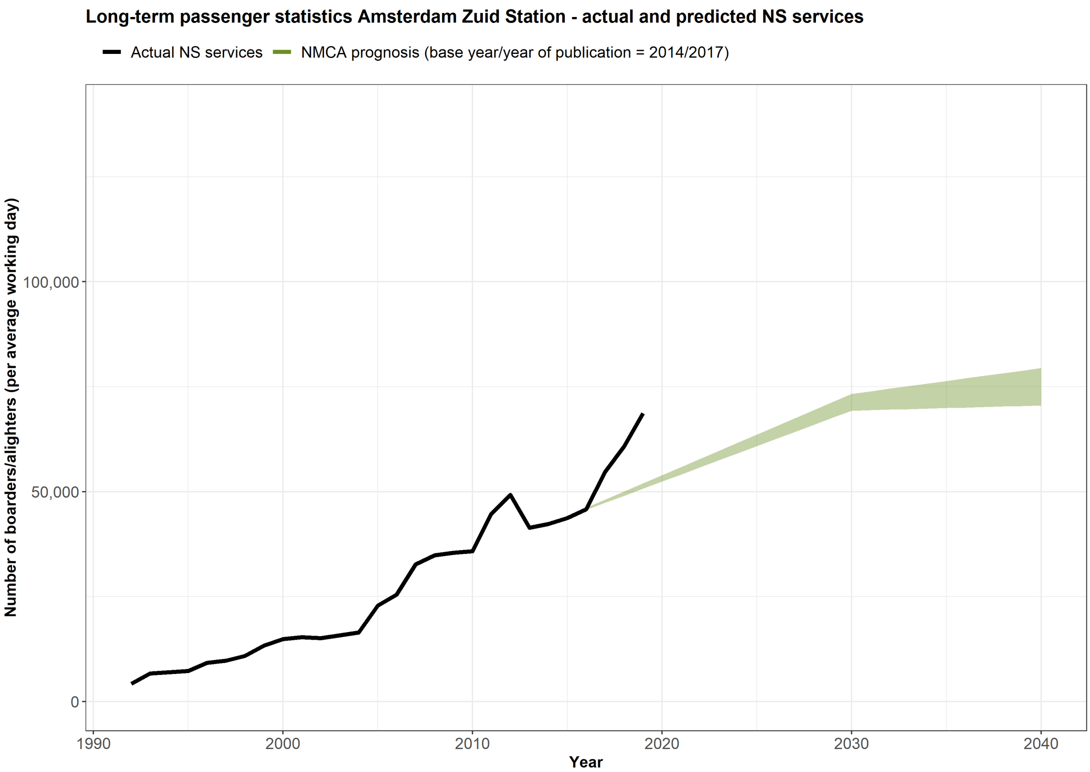
1.1 Background

Since the 2010s, Nederlandse Spoorwegen (NS, the Dutch railways) [1] and infrastructure manager ProRail [2] have been warning that the Dutch rail network is becoming "full". This is the result of the above-average increase in passenger numbers of recent years, which is expected to continue in coming decades. At the same time, numerous limitations within the rail network make it difficult to run longer trains and/or increase service frequency on busy lines.

Station platforms also appear to be getting "full". Over the last decade, there have been increasingly frequent indications of problems resulting from crowding at stations. In Autumn 2013, the police closed a number of platforms at Amsterdam Centraal, as they had become overcrowded during major disruption to train services [3]. But the platforms at Amsterdam Centraal suffer from overcrowding at certain times even in the absence of service disruptions [4]. At the end of 2016, ProRail declared Platform 5 at Utrecht Centraal overloaded, because excessive numbers of passengers were present on that platform at peak times [5]. An official declaration of overloading means that operators' timetables are demanding more railway infrastructure capacity than the infrastructure is capable of providing. Since 2016–2018, ProRail and NS have been using crowd control to prevent overcrowding on the busiest platforms at Utrecht Centraal, Schiphol Airport and Amsterdam Zuid [6] [7] [8]. The number of passengers using those three stations has risen much faster than predicted by a recent (2017) national market and capacity analysis [9] (see Figure 1.1 and Figs A.1a and A.1b in Appendix A). When we say that a platform is "overcrowded", we mean that the number of passengers on the platform is so high as to create a hazard and the risk of accidents. Such a situation arose during major track work in Spring 2019, for example, when the platforms at Leiden Centraal became overcrowded [10]. In Spring 2019, a modified form of crowd control was introduced at Amsterdam Bijlmer ArenA on account of the increasing numbers of people attending events nearby [11]. These measures were taken to ensure that there were not too many passengers on railway and metro platforms following those events. There are also occasional media reports of narrow platforms – or excessively narrow platforms – at smaller stations and the hazards that these cause. The earliest such report of which the author is aware involved Wijchen station, where a near-accident was reported in 2011; a child fell from the narrow platform onto the track as a result of crowding [12]. Other stations with narrow platforms include Tilburg Universiteit [13] and Ommen [14]. Platform capacity has since been increased at these three stations by widening an existing platform or building an additional one.

Railway policy is also addressing the issue of station and platform capacity: the ongoing *Programma Hoogfrequent Spoor* (PHS, High-Frequency Rail Programme) involves eliminating a number of capacity bottlenecks at stations, as part of the introduction of high-frequency train services [15]. In a recent national market and capacity analysis [9] [16], the Ministry of Infrastructure and Water Management lists dozens of stations with one or more safety bottlenecks on platforms. These bottlenecks were identified using Version 1.0 of the *Risicomodel Perronveiligheid* (platform safety risk model) developed by ProRail and NS. That model is used to determine the degree to which passengers are at risk of falling onto the track from the platform under peak crowding conditions, as a result of limited space on the platform, possibly in combination with the passage of a train. In a recent review of Version 2.0 of the ProRail risk model [17], Helsloot and Vis conclude that historically speaking, the risk of a crowding-related accident on a platform in the Netherlands is nil. This corresponds to the annual reports of the Human Environment and Transport Inspectorate for 2014 to 2018 [18] [19], which report no accidents resulting from crowding on a platform. Helsloot and Vis [17] state that platform crowding could become a problem in the future. The *Toekomstbeeld Openbaar Vervoer 2040* programme (Public Transport in 2040. Outlines of a vision for the future.) makes addressing platform capacity bottlenecks a precondition for achieving the programme’s aims [20].

It is striking that social debate in the Netherlands regarding platform capacity focuses primarily on safety. In the United Kingdom, trains are unable to depart on time at some stations, owing to crowding in the train and on the platform. This leads to delays, and to reductions in network capacity [21]. In the Netherlands, the connection is rarely made between station crowding on the one hand and punctuality and line capacity on the other. At the same time, there are plans to increase service frequency on the Dutch rail network still further following the implementation of PHS [22]. This raises the question as to whether situations such as those observed in the UK could occur in the Netherlands if service frequency increases.



(a) Passenger numbers and prognoses

(b) Platform 3-4, 27 January 2020, 08.37 hrs. (Photo: Jeroen van den Heuvel)

Figure 1.1: Passenger numbers and prognosis, Amsterdam Zuid

1.2 Formulation of the problem

The discussion above raises the question as to when a platform can be described as "full". Or to put it differently, at what point the service capacity of a platform has been reached in terms of passenger numbers – crowding. As the previous section suggests, a number of perspectives may be relevant. This may mean that there is no such thing as "the capacity of a platform", and that we must examine the passenger capacity of a platform from a number of angles. This is illustrated in Figure 1.2.

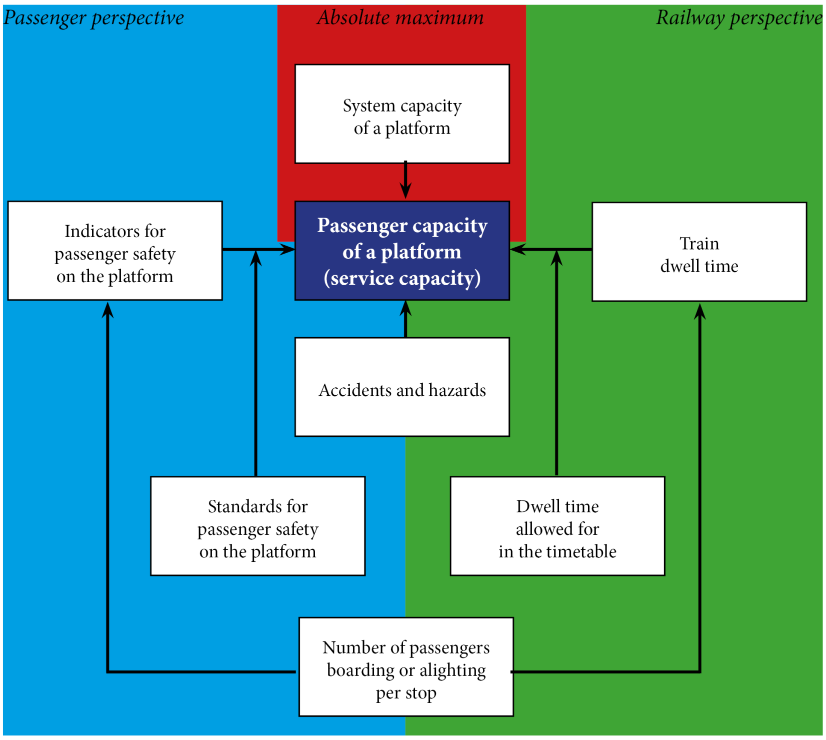


Figure 1.2: Relationship between the three perspectives

First, we have the passenger perspective, which primarily focuses on the safety of platform users. Here, the question is under what circumstances so many passengers are present simultaneously that hazards or accidents occur. In this context, "safety" is taken to mean the standards that are applied in order to limit risk to a specified level. Accidents and the existence of hazards can indicate that the service capacity of a platform has been reached. Then there is the railway perspective. The railway perspective addresses line capacity and punctuality, and how these are affected by any difference between actual dwell time and the dwell time allowed for in the timetable. Here, the question is how many passengers (alighters and boarders) must be present in order for a stop to last too long. If stops at a specific station regularly last longer than provided for in the timetable, fewer trains will be able to run (i.e. line capacity will be reduced) and/or trains will be less punctual. Here, there is a certain margin for arriving at a compromise between capacity and punctuality. The third perspective is that of the absolute maximum, i.e. the maximum number of passengers that a platform can theoretically handle. This absolute maximum is sometimes known as the "system capacity" or "physical capacity".

We do not know how these three perspectives relate to one another. Nor do we know how they can be rendered measurable in the sense of a platform capacity expressed in number of passengers. The central research question for this thesis is therefore:

How can we measure the passenger capacity of railway platforms in the Netherlands?

This central research question has been expressed in broad terms, as the literature contains little research on the passenger capacity of station platforms, either for railways or for metro systems (see Chapter 3). The first two factors that serve to delimit this study are the means available (see Section 1.3 and Chapter 4). The field of study is further delimited at the end of Chapter 3, in which the elements shown in Figure 1.2 are investigated by means of an exploratory literature study. This makes it possible to define the passenger capacity of a railway platform via three factors that limit service capacity. The present research does not investigate the "absolute maximum" perspective, arguing on the basis of the literature study that service capacity is lower than system capacity.

The first two limits on service capacity are related to the passenger perspective, while the third is related to the railway perspective. These limits are defined as follows:

1. As a result of queues forming at an exit escalator immediately following the arrival of a train, passengers stand or walk too close to the platform edge, and/or passengers in the queue for the exit escalator wait in the run-off from the incoming escalator.

2. As a result of crowding on the platform, passengers stand or walk too close to the edge.

3. As a result of the number of alighting and boarding passengers, trains regularly depart with a delay, or with more delay.

The second part of this thesis will look at whether these three capacity limits can be measured on a number of platforms in the Netherlands.

In the interests of readability, the terms "passenger capacity", "service capacity" and "platform capacity" will be used interchangeably throughout the remainder of this thesis. All three terms have the same meaning unless otherwise indicated.

1.3 Scope

As mentioned above, the central research question has been formulated in broad terms, as there is no unambiguous definition of “platform capacity”. To make it possible to investigate this topic in the framework of a doctoral thesis, it has been delimited as follows:

- Research is restricted to the platforms of railway stations. The reason for this choice is that most capacity bottlenecks in stations occur on platforms (see Chapter 2). The capacity of other parts of the station, and of the station as a whole, are seen as part of the context of this study.

- Examination of capacity will be limited to that available during normal service. For the purposes of this study, “normal” service includes operations affected by disruptions (delays and cancellations) but excludes operations during major incidents that shut down large parts of the rail network and situations in which it is necessary to evacuate a platform or a station (e.g. fire). Selecting these criteria ensures that the vast majority of situations that arise in practice are included in the study.

- This study focuses on main-line railway systems. The literature often refers to such systems as *heavy rail* or, in North America, as *commuter rail*. Railway systems differ from other networks (such as metro and light rail systems) in that they use open tracks, with trains running at comparatively high speeds. A given track is likely to be used by different types of train (e.g. both passenger and freight). Furthermore, a given platform at an interchange station may serve trains for a number of different destinations. This means that not all passengers waiting on the platform will board the first train to arrive, and hence that overlap occurs between passenger flows related to multiple trains. The literature study does include other urban rail systems, such as metros, because study of such systems can yield results that are relevant to main-line systems (see Chapter 3). Beyond this, however, other urban rail systems fall outside the scope of this study.

- Because the author is employed by NS, and because of the availability of data, this study focuses on the situation obtaining in the Netherlands. The literature study (Chapter 3) encompasses other countries, especially Switzerland and the UK. This was possible thanks to the close working relationships that the author maintains with railways and infrastructure providers in those countries. Those relationships gave the author an insight into the situations in those countries in general, and the regulations (and how they are applied) in particular.

- Because of the research group within which this study was conducted and the work that the author undertook for his masters degree, the present thesis addresses capacity from a transport point of view. Other perspectives, such as passenger perception (environmental psychology) and safety/risk management (organizational, business and/or public administration management) are seen as part of the context for this research.

- This research uses secondary data from the SMART Station and ROCKT Station systems, which were developed within NS Stations during this study. Extensive use of pedestrian sensors at stations over several years meant that trajectory data were available for busy platforms at Utrecht Centraal, Amsterdam Zuid and Schiphol Airport. Use of the OV-chipkaart (the smart card used to pay for public transport) throughout the Netherlands meant that passenger numbers for each train, and for each stop made by each train, were available for approximately 300 stations (75% of stations in the Netherlands). The present research therefor focused on drawing conclusions from the very extensive datasets that were already available, rather than on acquiring new data (see Chapter 4).

1.4 How this thesis contributes to research and practice

There has been relatively little academic or practical research on platform capacity. In carrying out the research reported here, considerable attention was therefore devoted to mapping out and delimiting the subject area and defining the concept. This involved examining not only the station of which the platform constitutes a part, but also the rail network to which both the station and the platform belong. It is the author's intention that this thesis make the following contributions to research and practice:

1.4.1 Research

This study makes the following contributions to research:

- Positioning of railway platform capacity as a relevant research topic.
- Definition of the concept of "platform capacity".
- Quantitative measurement of capacity limits for specific cases in the Netherlands.
- Creation of prepared datasets for further study.

Positioning of railway platform capacity as a relevant research topic.
Existing research on platform capacity is very limited and highly fragmented. Until about 2010, virtually all research focused on either the passenger perspective or the railway perspective, but not both. Little research has been identified that specifically addressed the issue of platform capacity – from either a passenger or a railway perspective. Over the last decade, other researchers have published a small number of studies that took a combined passenger and railway perspective. While those studies did cite platform capacity as an important aspect, they did not address the topic further. The author hopes that the present study will go some way towards filling this research gap. It will also become apparent why research on platform capacity is desirable from a societal point of view.

The present thesis is not the only result of the author's doctoral research. A number of master's students used the empirical data to study various topics in the field of pedestrian flow under the author's supervision, as part of their final projects. See for instance [23] and [24]. In 2013, the author carried out a large-scale empirical study of the relationship between stopping location along the platform and train dwell time [25]. In 2016–2017, fellow researchers at Delft University of Technology and the author took steps towards creating a mesoscopic pedestrian model capable of estimating platform entrance utilization and crowding distribution on the platform and in the train within a short time-frame, using a number of generic parameters plus passenger inflow and outflow at the station entrance [26].

What is "platform capacity"?
Platform capacity depends on many factors. Whether capacity has been exceeded depends on how one defines it. From a passenger perspective, the threshold may be the point at which pedestrian traffic comes to a halt, or at which the situation becomes unmanageable or dangerous. From a railway perspective, the question is more whether a train can be processed within the time allocated to it and, if not, the extent to which its delayed departure causes delays elsewhere in the network, disrupting traffic. To avoid the negative consequences of unstable traffic flows as a result of capacity limits being reached, margins are built into real-life systems, whether we look at them from a passenger or a railway perspective. In this thesis, the author describes platform capacity in terms of three boundaries, defined from two perspectives.

A quantitative, empirical approach to platform capacity
The present study shows that the three capacity limits can be measured under practical conditions in the Netherlands. This is achieved by means of various statistical methods and techniques. In this study, the author uses case studies from earlier work by other researchers. One factor that distinguishes the present thesis from earlier research is the large number of empirical observations used. This applies to both the "passenger perspective" and the "railway perspective" aspects of this study. Earlier research has been conducted from one single perspective, using either a relatively small number of empirical observations or else synthetic observations generated by passenger models, which were often microscopic in nature. This thesis gives a clearer picture of the degree to which one can generalize the empirically-observed relationships.

Creation of prepared datasets for further study.
Earlier research shows that the study of pedestrian movement in general is restricted by the limited availability of data or the high cost of data acquisition (see Chapter 3). This thesis makes the sets of raw trajectory data available for other researchers (see Chapter 4). By making this data available, the author and NS Stations hope to contribute to future research.

Between the development of SMART Station and ROCKT and the use of the data for this thesis, regular discussions took place concerning data quality. One result was an experiment to assess the quality of the trajectory data [27]. Through this research, the author shows that the data may be assumed to be of good quality, while at the same time indicating points that require further attention (see Chapter 4).

1.4.2 Practical recommendations

This study makes the following practical contributions:

- Establishing a link between platform and network capacity.
- Positioning of railway platform capacity as a design variable.
- Creation of platform capacity indicators.

Establishing a link between platform and network capacity.
The present thesis makes an explicit connection between platform and network capacity, placing this in the context of the development of the rail network, stations and cities. This is achieved by means of a historical and prospective study of the development of the rail network and the major railway stations in the Netherlands. The present thesis thereby makes a contribution to highlighting the fact that specific platforms in a railway network can determine network capacity, either now or in the future. For instance, a platform that lacks the capacity necessary to allow passengers to alight and board quickly enough may render it impossible to increase service frequency. At the same time, such an increase in service frequency would reduce the number of alighters and boarders per train. Or a platform with limited space in which passengers can wait for their train could become a problem if the number of passengers increases. Passenger numbers at a particular location may rise because the overall number of passengers is increasing (which generally happens gradually) or because of timetable changes (which generally happen suddenly).

This thesis also shows that resolving these bottlenecks is becoming steadily more difficult because of the situation in urban areas. In the past, a station's platform capacity was often increased by building an additional platform and tracks. This was relatively simple in many cases, as stations were often located next to large shunting yards or industrial areas. But in today's intensively built-up cities, this solution is either very expensive (e.g. in the case of Amsterdam Zuid [28] or Schiphol Airport [29]) or completely impossible because of the existing situation (e.g. in the case of Amsterdam Centraal [4]). This point is relevant to network and station strategy, such as that set out in *Toekomstbeeld Openbaar Vervoer 2040* ("Public Transport in 2040. Outlines of a vision for the future.") [22]. The lack of space and the high cost of making changes mean that it is more important than ever to plan for possible developments at an early stage.

Positioning of railway platform capacity as a design variable.
The intermediate results and insights contained in this thesis have already contributed to the growing realization that platform capacity is a design variable for both stations and platforms. For instance, insights into the use of platform space by waiting passengers and the way queues develop at escalators have been integrated into updated transfer standards and the ProRail/NS platform safety risk model (*Risicomodel Perronveiligheid*), Version 1.0. The results of sub-studies have been used in the planning of future alterations to stations including Amsterdam Centraal (Programma Hoogfrequent Spoor) [4] [15], Schiphol Airport (Multimodale Knoop Schiphol) [29] and Amsterdam Zuid (ZuidAsDok) [28]. Since 2017, NS has been assessing each new

timetable using the *Risicomodel Perronveiligheid* Version 1.0 and other tools to establish whether changes to platform use in a new timetable could lead to hazards related to overcrowding on platforms and elsewhere in stations. The results of this thesis offer a basis for reinforcing the links between the functions of the rail network (infrastructure), track use (timetable) and stations (including platforms).

Platform capacity indicators.
This study of platform capacity results in indicators that can be used to assess real-life situations. Targeted observations when crowding is at a maximum (e.g. at peak times) can give an initial indication as to whether capacity bottlenecks are occurring. This can involve examining use of the area along the platform edge and the nature and duration of the alighting and boarding process. The results of this thesis also provide a basis for validating models of existing or future situations. For instance, it is possible to compare the predicted use of the platform-edge zone and width of queues at escalators with the observations and results of the present study. Such a comparison also gives an insight into the dynamics that may underlie bottlenecks identified using a model.

1.5 Reading guide

Figure 1.3 shows the structure of this thesis. The present chapter describes why this thesis was written and why its broad central research question was selected. Chapters 2 and 3 go into more detail regarding the motivation behind this thesis and the definition of “platform capacity” in terms of the three limits on capacity that result from the two perspectives adopted. Those limits are examined in Chapters 5, 6 and 7. Those chapters use the data sources and data-processing methods described in Chapter 4. The final chapter of this thesis is Chapter 8 – Conclusions. That chapter also discusses the implications of the conclusions for further research and for development of the rail network.

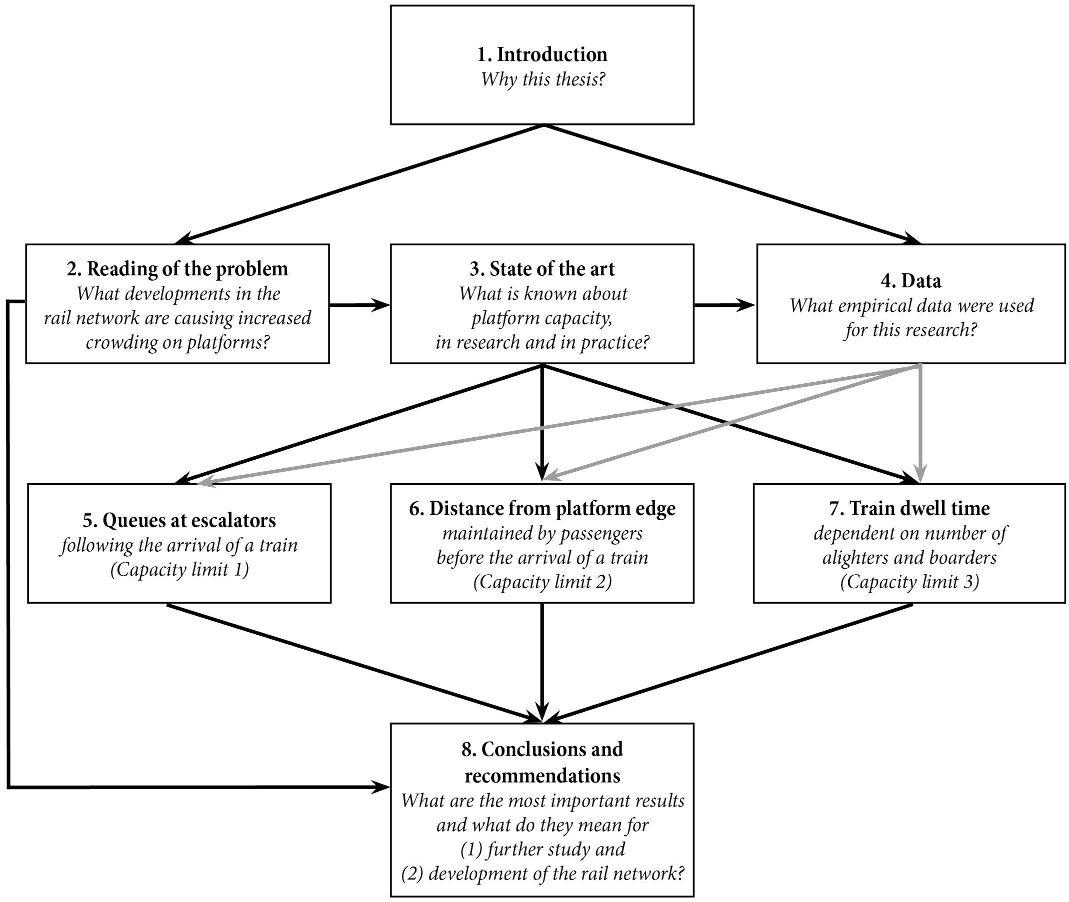


Figure 1.3: Structure of the thesis

Chapter 2

Background

Later chapters in this thesis will examine platform capacity in more detail. First, however, the present chapter will set out a broader perspective regarding the development of stations in the Netherlands – and of their platforms. Clearly, a platform is part of a station. In turn, stations constitute the link between the railway network and a town or village [30]. Multiple traffic flows come together *around* a station, linking it to other modes such as pedestrian, bicycle, car and bus. Traffic flows *inside* a station consist of trains (including passengers who are not alighting) and pedestrians, most of whom are railway or other passengers [31]. On platforms, passengers account for the vast majority of persons present.

Passengers in a station move between the various transport modes by which they have arrived or will be leaving on the one hand, and the train on the other. They may also spend time at the station engaged in activities other than moving to or from their trains, either because they have planned to do so or as a result of circumstances. This time is generally short. In the Netherlands, passengers generally spend approximately 7 minutes at the station before commencing their rail journey, of which 5 minutes are spent on the platform [32]. The number of passengers on a platform at any given time depends on the number of trains and on the number of passengers alighting from or boarding those trains. The frequency of trains and variability in their destinations may also play a role. The more passengers arrive or depart simultaneously on one or more trains, the greater the peak in traffic flow [31]. It therefore follows that the development of stations is related to the development of the railway network, of the area immediately around the station and of the area that the station serves.

This chapter will examine that relationship in the Netherlands, covering the period since the Second World War. We shall start by looking behind the scenes of network and station development, to identify the driving forces behind station development (Section 2.1). From this, it will become clear that in the past, the number, width and length of platforms were often increased in combination with the rebuilding of existing tracks in and adjacent to the station, with the aim of providing the additional capacity needed to handle increasing numbers of trains and passengers. Increased construction outwards from urban centres towards and around stations over recent decades means that today there is much less space available around many stations. This makes it more difficult to widen or lengthen existing platforms, or to build new ones. Section 2.2 will then explain the long-term quantitative trends in the productivity of trains, stations and platforms. As that analysis will demonstrate, Dutch stations (and their platforms) have become considerably busier in recent years. Forecasts of passenger numbers indicate that this increase will continue. This chapter ends with the conclusion (see Section 2.3) that the problem of overcrowded platforms mentioned in Chapter 1 will occur more often in the future, because (1) it is becoming increasingly difficult to expand platform capacity and (2) platforms will become increasingly busy in the future.

2.1 Network and station development

This section presents a summary, qualitative analysis of the development of the Dutch railway network since the Second World War and of the largest stations in that network. The summary covers the rail network and major stations as of 2020 (see Appendix B for a more detailed definition and explanation). For a more detailed account, broken down into time periods, please see Appendix B, Section B.1. Figure 2.1 provides a complete overview.

Immediately after the Second World War, the top priority regarding network and station development was to repair the damage that the war had left behind. A number of stations were rebuilt because tracks in towns and cities had been moved to embankments, to eliminate the barrier that the railway line created in the town and the barrier to rail traffic caused by the town. A number of pedestrian level crossings on the periphery of the network were replaced by subways, on account of the increased number of trains and passengers. There was a dip in rail traffic between 1960 and the mid-1970s, as a result of which only a relatively small number of network and station projects took place in that period. However, the processes of raising tracks above ground level in towns and modifying stations continued, with the last remaining pedestrian level crossings in stations being replaced by subways. One new feature of this period was the combined development of city centre and station, in The Hague and Utrecht.

Between 1975 and 1989, the rail network in the Randstad (a region of the western Netherlands that encompasses Amsterdam, Rotterdam, The Hague and Utrecht) underwent significant expansion. In and around The Hague and Utrecht, railway lines were built to link new residential areas with the existing cities. The Schiphol Line was built, linking The Hague and Amsterdam and incorporating a large number of stations. The Flevolijn was built, running east from Amsterdam, to link the new towns on the land created by draining part of the former Zuiderzee with the capital. As towns and cities expanded around stations, many of them acquired an entrance on the side furthest from the town centre.

The Schiphol Line was completed between 1990 and 2004. The number of tracks on existing lines was increased, especially along the north-south axis in the west of the country, and this involved rebuilding a number of stations. As in the cases of Den Haag Centraal and Utrecht Centraal, new stations were built in Hilversum, ’s Hertogenbosch and Amersfoort as part of urban redevelopment projects. [The Dutch name for the city known in English as “The Hague” is Den Haag, and this is the name used in the present thesis when referring to the stations in The Hague.] The number of passengers increased considerably, partly thanks to the introduction of the OV-Studentenkaart, a nationwide public transport pass for students.

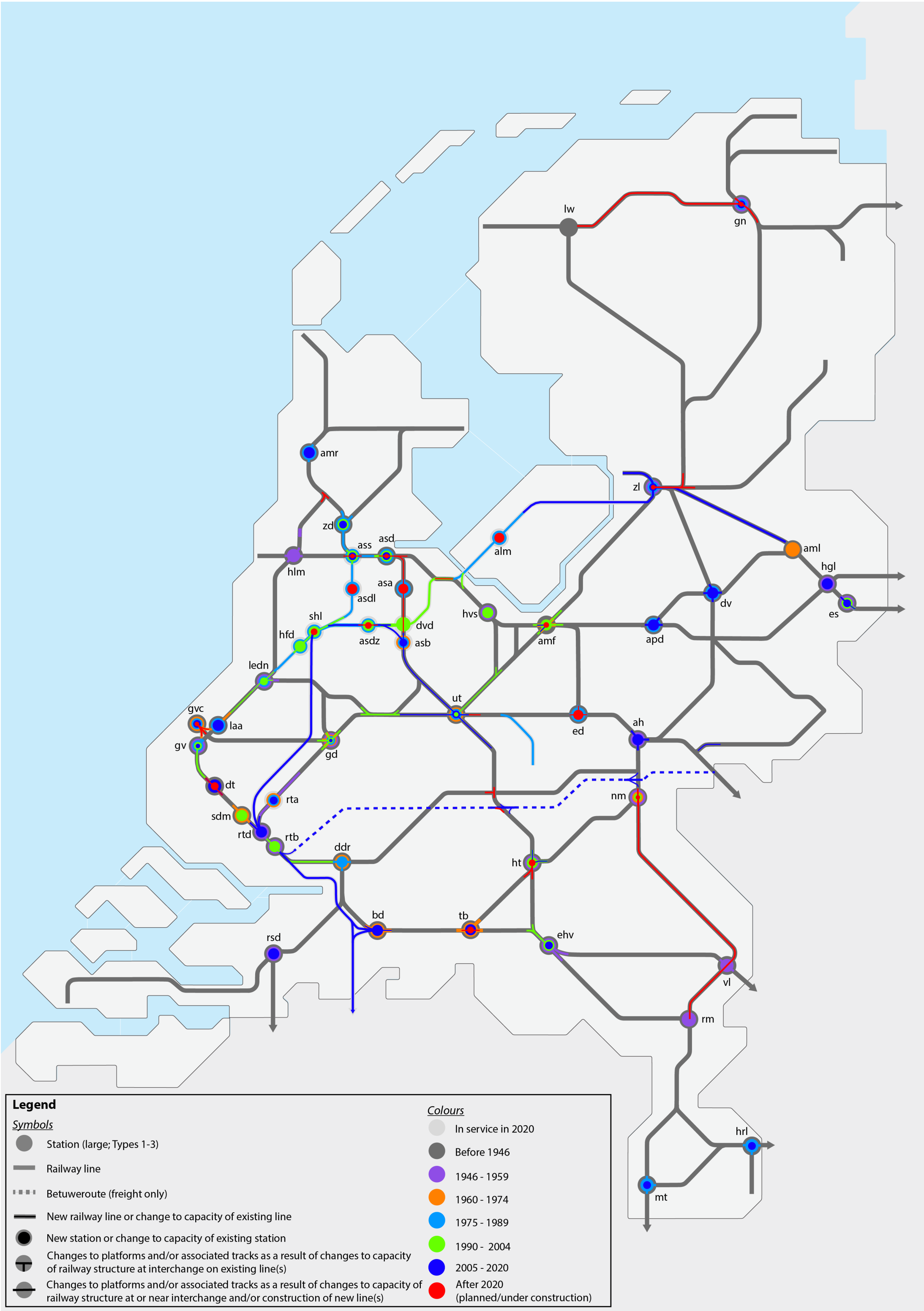


Figure 2.1: The Dutch railway network as of 2020, showing changes over the period 1946–2020 and planned development

The period 2005–2020 saw the completion of four major rail projects: the High-Speed Line South (linking Amsterdam and the Belgian border), the Betuweroute freight line from the Port of Rotterdam to the German border, the Hanzelijn (Lelystad–Zwolle) and the Delft railway tunnel. Increases in the number of tracks on the busiest routes continued, especially around Utrecht and between Schiphol/Amsterdam and Utrecht. The stations Rotterdam Centraal, Utrecht Centraal, Den Haag Centraal, Breda, Arnhem Centraal, Eindhoven Centraal, Zwolle and Delft, together with their associated tracks, all underwent extensive renewal and expansion, partly as a result of the major projects and partly as part of measures to compensate for the abandoning of the planned High-Speed Line East. A number of urban railway lines and their stations in and around The Hague and Rotterdam were dropped from the railway network and converted to light rail. The towns of Heerlen and Zaandam were expanded by building above the railway tracks.

A large number of modifications to the rail network and stations are planned from 2020, with the aim of increasing the frequency of services on the busiest rail corridors. Major track and station projects include the rebuilding of Amsterdam Centraal, along with the tracks to the east of the station; the extension of Amsterdam Zuid in combination with moving the A10 motorway underground and increasing the number of tracks around Delft, Zwolle and 's Hertogenbosch. The new ERTMS (European Rail Traffic Management System) train control system is being introduced nationwide, and the electrification system is being upgraded. No new lines are planned for the time being.

On the basis of the above, and of Appendix B, four driving forces can be identified which, together, prompt the rebuilding of a station.

1. **Construction, expansion or renewal of railway infrastructure**, e.g. the building of railway embankments or tunnels, increases in the number of tracks or the renewal of sidings and station tracks. In the specific cases of Amsterdam, Rotterdam and The Hague, the building or rebuilding of urban railway lines should also be included. Changes to platforms are often undertaken in connection with changes to station tracks. In some cases, modifications are motivated by changes in the use of tracks, in others by a shortage of capacity in the station (see next point). Modifications to platforms are usually carried out in response to a combination of the above factors.

2. **Increased passenger and/or train traffic**, e.g. the construction or expansion of passenger tunnels/subways/footbridges and station entrances, and the lengthening, widening or construction of platforms.

3. **Urban development**, e.g. the creation of new station entrances, integration of a station building in the urban environment or the linking of two areas of a town separated by the railway.

4. **Renewal** necessitated by functional or structural factors, e.g. construction of a new station because the existing building is in poor condition or major renovation of a station that can be conserved.

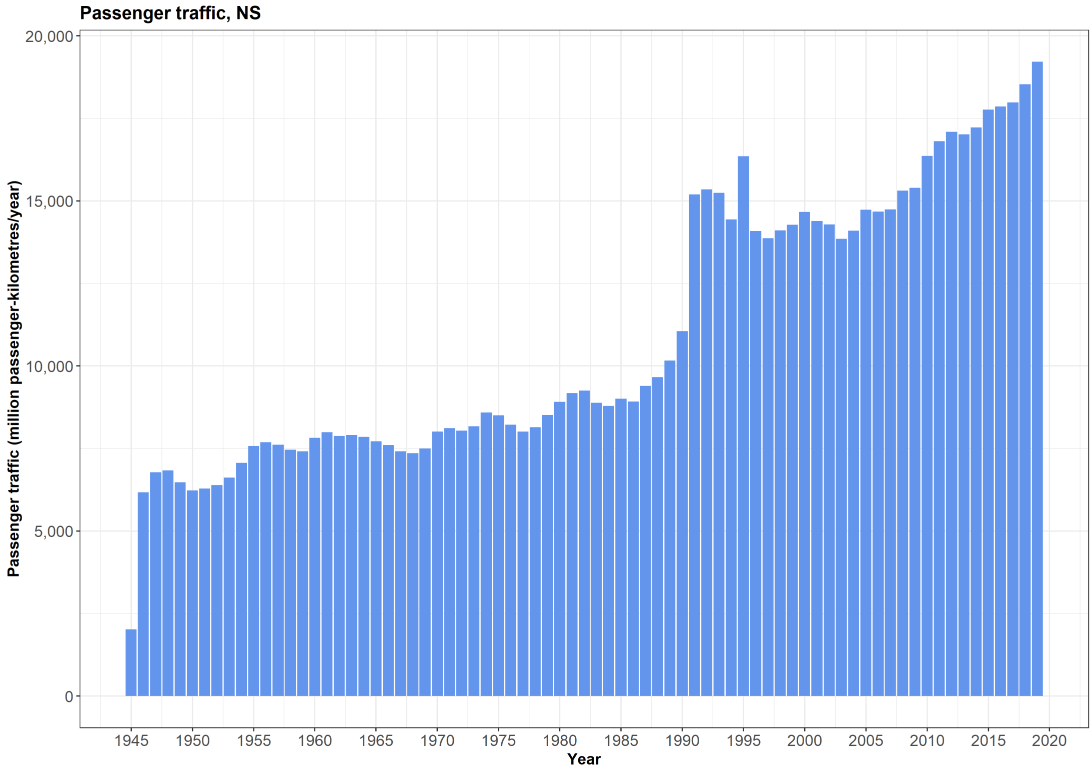
(a) 2010 (Source: Collectie Utrechts Archief, No. 802608)

(b) 2019 (Source: CU2030/Utrecht City Council)

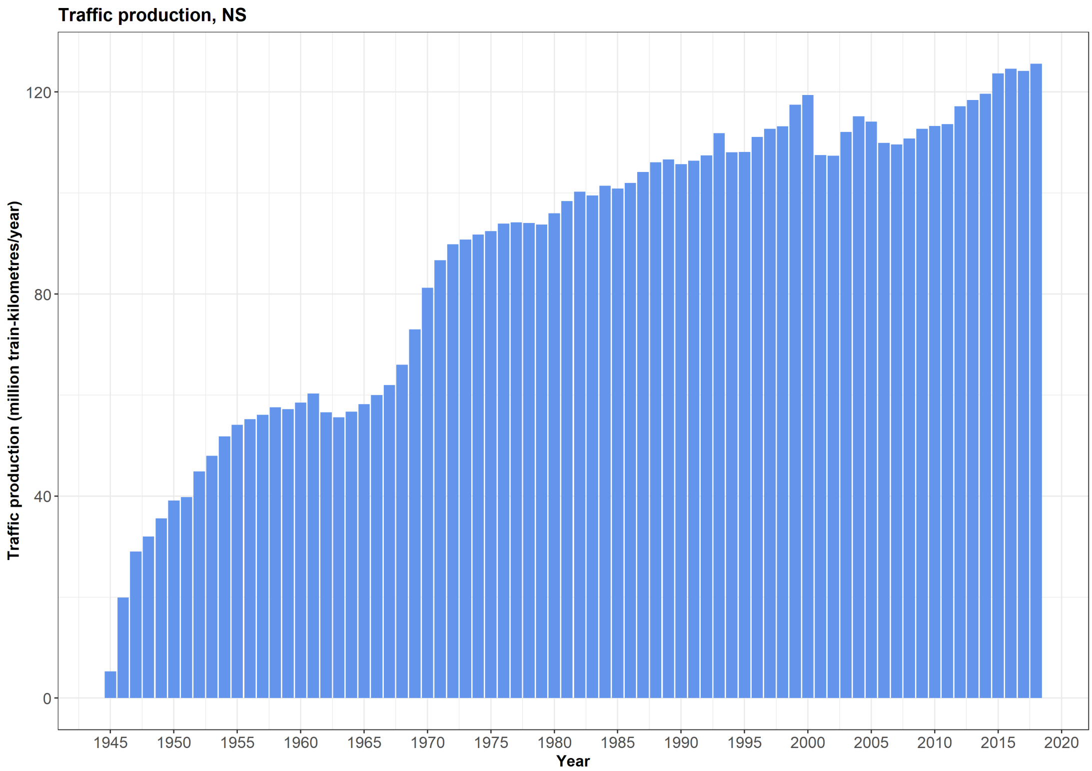
Figure 2.2: Development of the area around Utrecht Centraal, 2010–2019

The first two of these four "driving forces" are relevant to platform capacity. Figure 2.2 shows how the city of Utrecht and Utrecht Centraal station have expanded towards each other, making it difficult to continue expanding the station by adding extra tracks and platforms. This applies not only to Utrecht Centraal and the other *Nieuwe Sleutelprojecten* (new key projects) – Breda, Rotterdam Centraal, Den Haag Centraal and Arnhem Centraal – but also to other large stations, such as Zwolle, Eindhoven, 's Hertogenbosch, Amersfoort Centraal and Leiden Centraal. In some cases (e.g. Zaandam and Heerlen), the town has expanded over the top of the railway line at surface level. In other cases (e.g. Delft, Rotterdam Blaak and Schiphol Airport (Figure 2.3)) the tracks and platforms are underground, and construction has expanded over the subterranean area of the station. In the future, therefore, network and station development will increasingly occur at densely-occupied urban locations around stations. This will limit the options for expansion of tracks and platforms at stations, and will increase the cost of doing so. As a result, increasing platform capacity will be more difficult in future.

Figure 2.3: Crowds on Platform 3 at Schiphol Airport, where the platforms are located underground (Photo: Jeroen van den Heuvel)



(a) Passenger-kilometres



(b) Train-kilometres

Figure 2.4: Passenger traffic on NS, 1945–2018

2.2 Quantitative development

This section presents a quantitative analysis of the long-term development of passenger traffic on NS. The aim is to see how crowding has developed, at stations and on platforms. The question will be posed as to whether the crowding in trains and on platforms mentioned in Chapter 1 can also be discerned in the long-term statistics available at NS. To make the trend as clear as possible, data have been collected covering as long a period as possible. As this is a historical analysis, secondary data were used, which means that it was not possible to choose variables and aggregation levels. Nor was it possible to establish statistics for individual stations, so these analyses cover all stations, and NS passenger traffic as a whole. Appendix B describes the data and data sources. Where relevant, the analyses have been limited to those stations that constitute "large" stations as of 2020, as defined in the same appendix.

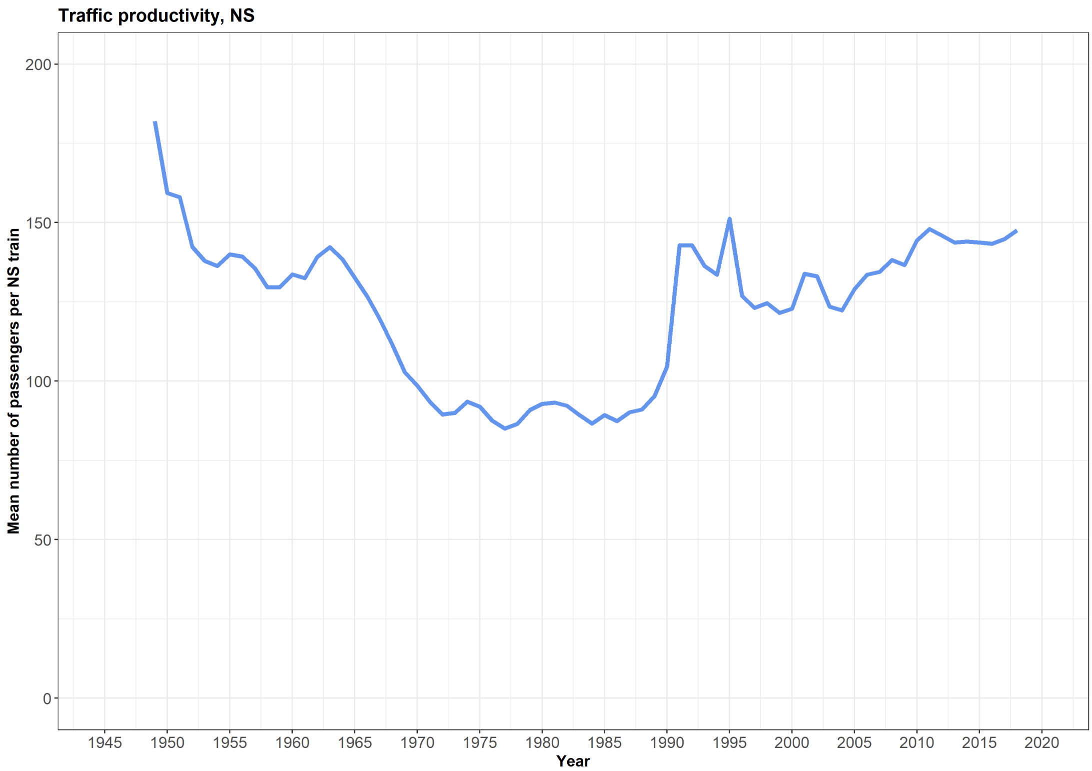


Figure 2.5: Mean number of passengers per train on NS, 1950–2018

2.2.1 Passenger-kilometres, train-kilometres and productivity

Figure 2.4 shows passenger traffic on NS, expressed in terms of passenger-kilometres per year and train-kilometres per year, for the period 1945–2020, using NS data (see Section B.3). The ratio of passenger-kilometres to train-kilometres gives the mean number of passengers per train ("passenger traffic productivity").

Figure 2.5 shows that after the Second World War, the mean number of passengers per train fell to a stable figure of between 130 and 140. Between the mid-1960s and the 1970s/1980s, this figure fell to well under 100, as train-kilometres increased but passenger-kilometres remained the same. Introduction of the OV-Studentenkaart at the beginning of the 1990s brought a substantial increase in the number of passenger-kilometres, while the number of train-kilometres remained relatively stable. As a result, train occupancy rose to approximately 150 passengers per train. This figure fell to approximately 125 in 2005, before rising to approximately 150 in 2015, a level it has maintained since then.

This means that mean train occupancy on NS over the last 10 years lies within the range for the past 75 years. It should be pointed out that the decentralization of regional lines that started in 1999 (generally involving lines with less passenger traffic) could distort this picture. No data were available for the present research that would have made it possible to state whether numbers are rising for all railway operators in the Netherlands. However, this would be a reasonable assumption, given recent and future projects involving the upgrading of regional lines to increase their capacity (see Section 2.1). On the other hand, one cannot say with certainty on the basis of this indicator that trains have become significantly more crowded over the last decade on average.

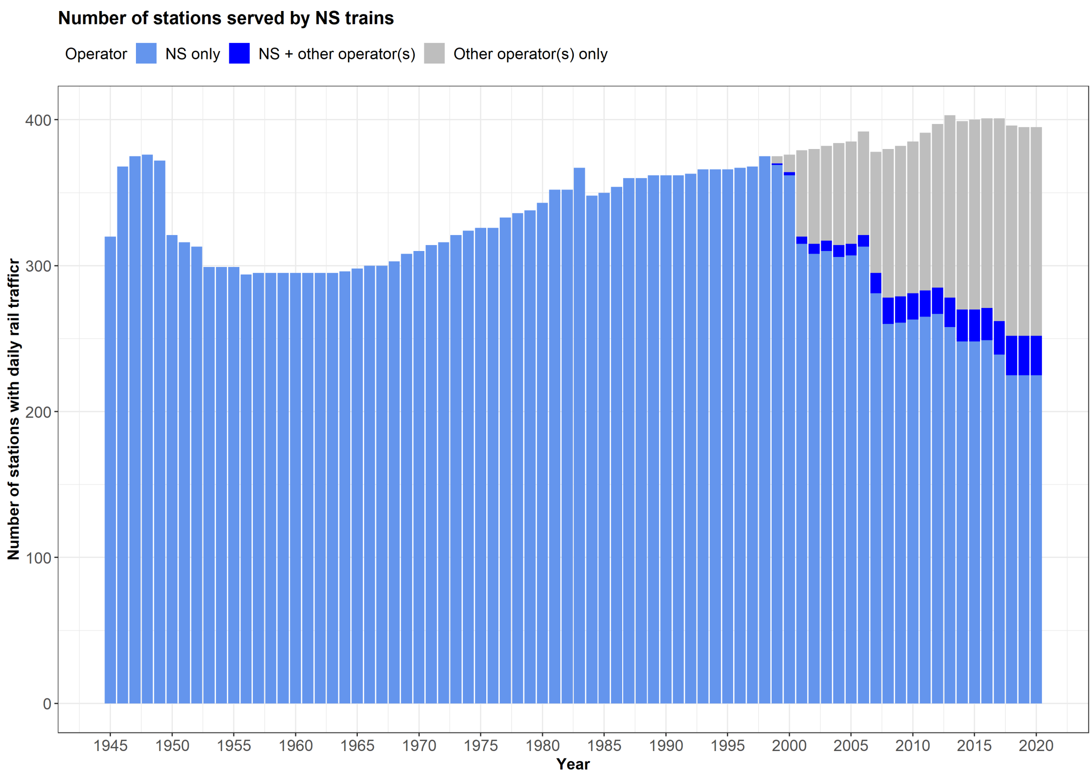
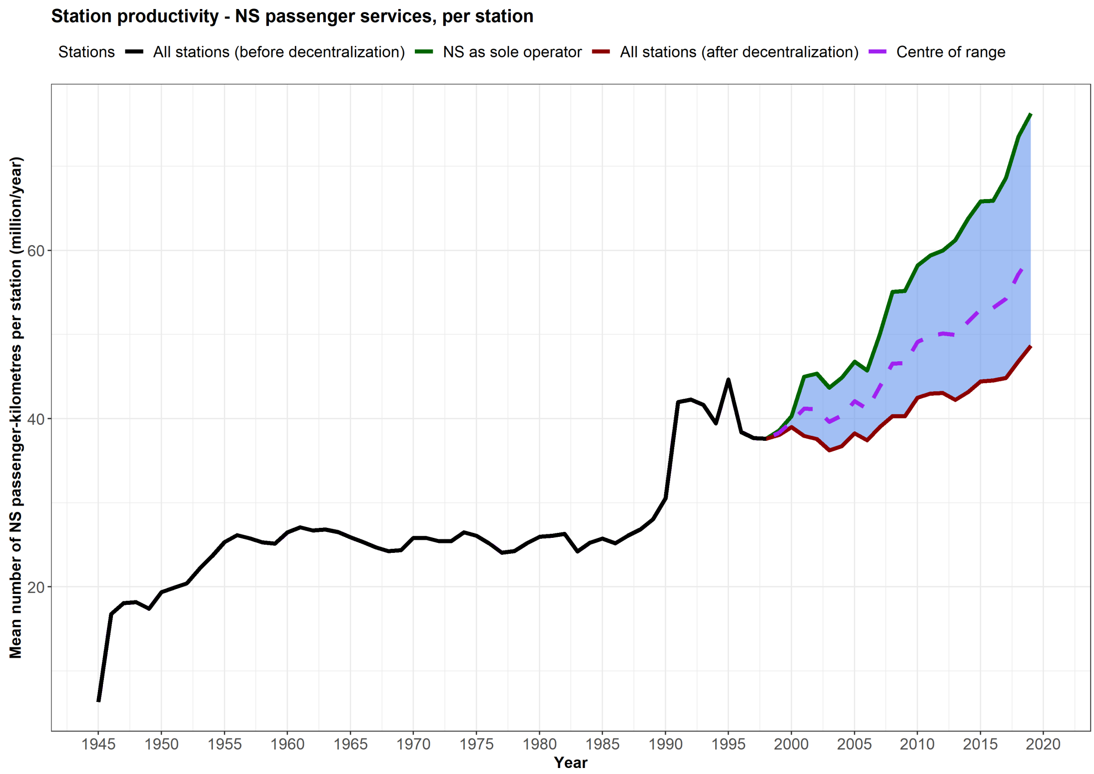
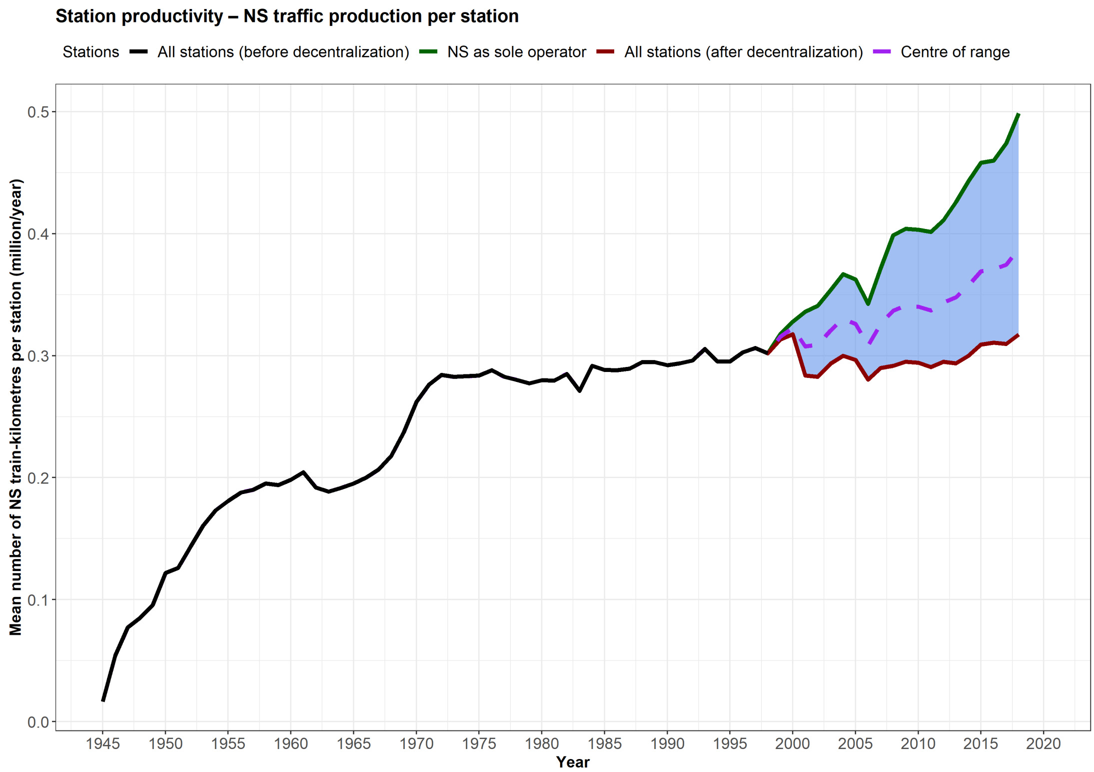


Figure 2.6: Number of stations, 1945–2018

Figure 2.6 shows the number of stations in the Netherlands over the last 75 years. Following an initial peak during the reconstruction period following the Second World War, the number of stations fell to around 300. From the 1970s onwards, the number of stations gradually increased to reach today's figure of approximately 400. As a result of partial privatization, the number of stations at which NS is no longer an operator has risen to approximately 150 since the end of the 1990s. In addition, there are some 30 stations at which both NS and other operators operate passenger services. See Section B.4 for more information.



(a) Mean passenger-kilometres per station



(b) Mean train-kilometres per station

Figure 2.7: Mean NS station productivity, 1945–2018

As in the case of mean traffic productivity, stations with a relatively small number of passengers are over-represented among those affected by the decentralization of regional lines. For that reason, the graphs of station productivity in Figure 2.7 (mean passenger-kilometres per station and mean train-kilometres per station) display upper and lower bounds from the mid-1990s onwards, rather than single lines. The lower line shows the value obtained by dividing NS passenger-kilometres and train-kilometres per year by the total number of stations. This underestimates the figures for NS, and corresponds to the lowest possible value of mean station productivity. The upper line shows the value obtained by dividing NS passenger-kilometres and train-kilometres per year by the number of stations at which NS operates trains. This overestimates the figures for NS, and corresponds to the highest possible value of mean station productivity.

The range in Figure 2.7 shows clearly that the mean number of passenger- and train-kilometres per station has been well above 40 million per year since the 1990s, and has risen by 0.3 million train-kilometres per year. If we take the middle of the range, we can say that mean passenger traffic per station increased by a factor of 1.5 between the first half of the 1990s and 2018. Traffic productivity was a third higher in 2018 than in 1970. Taken in combination with the increase in the mean number of passengers per train (Figure 2.5), it is reasonable to assume on the basis of this analysis that stations have become considerably more crowded on average.

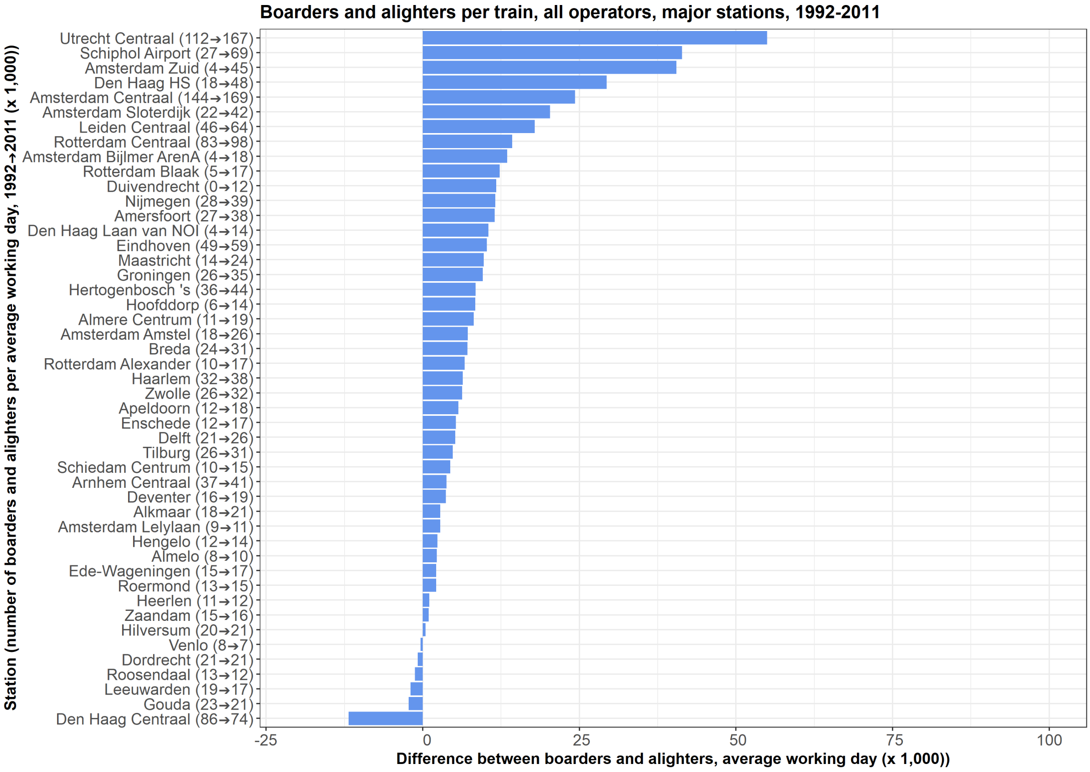
2.2.2 Passenger traffic per station

Since 1992, NS has been using the traffic data for each station to calculate the mean number of boarders and alighters per working day. Transferring passengers are not included, both because full data are not available for this category of passenger and because the number of transferring passengers depends in part on the timetable. Using the statistics for the number of boarders and alighters, it is possible to compare passenger traffic figures between stations over an extended period.

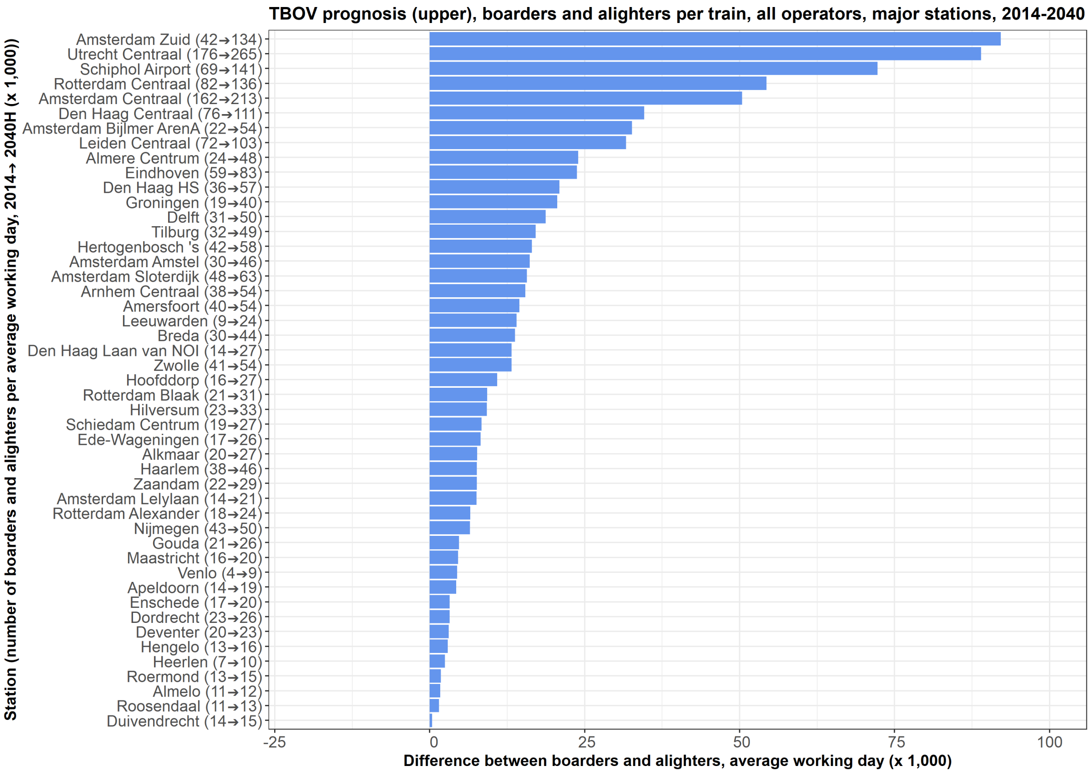
Up to and including 2011, the figures included data for all operators. This avoids any distortion due to the decentralization of rail routes mentioned above. However, the conversion of the Zoetermeerlijn and the Hofpleinlijn to urban transit lines in 2006 does distort the figures for Den Haag Centraal and Rotterdam Centraal. As a result of those measures, the corresponding passengers are missing from the statistics from 2011 onwards, figures are lower for Den Haag Centraal and the growth in passenger numbers at Rotterdam Centraal is understated.

Central government transport prognoses for the period up to 2040 are available, giving figures for each station expressed using the same variable and units as for the statistics collected since 1992. These statistics were collected as part of the process of producing a joint vision document entitled *Toekomstbeeld Openbaar Vervoer 2040* ("Public Transport in 2040. Outlines of a vision for the future.") [22]. The upper growth prognosis was used for this analysis. This dataset also includes some distortion, owing to the conversion of the Hoekselijn (the line linking Rotterdam with the Hook of Holland ferry terminal) to an urban transit line in 2017.

Together, the two graphs in Figure 2.8 give a picture of the relative changes in the number of passengers using the major stations in the Netherlands over the last 50 years, based on the statistics mentioned above. The absolute growth in the number of



(a) Alighters and boarders, 1992–2011



(b) Upper prognosis for 2014–2040, based on "Public Transport in 2040. Outlines of a vision for the future." Reference year: 2014.

Figure 2.8: Number of passengers per station

boarders and alighters is shown for each station, with the stations ranked from high to low. For 1992–2011, Utrecht Centraal occupies first place, with approximately 55,000 more alighters and boarders per average working day in 2011 than in 1992. Den Haag Centraal is in last place, having lost approximately 10,000 passengers per average working day as a result of the conversion of railway lines to urban transit (see above). The name of each station is followed by the number of alighters and boarders for the first and last years shown in the figure. Those figures show that in 1992, Utrecht Centraal and Amsterdam Centraal were the stations with the most passengers, followed by Den Haag Centraal and Rotterdam Centraal. At that time, these were the only stations with approximately 70,000 boarders and alighters per working day or more. In 2014, Schiphol Airport and Leiden Centraal joined this category of “largest stations”. According to the prognoses, Amsterdam Zuid and Eindhoven Centraal will join this group by 2040 at the latest.

Figure 2.8 shows that the increase in passengers is concentrated on the largest of the large stations. Between 1992 and 2011, the number of boarders and alighters at all stations in the figure together rose from approximately 1.2 to 1.6 million per average working day (+36%). The ten largest stations in 2011 account for 42% of this absolute increase. The ten stations with the highest absolute growth in passenger numbers account for 62% of that growth. If the upper growth prognosis for 2014–2040 proves to be correct, the number of boarders and alighters per average working day will increase from approximately 1.6 million to 2.5 million, an increase of 52%. The ten largest stations in 2040 will account for 57% of this increase, with the ten fastest-growing stations accounting for 60%.

The traffic growth expected at each station shows that the largest increases will continue to occur at those stations which were largest in 2014, plus Amsterdam Zuid and Eindhoven Centraal. This leads to the conclusion that these stations in particular will become even busier than they were at the end of 2019.

2.2.3 Passenger load per station

At the initiative of the author, NS Stations has been keeping a record of the number of passengers boarding and alighting from NS services per platform per average working day [33], (known as the “passenger load”) since 2014. Figure 2.9 shows these figures for all platforms at the major stations, for the years 2014 and 2019. For each year, the platforms are ranked from high to low. For instance, the platform with the highest load in 2014 was Amsterdam Centraal Platform 11, whereas in 2019 it was Platform 2 at the same station. See Table 2.1. The figure also shows that there were more platforms in existence in 2019 than in 2014 (e.g. as a result of the construction of a two-platform island at Utrecht Centraal).

It is clear from the figure that passenger load has increased on virtually all platforms. Table 2.1 gives the figures for the top 15 platforms. These statistics reveal that the highest platform loads have risen from just over 20,000 to just under 30,000 boarders/alighters per average working day The table also shows that the number of platforms with relatively high platform loads – more than 20,000 boarders/alighters per average working day – has increased from 5 to 13. This shows that platforms have become busier, and that the highest platform loads have increased substantially. This stems from a combination of increased passenger numbers (i.e. growth in passenger traffic) and changes in the use of platforms (i.e. timetable changes).

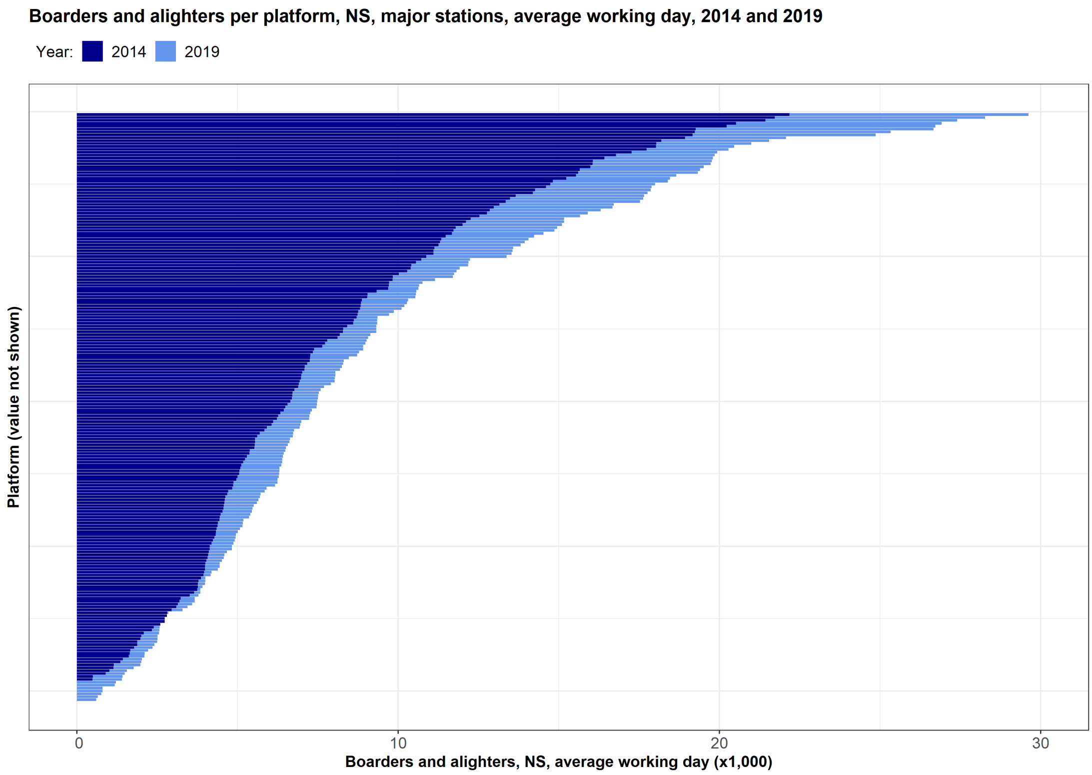


Figure 2.9: Distribution of number of passengers per platform

2.3 Conclusions

This chapter has identified changes in track use and timetables, traffic growth, urban development and maintenance/replacement as the four driving forces behind station development and redevelopment. Over the last 75 years, various combinations of these driving forces have resulted in modifications to stations. Those driving forces are also behind the projects currently planned.

Changes in platforms and their associated tracks, and/or the addition of new platforms and tracks, are often related to changes in track usage and in the timetable. Under such circumstances, new routes, additional tracks on existing routes or upgrading of lines result in modifications to station tracks and platforms. New platforms and tracks have been built at innumerable stations over the last 75 years. At other stations, platforms have been lengthened, allowing two trains to use the same side of a platform at the same time. As a result, many stations have become wider and/or longer over the last 75 years. This relationship is also apparent as regards future projects. As in the past, new developments in the fields of signalling and electric traction power systems will allow more trains to use the same tracks.

Many stations were built on what was then the edge of a town or city. Since then, the town or city has expanded towards and indeed beyond the railway line and the station. This has resulted in changes to the tracks and the station, to reduce the bar-

Position	2014 Station	Plat.	Boarders alighters	2019 Station	Plat.	Boarders/ alighters
1	Amsterdam C.	11	22,000	Amsterdam C.	2	29,500
2	Amsterdam C.	2	21,500	Amsterdam C.	14	28,500
3	Utrecht C.	5	21,500	Utrecht C.	7	27,500
4	Utrecht C.	7	20,500	Nijmegen	4	27,000
5	Amsterdam C.	10	20,000	Amsterdam C.	4	26,500
6	Utrecht C.	14	19,500	Amsterdam C.	8	26,500
7	Amsterdam C.	5	19,000	Utrecht C.	18	25,500
8	Utrecht C.	15	19,000	Amsterdam C.	11	25,000
9	Leiden C.	8	19,000	Nijmegen	3	22,000
10	Amsterdam C.	8	18,000	Utrecht C.	19	21,500
11	Nijmegen	4	18,000	Leiden C.	8	21,000
12	Leiden C.	5	18,000	Leiden C.	5	20,500
13	Utrecht C.	19	17,500	Eindhoven C.	2	20,500
14	Utrecht C.	11	17,500	Amsterdam Zuid	2	20,000
15	Rotterdam C.	9	17,000	Delft	1	20,000

Table 2.1: The fifteen busiest platforms in 2014 and 2019 (passengers boarding/alighting from NS services, numbers per average working day, rounded to the nearest 500)

rier effect of the railway. Those changes have involved running railway lines along embankments, viaducts or tunnels, in some cases with the station being moved to the embankment, viaduct or tunnel. Many stations now have new entrances, on the side away from the city centre. Since the 1970s, stations and the towns around them have increasingly grown in tandem. The Nieuwe Sleutelprojecten are a large-scale example. Today, in 2020, many stations are located in densely built-up zones, with multiple station and urban functions concentrated into a relatively small surface area. As a result, it has become difficult to add extra platforms.

At the same time, train and passenger traffic between stations has intensified. The indicator for this is not so much traffic productivity in mean number of passengers per train; this has remained relatively stable since the beginning of the 1990s, at 130 to 150. Indeed, that level had already been reached in the 1950s. What does reveal an increase in the intensity of traffic is the intensification of station productivity. In 2019, traffic production per station (in train-kilometres) reached its highest level since the introduction of today's timetable concept in the 1970s (Spoorslag '70) and it is continuing to increase. Since the 1990s, the largest stations have been responsible for generating the largest number of new passengers. This trend is expected to continue in the coming decades. Over the last five years, passenger loads on the busiest platforms have risen by almost 50%. At the same time, the number of platforms with a relatively high peak load has more than doubled.

The intensity of train and passenger traffic is expected to increase further in the coming decades. In view of the limited space for stations to expand into, this intensification will result in a further increase in platform loads at many stations. At the same time, ProRail and NS were already having to take crowd-management measures on certain platforms in 2019 (see Chapter 1). From this, one may conclude that the passenger capacity of railway platforms has become a socially-relevant research topic. The following chapter, Chapter 3, uses a literature study to build an overview of existing knowledge regarding the passenger capacity of railway platforms.

Chapter 3

Literature on platform capacity

This chapter gives an overview of the current state of knowledge regarding platform capacity. From a transportation point of view, we see capacity in terms of maximum occupation (storage) or maximum traffic flow (flow). Van Dale [34], the standard dictionary of Dutch, defines capacity as "*vermogen, kracht om een bepaalde prestatie te leveren*", i.e. the ability or power to deliver a given service. Here, delivering a service means to comprise, transport, process or produce. The Oxford Dictionary [35] defines capacity as "the maximum amount that something can contain". One indicator that system capacity has been exceeded is the occurrence of accidents as a result of crowding. However, few publications were identified that address crowding-related hazards and accidents. One possible explanation for this is that designers, owners and operators are successful in preventing traffic loads becoming so high as to cause safety incidents. This implies that the (practical) service capacity is lower than the (theoretical) system capacity. The present study will define service capacity in terms of three capacity limits emanating from the literature study in this chapter.

Figure 3.1 shows the structure of the chapter. The formulation of the problem in Chapter 1 explains that figure in more detail. Following a review of publications on hazards and accidents (Section 3.1), Section 3.2 will address the concept of platform capacity from a practical point of view, on the basis of standards, guidelines, general handbooks and case studies. This will be followed by consideration of the pedestrian perspective, the railway perspective and the combined perspective, on the basis of the literature (Section 3.3). The reason for that sequence is that – as is apparent from this chapter – platform capacity is determined more by safety standards and by what is possible in practice than by the theoretical system capacity. This question is addressed differently in the United Kingdom, Switzerland and the Netherlands, indicating that there is no standard definition of "platform capacity". That was also clear from the literature, which presents no unambiguous, agreed definition. This chapter therefore ends with a proposed definition of platform capacity (see Section 3.4) and further delineation of the topics covered in this study (Section 3.5). Sections 3.2 and 3.3 contain a brief description of the methodology adopted for the literature study.

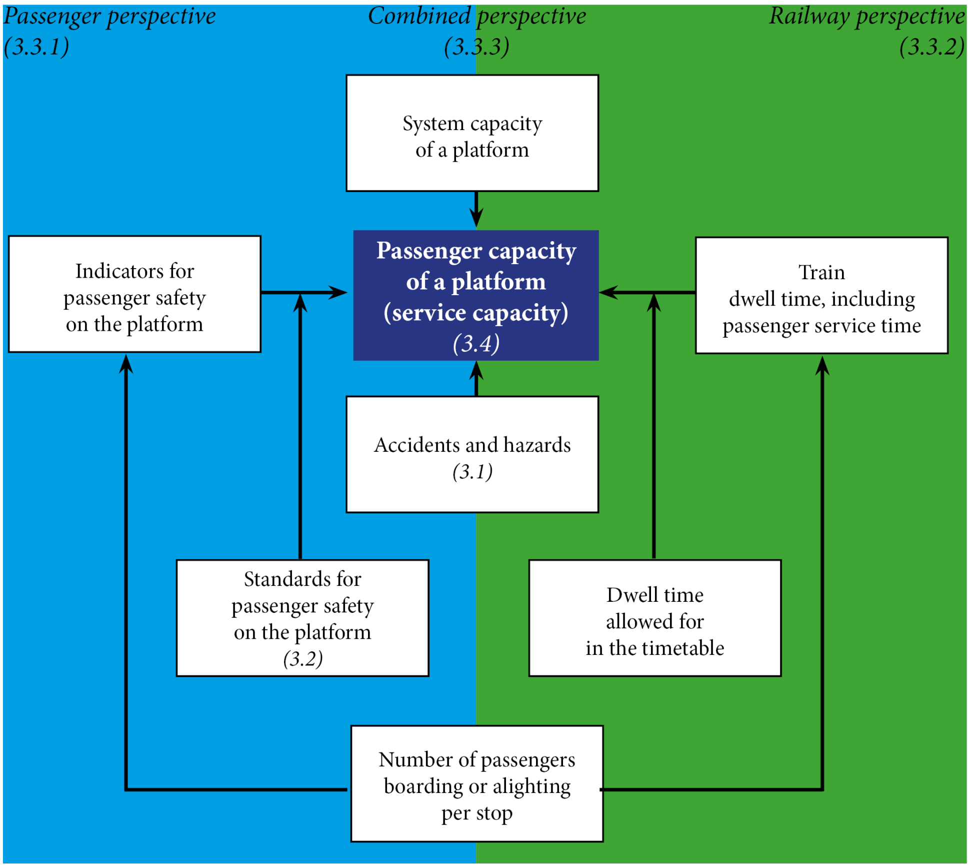


Figure 3.1: Literature study: structure

3.1 Accidents and hazards

Accidents, near-misses and safety hazards can indicate that the service capacity of a platform is being exceeded. Indeed, it is generally accepted that the risk of safety incidents under high traffic loads render it unwise to utilize the maximum system capacity of pedestrian infrastructure [36] [37] [38].

This section sets out current perspectives on accidents and safety hazards. As not all accidents and hazards are linked to crowding, this very broad subject area will first be divided into categories, and the categories relevant to this study will be selected. For the selected categories, the perspectives from earlier research will be outlined as regards: accidents (Sub-section 3.1.2), hazards (Sub-section 3.1.3), causes of accidents and hazards (Sub-section 3.1.4) and mitigation measures (Sub-section 3.1.5).

3.1.1 Categories

Accidents involving pedestrians at railway and metro stations are of several types. Some of these accidents (or the risk thereof) are related to the boarding and alighting process. The location where that process takes place, and the associated processes, are sometimes referred to as the *platform-train-interface*, or PTI. Previous research indicates that we can divide PTI-related accidents and risks into the following categories:

1. A passenger or their baggage becomes trapped in train doors as a train is departing [39] [40] [41].

2. A passenger is struck by a train while committing suicide [42] [43] [44] [45] [46] [47].

3. A person trespasses on the track and is then struck by a train [48] [49] [42] [45] [47].

4. A passenger is injured while boarding or alighting [39] [40].

5. A passenger falls between the platform edge and the train as it is coming to a halt [39] [40] [50] [41].

6. A person falls onto the track from the platform while there is no train arriving at that platform, and is then possibly hit by an arriving or passing train [39] [51] [40] [52] [53] [54] [55].

7. A train passing at speed generates a slipstream, thereby moving passengers' property that is standing on the platform (e.g. push-chairs, wheelchairs or luggage) and/or passengers lose their balance and fall [39] [40] [51] [52] [56] [57], which may or may not result in passengers and/or their property falling onto the track.

The last four of these categories may have a causal relationship with platform crowding. The remainder of this section will address only the last two categories, as these are the only ones for which publications have been identified that deal with crowding-related accidents and hazards.

3.1.2 Accidents

The first group of publications focuses on accident statistics. An analysis by Yeo et al. [58] covering the period 1995–2004 indicates that some 5% of safety incidents on South Korean metro systems involved a fall from the platform. This corresponds to approximately 30 incidents per year. The authors do not categorize the incidents according to causes and consequences.

Yamada et al. [54] mention the annual transportation safety report published by the Japanese government, which reported 431 cases of a train striking a person in 2011. In 208 of those incidents (48%), a person had fallen from the platform. The victim died In 29 of those cases (14%). The publication gives no further information regarding the conditions under which the incidents occurred.

The UK *Rail Safety and Standards Board* (RSSB) reports that over 80% of all accidents in the country between 2001 and 2005 (excluding suicides) were linked to boarding or alighting, the departure of a train or falling between platform edge and train [40]. This category of incident involved a train that was arriving at a platform. PTI accidents not due to boarding or alighting accounted for 29% of deaths between 2001 and 2010 (of which there were 11 to 12 per year on average) [59]. This was the largest category of fatal accidents, accounting for more fatalities than train-related accidents. The most common cause mentioned was that a passenger was hit by a train, either because they had fallen off the platform onto the track, or because they were standing too close to the platform edge. The report also mentioned that intoxication played a major role in the occurrence of accidents and that most accidents occurred at off-peak travel times. It is not possible on the basis of this report to identify the role that platform crowding might have played in the accidents.

In another study on the health and safety consequences of crowding, the RSSB reports that there are no records of platform crowding being the cause (or one of the causes) of a safety incident [39]. Incident logbooks for the period 1999–2003 were analysed nonetheless, to establish whether crowding was the cause of an incident, or contributed to it. The researchers concluded that the objective safety risk due to platform crowding as such was small. At the same time, they maintain that high levels of crowding can exacerbate other safety risks.

In a 2007 follow-up study, the RSSB looked more closely at the impact of train slipstreams on platform safety. That study revealed that 25 slipstream-related incidents occurred in the UK between 1972 and 2005. More than half of these involved the slipstream from a passing train displacing a pushchair. In 2008, the RSSB concluded that the number of incidents related to train slipstreams was so small that it was not possible to draw statistically significant conclusions from the accident data [52].

The Dutch Human Environment and Transport Inspectorate (part of the Ministry of Infrastructure and Water Management) reported a total of 742 transfer accidents in 2016, of which 11 (1.5%) involved a fall from the platform [18]. The report states explicitly that the numbers are only an indication, as not all accidents are recorded. The report does not classify the incidents according to causes and consequences.

Working on the basis of 2013 accident statistics for four rail networks in the US, Hunter-Zaworski [60] [47] reports that the vast majority of accidents consist of falling on the platform, in the train, on stairs or on escalators. A relatively small proportion of recorded accidents (9%) are related to the platform edge. The study does not go into detail regarding the causes and consequences of the specific accidents. The author does, however, report in general terms that crowding and pushing may have been contributing factors. She advocates standardizing accident reporting, to enable better comparisons to be made between transportation networks.

3.1.3 Risks

In addition to the above-mentioned research based on accident statistics, a second group of studies was identified that focus on the risks and consequences of accidents. Baker et al. [51] have attempted to use multi-annual incident data and the societal (monetary) value of a human life to attach a financial value to preventing a slipstream-related incident in the UK. For 2005, the authors arrive at a “value of loss” of €45,000 (£41,000) for the UK rail network as a whole. They point out that the absence of fatal incidents in the dataset has a significant impact on this value. A single fatality would increase the value to €192,000 (£174,000). The authors mention one important caveat with regard to both of these low values: the cost of risk-mitigation measures could rise substantially owing to a combination of the high expected growth in passenger and freight traffic and an increase in train speeds on the UK rail network. The RSSB also gives the €45,000 (£41,000) value of loss figure [61]. Without going into further detail, the RSSB researchers compare this with the “value to prevent a fatality”. In so doing, they are aiming to highlight not only the indirect effects of a fatal incident but also the option value of preventing a serious incident.

On the basis of Law and Yip [53], Silla and Luoma [62] and Santoso et al. [63], it is possible to divide the consequences of incidents that involve a person falling onto the track from the platform into four categories:

1. Death or injury
2. Delays to train passengers owing to disruption to railway traffic resulting from the incident
3. Trauma affecting railway personnel, emergency services and bystanders who are confronted by the incident
4. Damage to the safety reputation of the railway system in several countries

Because the number of recorded accidents is too small, Kriakidis et al. [64] have studied accident precursors. For these purposes, a precursor is a situation that results in a heightened risk of death or injury. The authors divide these precursors into six categories:

1. Human errors on the part of railway personnel
2. Technical failures
3. Passenger behaviour
4. Fire
5. Malicious (i.e. unauthorized or illegal) action
6. Management action

They conclude that technical failures produce the largest number of precursors, but that passenger behaviour appears to cause the majority of incidents.

Cynk et al. [65] studied risky behaviour on the part of passengers on the platforms of ten railway stations in the United Kingdom. From their analysis of observation data covering 171 risky situations, the authors concluded that standing dangerously close to the platform edge and standing on the track side of the safety line (the yellow line in Figure 3.2) played a role in more than one third of the potential accidents. Crowding was a factor in more than one in five situations and having to avoid other passengers was a factor in approximately one in six. Many instances of risky behaviour involved more than one factor. The researchers showed that passengers stand dangerously close to the platform edge relatively frequently when the platform is crowded or when passengers need to avoid each other. Most potential falls from the platform to the track occurred when there was no train standing at the platform, with just under half of all such situations arising when a train was due.

Figure 3.2: Clapham Junction station, UK, Platform 5. 29 March 2017, 07.58 hrs. (Photo: Jeroen van den Heuvel)

3.1.4 Causes

A third group of studies focuses on the causes of accidents and hazards. On the basis of those studies, we can divide the causes of hazards and accidents on platforms into two categories:

1. *Train slipstreams*. A number of studies have examined the hazards that result from train slipstreams [51] [52] [66]. Baker et al. [51] suggest a figure of 15 m/s (54 km/h) as the maximum “safe” wind for people standing on a platform. Research by the RSSB [52] gives a figure of 11 m/s (40 km/h) for the UK rail network. At the same time, Baker et al. [51] report that maximum wind speeds of over 25 m/s have been recorded immediately adjacent to the track in the UK. Wind speeds are strongly influenced by train type and speed, and by distance from the track. Because of their aerodynamics, freight trains constitute a hazard even at lower speeds, with passenger trains becoming a potential hazard at higher speeds. The number of trains passing also influences the probability of risk. Measurements taken in the UK, Germany and Spain point to a wide variation in train slipstreams [67] [56] [68]. The danger is most acute immediately after the rear of a passenger train passes at high speed and when the gaps between freight wagons pass a platform. With the exception of extremely low passenger platforms (approximately 20 cm in the case of this study), platforms themselves have no effect on the intensity of the slipstream. Wind speeds are slightly higher on platforms in tunnels [66].

2. *Platform dimensions, layout and use, as compared with use of the line*. A survey of risk factors by Yamada et al. [54] identifies the following four main factors, along with a number of sub-factors:

   (a) *Platform layout, determined by dimensions and furniture*. This factor is divided into four sub-factors:

      i. Narrower platform sections
      ii. Distance between train and platform edge
      iii. Available platform surface and the form of the platform
      iv. Whether the platform is curved owing to the track being curved

   (b) *The passenger flows that pass through the platform.* This factor is divided into four sub-factors:

      i. Concentration and crowding at specific locations
      ii. Cross flows on the platform
      iii. Use of the strip of platform closest to the edge
      iv. Crowding near the platform access points (e.g. at stairs and escalators).

   Platform crowding is cited as a risk-exacerbating factor by the RSSB [39] [40] [63], Cynk et al. [65] and Hunter-Zaworski et al. [47]. Crowding near platform access points is mentioned by RSSB [39], Pshaouliotis and Williams [69], Cynk et al. [65] and Hunter-Zaworski et al. [47]. Thurau et al. [70] were the first to establish a quantitative link between crowding and use of the platform edge, designated the "danger zone" in Switzerland and the "safety zone" in the Netherlands. They established that crowding plays an important role, but that other factors are also involved.

   (c) *The quantity and type of rail traffic on the track next to the platform.* This factor is divided into three sub-factors:

      i. The number of trains stopping and passing through
      ii. Whether or not trains are announced prior to arrival
      iii. The extent to which passengers know from which direction the train will arrive

   (d) The categories of passenger that use the platform, e.g. people with reduced mobility, older people or those under the influence of alcohol. To this last category, Ueda et al. [46] add inattention, illness and collisions with other passengers. Anderson and Hunter-Zaworski [71] and Hunter-Zaworski et al [47] also mention intoxicated passengers and inattention as relevant factors. Heinz [72] categorizes passengers according to how familiar they are with the situation.

Yamada et al. [54] have assessed the above factors using an analytic hierarchy process, on 28 platforms at ten stations in Tokyo. They ranked the platforms on the basis of that analysis and compared that ranking with the accident statistics for the same stations. This enabled them to identify the factors that make the most significant contribution to safety hazards. These proved to be narrow platform sections, intoxicated passengers and older passengers. Those factors were followed by crowding, cross flows and use of the area along the edge of the platform.

Wilms and Frieling [73] have developed a platform safety model, in conjunction with Dutch rail infrastructure manager ProRail and NS Stations (see Figure 3.3). This bow-tie shows involuntary presence in the safety zone to be one of the most important undesirable events. The safety zone is a 0.8-metre strip along the edge of the platform, which passengers are supposed to use only when a train is standing at the platform (see next sub-section for further information). To the left of this undesirable event are shown the factors that determine the probability of the event occurring. The effect is shown on the right, together with any exacerbating or mitigating factors. The model shows the factors that determine involuntary use of the safety zone to be crowding in comparison with the dimensions of the platform, local crowding as a result of distribution and queueing and the presence of obstacles. The risk model is linked to the standards that apply to platforms, but is not linked to accident statistics.

3.1.5 Mitigation measures

A fifth and final group of publications focuses on measures aimed at reducing risk and preventing accidents.

1. *Alerting passengers to hazards* e.g. via markings or marked zones along the platform edge, or warnings and awareness-raising campaigns regarding hazards related to the platform edge [51] [52] [74] [74] [71]. The RSSB [52] notes that awareness-raising campaigns are possibly less effective on the railway network than on the London Underground, because railway traffic is more diverse and the percentage of very experienced travellers is smaller.

2. *Crowd management*, including crowd control [74] [65] [69]; provision of real-time information regarding train occupation, allowing passengers to distribute themselves along the entire length of the train [69]; CCTV systems [41]; laser detection systems [71] and pedestrian measurement systems to facilitate monitoring of processes at and near the platform edge [70].

3. *Installing physical barriers (platform screen doors (PSD))* [51] [52] [53] [65] [45] [71]. In their study on the effectiveness and societal costs/benefits of installing PSD on metro stations in Hong Kong, Law and Yip [53] observed a reduction of approximately two thirds in the number of accidents in which people fell onto the track from the platform (excluding suicides). The study involved comparing the statistics for accidents before and after the installation of PSD at a number of stations on the metro network. Over a four-year period following the installation of PSD, the number of such incidents fell from over 50 per year to a little more than 15. It is noteworthy that at some stations where PSD were installed the number of such incidents did not fall. The study does not provide sufficient information to explain this phenomenon.

4. *Dimensioning and layout of the platform* [65] [45]. A broader platform with fewer obstacles results in fewer hazards and accidents, as users have more space.

3.1.6 Conclusions

The situation regarding the recording of crowding-related accidents on platforms is as follows:

1. Recording of incidents is incomplete in many cases.

2. The number of accidents recorded on platforms is so low that it is not possible to carry out statistical analyses or identify causal relationships (e.g. between crowding and accidents).

3. It is not possible to compare publications containing statistics between countries. This is because definitions and records of contexts, causes and consequences are either unknown or else are inconsistent between countries. This also applies to the role that platform crowding plays in the creation of hazards and the occurrence of accidents, and the recording of that role. No records have been found of serious accidents in the Netherlands where platform crowding was the primary cause.

But even though there is no clear picture of platform incidents, or the risk of such incidents, work is underway throughout the world to identify safety hazards on platforms, establish their causes and implement measures to reduce those hazards and prevent accidents. For the purposes of the present thesis, it is concluded that in practice, safety hazards are not identified solely on the basis of the accidents that occur. The literature surveyed neither confirms nor refutes the suggestion that the measures taken by station operators account for the rarity of serious incidents.

Capacity-related factors – such as platform dimensions, platform layout and crowding – are considered to be important factors in determining the occurrence of safety hazards. This also applies to what happens on the track next to the platform – number of trains, types of train and train speeds. Passenger behaviour and the composition of the passenger population constitutes a third factor. One single study (of the few studies found in this area) points to a link between accident precursors related to passenger behaviour on the one hand, and the occurrence of incidents on the other. For the present study, the conclusion from this is that the behaviour of passengers can play a role in the occurrence of safety hazards, and that little is currently known about the relationship between the two.

On the basis of this section, it is concluded for the purposes of the present study that the occurrence of accidents is not a good indicator for the service capacity of a platform. In practice, station operators determine service capacity on the basis of their own standards and guidelines.

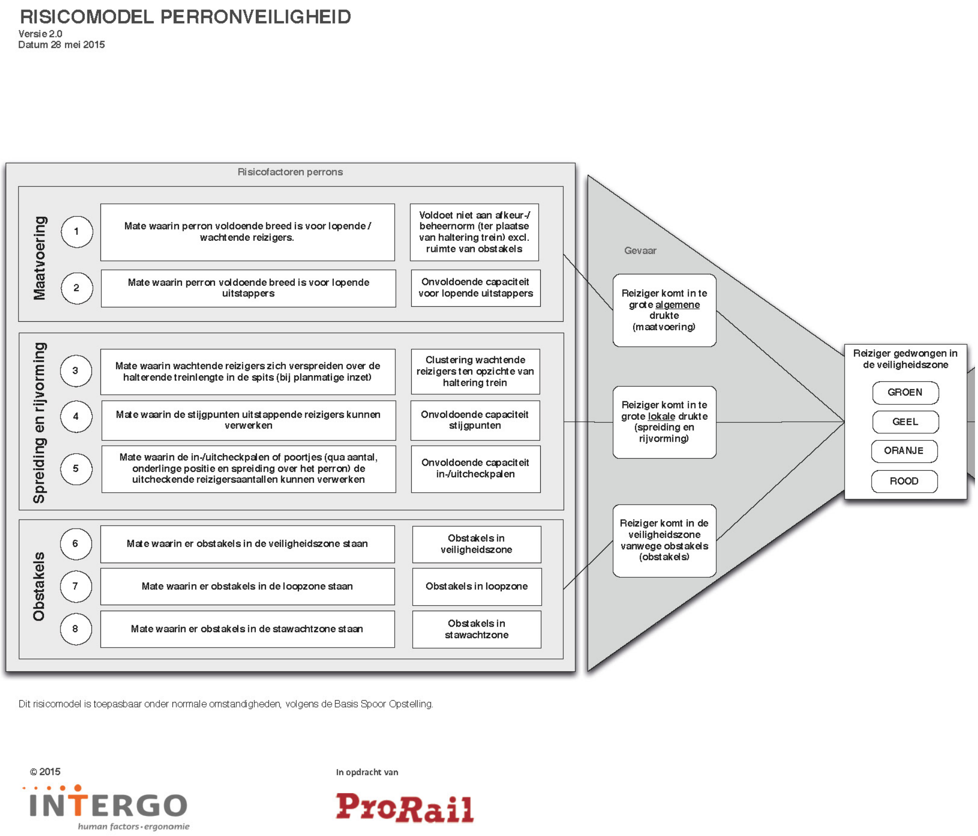
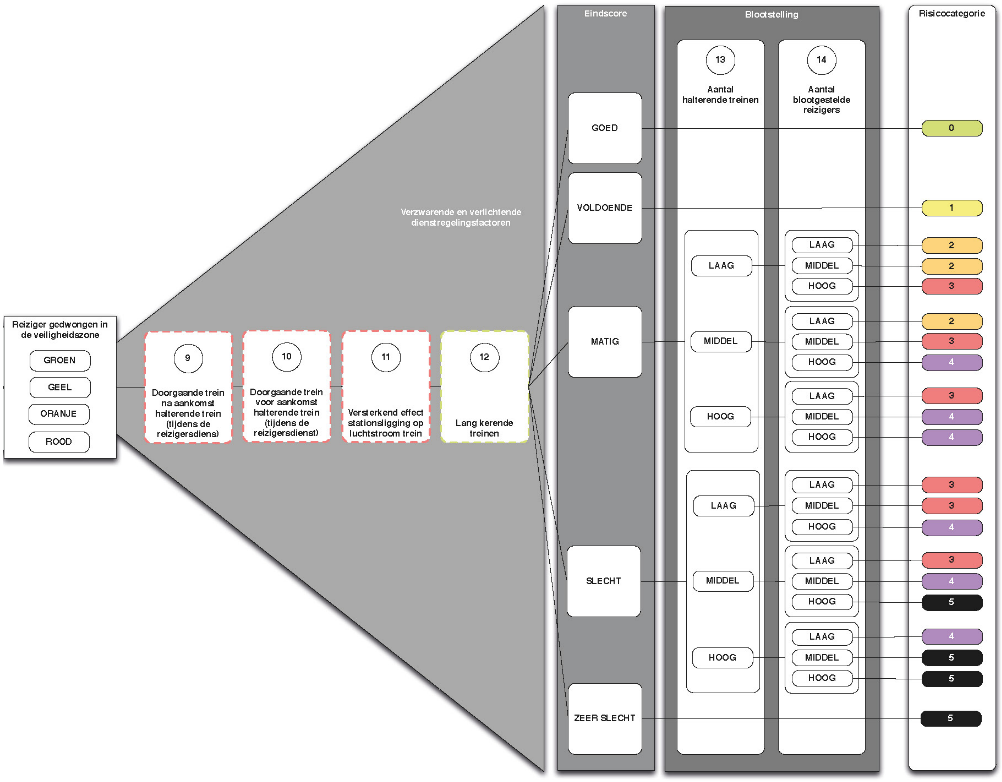


Figure 3.3: Risk model bow-tie ("Risicomodel Perronveiligheid (versie 1.0)") produced by ProRail and NS [73]


Reiziger gedwongen in de veiligheidszone
GROEN
GEEL
ORANJE
ROOD
9
Doorgaande trein na aankomst halterende trein (tijdens de reizigersdiens)
10
Doorgaande trein voor aankomst halterende trein (tijdens de reizigersdienst)
11
Versterkend effect stationsligging op luchtstroom trein
12
Lang kerende treinen
Verzwarende en verlichtende dienstregelingsfactoren
Eindscore
GOED
VOLDOENDE
MATIG
SLECHT
ZEER SLECHT
Blootstelling
13
Aantal halterende treinen
14
Aantal blootgestelde reizigers
LAAG
MIDDEL
HOOG
Risicocategorie
0
1
2
3
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5

3.2 Standards, guidelines and empirical studies

This section gives an overview of the manner in which platform capacity is incorporated in the standards and guidelines that are used for stations. The survey of standards and guidelines looks at the Netherlands, the United Kingdom and Switzerland separately. The UK and Switzerland were chosen because their rail networks – like that of the Netherlands – are heavily used, with stations being one of the causes of capacity bottlenecks. The author of this thesis has good contacts with colleagues from SBB (Swiss Federal Railways) and Network Rail in the UK. As a result, he is familiar with the standards and guidelines of those two countries and the way they are applied in practice. To provide as complete a picture as possible, discussion of each country's standards and guidelines concludes with an overview of empirical studies of relevance to the question of platform capacity. The country-specific survey is followed by an overview of guidelines contained in a number of generic (i.e. non-national) handbooks identified as part of the present study.

3.2.1 The Netherlands

Railway infrastructure manager ProRail and station operator NS Stations use four guidelines, sets of design regulations and standards for the pedestrian function of railway stations in the Netherlands. The parts of these documents that are of relevance to the present thesis are those that address dimensions and layout from the perspective of platform functionality and capacity. The first of these is the *Basisstation*, or basic station [75] [76]. That document describes the desired functionality of new stations, and of new elements of existing stations. The second document is the 2010 *Ontwerprichtlijnen, Beheerrichtlijnen en Afkeurnormen voor de transferkwaliteit van treinstations in Nederland* (OBA) ("Design, Operating and Minimum Standards for transfer quality at railway stations in the Netherlands") [77], which is based on the Basisstation concept. The functionality described in the OBA is further detailed in a number of design regulations, of which the *Ontwerpvoorschrift Perrons* ("Platform design regulations") [78] are relevant to the present study. Finally, ProRail published a document in 2016, setting out the *Regels voor het functioneel ontwerp van railinfrastructuur* ("Rules for the functional design of railway infrastructure") [79]. The present literature study refers to the versions of the Platform Design Regulations and Design, Operating and Minimum Standards for transfer quality at railway stations in the Netherlands that were in force as of June 2020 and January 2021 respectively. These documents reflect the situation obtaining at the time of this study. Updated versions of both documents have since been published. The main points of each remain unchanged but certain details have been modified.

The transport function of stations is central to both the Basisstation and the OBA [75] [77]. The basic principle is that a station must offer sufficient space for passengers, visitors, people passing through and the facilities provided. Both documents link the transport function with safety and reliability, speed and comfort, based on Van Hagen's pyramid of customer needs for stations ((see Figure 3.4). Basisstation ranks stations according to a functional area plan, and the OBA adds additional detail to this using the Stationsconcept drawn up by Bureau Spoorbouwmeester [30].

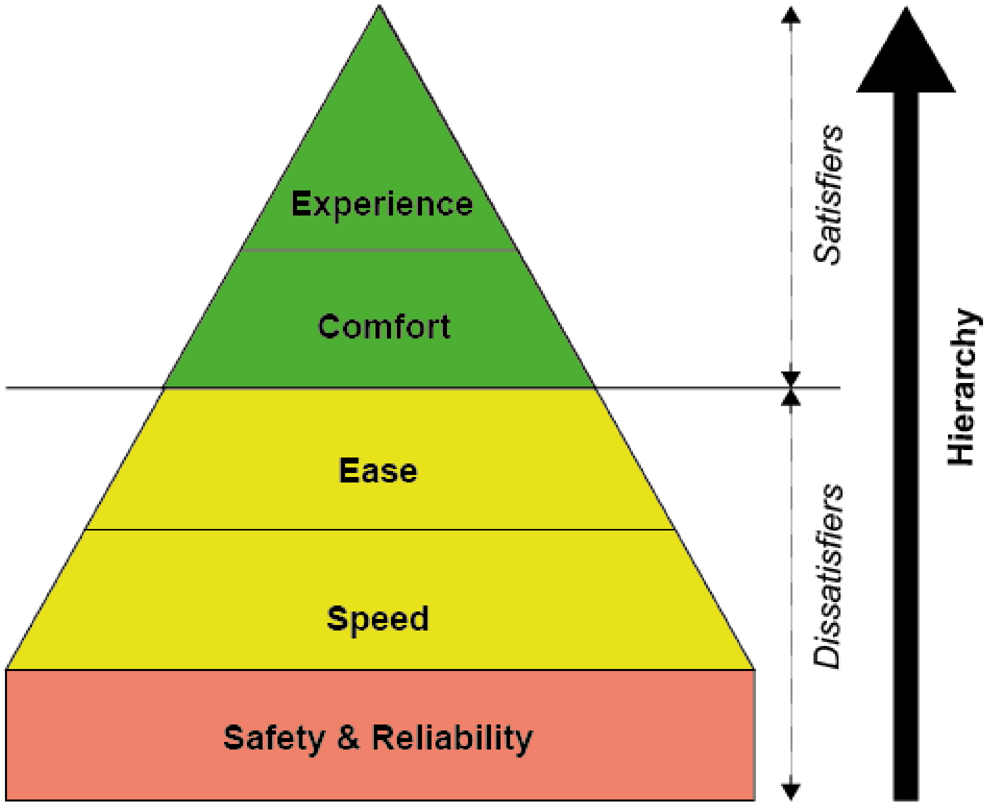


Figure 3.4: Van Hagen's pyramid of customer needs [32]

The functional area plan/Stationsconcept divides stations into a Surrounding Area, Entrance Area, Travel Area, Waiting Area and Pedestrian Transit Zone. The intention behind this is to categorize both space and facilities in a manner that passengers will perceive as optimal and predictable. Qualitative and/or quantitative guidelines and standards are laid down for a large number of passenger processes, such as horizontal movement. Where relevant, the guidelines and standards for passenger processes are differentiated according to the various areas of a station. A distinction is made between regular situations and temporary situations, such as rebuilding or maintenance. The areas of greatest relevance to the present study are the pedestrian transit zone and the travel area, as the pedestrian transit zone is the primary route for pedestrian traffic between the train (in the travel area) and the station entrance (in the entrance area). On Dutch stations, the boundary between the travel and entrance areas is marked by the smart-card readers where passengers check in and out with their OV-chipkaart. Platforms form part of the travel area, enabling passengers to move between station and train.

As far as speed is concerned, the OBA makes a direct link with the "level of service" (LOS) concept developed by John Fruin [36]. The values that define the service levels in the OBA are based on Fruin's LOS values. The OBA uses those values to define three service levels: Design Standard, Operating Standard and Minimum Standard (see Figure 3.5). The Design Standard is the level to be provided by a new or rebuilt station. The Operating Standard is the lowest level of service that passengers should encounter. The Minimum Standard corresponds to the lowest safe level. The Design

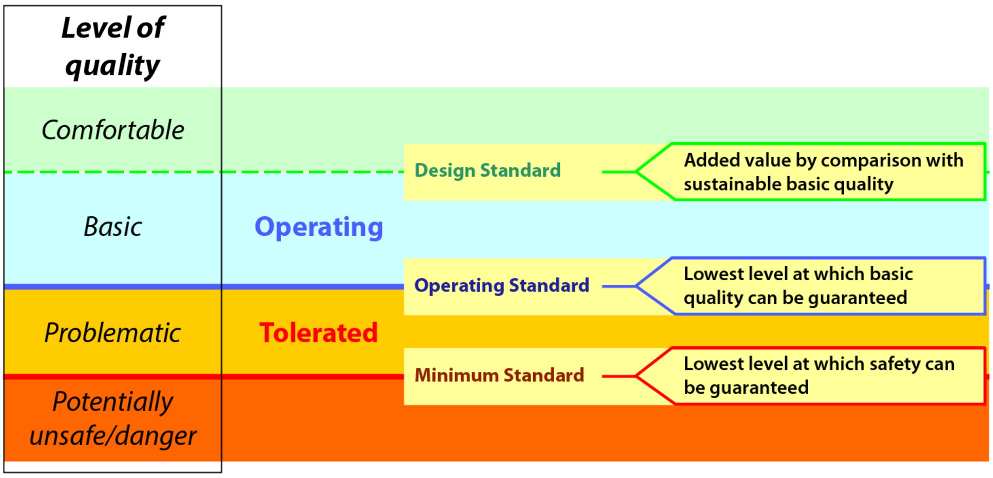


Figure 3.5: Definitions of Minimum Standard, Operating Standard and Design Standard (from [77])

and Operating Standards apply to all parts of the pyramid of customer needs. The Minimum Standard applies only to the safety aspect. When service quality lies between the Operating Standard and the Design Standard, the station operator *may* take measures to increase the service level. If service quality falls to a level between the Minimum Standard and the Operating Standard, the station operator *must* take measures to increase the service level. If service quality falls to below the Minimum Standard, the corresponding process must be halted until measures have been taken at the source.

The Platform Design Regulations [78] specify how to determine the dimensions of a platform. The length is determined by the length of the longest train, with allowance made for the platform being divided into a and b sections where appropriate and for the type of platform. A platform adjacent to a dead-end track must be longer than a platform adjacent to a through track, to reduce the hazard associated with a train overrunning. A number of functional capacity characteristics are specified with regard to platform width (see Figure 3.6). (1) The platform must provide sufficient space not to become overcrowded. (2) Alighting must not be hindered by obstacles. (3) The platform must be wide enough that passengers do not have to wait in the safety zone. For the purposes of deciding platform width, the platform is divided into four zones, starting from the edge closest to the track. 1. The safety zone along the platform edge, indicated by a solid white line. This zone forms a buffer, or safety margin, between people and the track. 2. The walking zone, within which people move around on the platform. The walking zone is immediately adjacent to the safety zone and its markings. 3. The standing waiting area, the width of which depends on the number of waiting passengers per train (i.e. boarders, including transferring passengers). 4. The circulation zone, which is a percentage of the sum of the other three zones. All obstacles must be placed in this zone, i.e. all the facilities of the platform, such as waiting rooms, shops and platform entrances. The floor area occupied by large obstacles (longer than 10 m), does not count as part of the available platform width. How much width must be included for the circulation zone depends on whether the platform is a new or existing one. The actual width of the platform therefore depends on the number of persons who will board the busiest train, the additional width to be added for the

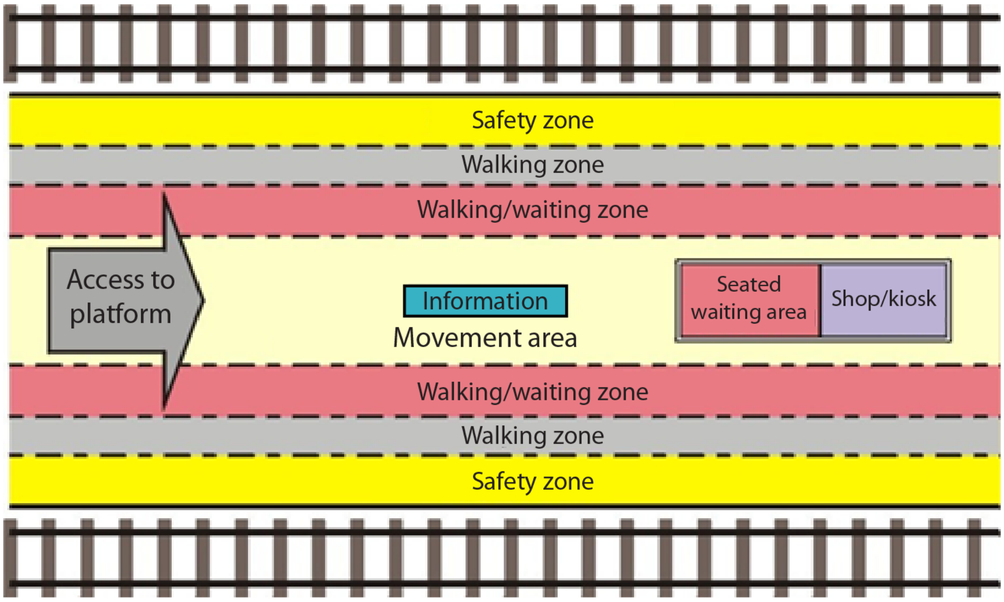


Figure 3.6: Functional characteristics taken into account when determining platform width (from [78])

circulation zone and the presence on the platform of obstacles longer than 10 m. The platform design regulations do not specify how to determine platform occupation.

The Rules for the Functional Design of Railway Infrastructure [79] state that walk times for passengers on platforms must not be too long. The intention behind this is to ensure that passengers distribute themselves as evenly as possible along the train. Where possible, dividing a platform into a and b sections should not result in walking distances within the platform of greater than 170 m. The rules also stipulate minimum dwell times for passenger trains of between 30 s (for single-crewed trains) and 2 minutes (for high-speed trains). If a train is changing direction, it must remain at the platform for at least 4 minutes. In the case of small stations, the timetable allows only for the minimum dwell time. At a number of specified larger stations, dwell time is increased by 1 minute, to allow sufficient alighting, boarding and transfer time. It is also specified that trains with the largest transfer flows are to use the same platform wherever possible.

Hoogendoorn and Daamen [80] and Daamen et al. [81] evaluated the ProRail transfer crowding monitor in 2005. This monitor was set up under the 2005–2015 operating concession, which includes a critical service indicator for a safe pedestrian function with sufficient capacity. The evaluation was prompted by the discrepancy between the bottlenecks identified by station managers and those reported by the transfer crowding monitor. It involved measurements at 200 points on 67 platforms over two days during winter 2005. On the basis of the evaluation, the researchers proposed a refined definition of a bottleneck. This is based on Fruin's level-of-service concept [36], supplemented by the time for which service levels were lower than required and the frequency with which this occurred. Bottlenecks were defined as densities higher than LOS C (comfort) or D (capacity) for a continuous period of at least 30 s that occurred more than three times during a peak period and totalled more than 5 minutes per peak period. As densities vary widely within a station, the authors point out the importance of specifying measurement areas and time intervals appropriately. If one aggregates over too long a time span or too large an area, peaks get averaged away, which leads to bottlenecks being missed. Choosing excessively short periods or small areas will cause peaks that are not bottlenecks to dominate the output. The authors also mention that waiting time has a major influence on passenger comfort and safety. They maintain that after 30 s, passengers become impatient, and engage in more dangerous behaviour in an effort to shorten their wait.

In 2014, Starmans et al. [82] conducted research on pedestrian capacity at Amsterdam Centraal. In contrast to Daamen et al. in their study of Schiphol Plaza [83], the authors used a relatively simple macroscopic model in Microsoft Excel to identify bottlenecks in accordance with the OBA criteria [77]. There were two reasons for this choice. 1. The high speed at which it was necessary to calculate changes in pedestrian infrastructure. Re-calculating took a few seconds in Excel, as against a number of hours when using a microscopic pedestrian simulation. 2. The need for all those involved in the redevelopment of Amsterdam Centraal to understand the input, output and functioning of the model. The model was calibrated and validated using pedestrian flow data from OV-chipkaart scans [84].

3.2.2 United Kingdom

Six publications were found regarding the United Kingdom. The first two are the interconnected guidelines published by national infrastructure manager Network Rail: the *Station Design Principles for Network Rail* [85] and *Station Capacity Planning Guidance* [86]. The third is *Station Planning Standards and Guidelines* [87], published by London Underground, the company that operates and manages the infrastructure of London's metro system. The document is also published on behalf of Transport for London and the Mayor of London. The last three publications are: *Interface between Station Platforms, Track and Trains* [88], its accompanying document *Guidance on Interface between Station Platforms, Track and Trains* [89] and the RSSB's *Platform Train Interface Strategy* [90].

The first of the Network Rail guidelines [85] defines station capacity as "the ability of a station to safely, comfortably and conveniently accommodate and circulate the forecast passenger numbers". That document lists a number of capacity-related safety hazards on platforms:

1. Using the part of the platform near the edge, in proximity to moving trains
2. Excessive congestion under normal or abnormal operating conditions (e.g. service disruption or rebuilding)
3. Excessively long evacuation times in the event of an incident
4. Excessively long boarding and alighting times, leading to an increase in train dwell times

The second of the Network Rail guidelines [86] goes into more detail. That document looks at (1) peak passenger flows, (2) standard capacities of certain processes (e.g.

escalators and gates) and standard dimensions (of such items as platforms, stairs, footbridges and subways) and (3) minimum service quality, expressed in levels of service (LOS). Both the concept and the values for these levels of service are based on the work of John Fruin [36].

The peaks are based on the busiest times of a typical working day. The number of passengers taken into account is that on all trains arriving or departing during the chosen 15- or 5-minute peak period. Non-passengers using specific parts of the station during these peak times are included where appropriate. Whether to use a 5-minute or 1-minute peak depends on the part of the station under consideration. In most cases, Network Rail and London Underground use the 5-minute peak, but in some cases the 1-minute peak is used. The guidelines list a number of factors that are related to the peak load and to the processing of passenger flow on a station. Delays, overlapping flows from and to different trains and shorter trains all increase the level of the station peak load. The combination of train stopping position (relative to platform entrances) and the passenger and door capacity of the rolling stock also affect the peak load. Capacity restrictions in a station restrict flow, increasing the time needed to handle the peak load.

Minimum run-off distances are specified in front of escalators, stairs and gatelines, to provide a clear landing area for following passengers. These areas provide orientation time, time to decide where to go next (in the case of stairs and escalators) or time to get tickets out/put them away (in the case of gatelines). The reduced passenger flow that can result from these processes is allowed for by a specially created buffer zone, to ensure that no safety hazards occur.

The Network Rail station capacity guidelines divide "abnormal conditions" into four categories. 1. Service perturbation. For larger stations, this is a 15-minute delay to one group of services (e.g. in one direction). For smaller stations, perturbation means the cancellation of one train service. 2. Higher peak loads due to special events, which will require crowd management. 3. Emergency evacuation due to fire, for security reasons or in response to overcrowding. 4. Temporary construction works. The safety of passengers during service perturbation and emergency evacuation are of particular importance while such work is underway. Lower levels of service are accepted under such conditions, because of their temporary nature.

The London Underground guidelines [87] set out three main aims for normal operations: Public space in stations must (1) minimize congestion and (2) "be resilient to surges in demand and train service disruption". It is assumed that applying the Fruin level-of-service concept [36] and associated limiting values to station dimensions and layout will result in a well-functioning, optimal station. In other words, not too small but definitely not too big. The third main aim is to ensure minimum travel distances, a minimum of obstacles and good sight-lines. In addition to achieving the aims set out for normal service, it is also necessary to ensure that it will be possible to evacuate the station within a standardized, maximum time. In the case of special events, the guidelines make a distinction between those that last for up to three days and those that last longer. Consideration is also given to whether such events are occasional (e.g. a festival) or regular (e.g. if a station is located near a football stadium). As regards temporary works, the guidelines make a distinction between those that last for up to six months and those that last longer. A lower minimum level of service is acceptable during occasional events and short-term works.

London Underground uses the average 1-minute peak, derived from the peak 15-minute flow, in a manner similar to that of Network Rail. This applies to all areas of the station, with the exception of gates, where a 5-minute peak is used.

As in the case of Network Rail, the load of the busiest train is increased by an additional factor, to account for delays. Like Network Rail, London Underground lays down standard capacities, minimum dimensions and minimum distances for the various processes that take place in a station. However, London Underground diverges from Network Rail on certain aspects of platform dimensions and layout:

- The consequences of overcrowded platforms on train operations are a factor, in addition to passenger safety, Short, stable train dwell times are essential in this respect. Overcrowding on a platform is named as an important reason for implementing station control.

- To take account of passengers being distributed unevenly over the available platform area, it is assumed that 35% of the passengers occupy 25% of the platform, resulting in a density 40% higher than if they were evenly distributed.

- It is assumed that passengers stay 0.5 m from the platform edge when no train is standing at the platform. Passengers stand closer to the platform edge when platform doors are installed between platform and track. One important disadvantage of platform doors is that they can result in passengers being distributed less evenly, as it is more difficult to move along the platform. This is because passengers waiting at platform doors occupy the entire width of the platform. In the absence of platform doors, a strip along the platform edge remains free of waiting passengers, and that is used for circulation.

- The following factors are mentioned regarding the position of platform entrances:

  - Maximum distance between platform entrances is limited to 90 m, on account of the time that alighting passengers require to leave the platform, under normal circumstances and during an evacuation. This ensures that an alighting passenger never has to walk more than 45 m along the platform to reach an exit.
  - Where there is more than one entrance, the aim is to ensure that passengers are distributed along the platform as evenly as possible.
  - Platform access points are used either for entering or for leaving the platform, not both. This one-way traffic minimizes congestion in the passenger flow, and ensures that passengers are evenly distributed along the platform.
  - The positioning of platform entrances relative to the train plays an important role in the distribution of passengers over the train. It is therefore recommended that the locations of platform entrances be varied from one station to the next on a given line, to encourage balanced loading over a train.

The RSSB has drawn up a mandatory standard for railway stations in the UK, covering all aspects of the interface between platforms, tracks and trains [88] [89]. This standard contains the following provisions regarding platform capacity:

- New platforms must be so dimensioned that they do not become overcrowded when the maximum expected passenger flow occurs. Platforms must also be able to safely accommodate all the passengers of a fully occupied train, plus any passengers already waiting. For limiting values, including the effects of uneven distribution of passengers along the platform, the standards refer to the London Underground guidelines [87]. They do not describe any method for calculating the loading or peak loading of a platform.

- The danger area is defined as the area along the platform edge where passengers, their luggage and their belongings are insufficiently protected against the aerodynamic effects of passenger or freight trains passing at over 160 km/h or 100 km/h respectively. The danger zone is indicated by a yellow line on the platform.

- The danger zone indicated by a yellow line may not be counted as part of the platform area available to waiting passengers. If this would result in overcrowding on existing platforms, the danger zone may be reduced. In such cases, a risk assessment must be carried out to identify what measures are required in order to prevent any deterioration in safety.

- Adding new entrances to an existing platform may reduce the space between the new obstacle and the platform edge. The standard stipulates that a risk analysis must be carried out in such cases, to assess (*inter alia*) the effect on passenger flows and waiting areas on the platform.

This overview of UK standards and guidelines concludes with a review of some relevant case studies. In 2015, Network Rail informed the authorities (on the basis of a quantitative survey) that the poor punctuality record of some trains in and around London was due to increasing dwell times during peak hours [21]. Network Rail cited crowding in trains and on platforms as the most likely cause, with crowding causing alighting and boarding to take much longer than allowed for in the timetable. Analyses conducted by Network Rail showed that this effect was particularly marked during morning peak times, especially at stations further away from London. It was also claimed that pedestrian circulation on platforms was inadequate. Platforms had become longer over the last few decades, to accommodate longer trains, but they had not become wider. The number of passengers using the platforms had therefore increased considerably, and there was insufficient space at certain critical points. Attention was also drawn to the large number of obstructions on these narrow platforms, and the uneven distribution of passengers along their length.

Major reconstruction work on London Bridge station was completed in 2018. That work formed part of the Thameslink scheme, which is intended to increase the capacity of the rail corridor between north and south London. Once Thameslink enters service, longer trains will be able to run into and out of London, at shorter intervals. The design phase relied heavily on the LEGION pedestrian simulation model [91] and Network Rail's *Station capacity planning guidance* [86]. Platform design was based on three principles [91]. 1. The entire station is designed to accommodate an increase of 65% in passenger traffic by comparison with the reference year. 2. The station is designed in such a way that passengers will distribute themselves as evenly as possible along the platform, which will minimize train dwell times. To encourage this, efforts were made to distribute platform entrances along the platform in an "ideal" manner. 3. It must be possible for all alighting passengers to leave the platform before the following train arrives. This will ensure that trains do not have to be held outside the station for safety reasons.

3.2.3 Switzerland

Three publications were found regarding Switzerland. The first is the *Handbuch zur Anordnung und Dimensionierung von Fussgängeranlagen in Bahnhöfen* (Handbook for the layout and dimensioning of pedestrian facilities in stations) [92], published in 2008 by Swiss Federal Railways (Schweizerische Bundesbahnen, SBB). The second is a study regarding safety hazards on platforms, published by the Swiss federal transportation office (*Bundesamt für Verkehr*, BAV) [93]. The third document is the planning resource for public facilities (*Planungshilfe Publikumsanlagen*), published in 2017 by the Swiss public transport association (*Verband öffentlicher Verkehr*, VöV), which brings together a number of transport operators, the Swiss federal transportation office and infrastructure managers.

The SBB handbook [92] starts by defining the rail-side "transport concept" that a station must be able to facilitate. The transport concept is the set of trains that together produce the heaviest peak passenger flow through the public transport node. This involves calculating the number of trains, their capacity and the percentage of passengers on each train alighting or boarding at the station. In the case of platforms, the handbook looks at headways between trains, particularly where these are short, and at the stopping positions of trains along the platform. The transport concept differentiates between a normal situation, a planned deviation from normal conditions (e.g. works) and the situation obtaining during a special event.

The second step in the SBB handbook is the formulation of the functional requirements that the train station must fulfil. A distinction is made here between the three elements that make up the pedestrian infrastructure of the station. For each element, the handbook lays down a design requirement, with advice regarding a limiting value. In the case of platforms, the handbook looks at the usable platform surface at the platform section where the train comes to a halt. A maximum pedestrian density is stipulated. A distinction is made between the situation that obtains when passengers are waiting for their train, and that obtaining directly following the arrival of a train, when boarders and alighters are on the platform at the same time. The important factors for platform entrances are the time required for all passengers to leave the platform and the mean time that a person must wait before accessing a platform entrance (e.g. stairs or an escalator). In the case of subways, footbridges and tunnels, the significant factor is the cross-section width. The criterion applied is the intensity of pedestrian flow, with a distinction being made between short peaks (lasting up to one minute) and longer, mean intensity levels.

The BAV study regarding safety hazards on platforms [93] mentions the need to balance safety and risk against economic factors when dimensioning platforms. The Swiss standards divide the platform longitudinally into a safe zone (*Sicherer Bereich*) and a potentially dangerous zone (*Gefahrenbereich*). Passengers are supposed to stay out of the potentially dangerous zone when no train is standing at the platform. There were two reasons for carrying out the study. 1. The minimum widths for the two zones were laid down in the applicable standards in the 1980s. The increase in passenger and freight traffic on Swiss railways meant that those standards might no longer be appropriate. 2. The BAV had noted that there were major differences between European countries regarding minimum platform width. The study was to indicate whether it was necessary to revise the Swiss standard. The report specifically states that the widths concerned are the minimum required for reasons of safety. Whether or not to add additional space in the interests of passenger comfort was left to the discretion of the railway companies.

According to the BAV, the width of the *Gefahrenbereich* depends on the aerodynamic effects of passing trains. The train type and speed are determining factors. Because of their aerodynamics, freight trains demand a broader *Gefahrenbereich* than passenger trains. The study also established a causal link between crowding (i.e. high densities) and walking or standing in the *Gefahrenbereich*. On the basis of research by Fruin [94] [36], Pushkarev & Zupan [95] and Weidmann [96] (among others), the BAV concluded that at densities of 0.45 persons per square metre and above, people will regularly use the *Gefahrenbereich* for waiting or walking.

The VöV guideline [97] states that a station must guarantee the following three things regarding the flow of people through it, in order of priority: 1. Passenger safety, especially on platforms. To ensure the safety of passengers, they must not be tempted to enter the *Gefahrenbereich* on account of crowding. 2. The functionality of the station, both as a whole and as regards its various parts. Passengers (including those with reduced mobility) must be able to catch their connections. 3. The comfort of station users – both passengers and non-passengers. This involves considering not only the transport function of the station, but also its role as part of public life and the "visiting card" of the city, town or village, together with its contribution to the competitiveness of public transport versus the car. The VöV guideline translates the above three topics into the following five platform characteristics:

1. The number of passengers in the available platform area. This area is required in order to ensure that passengers do not enter the *Gefahrenbereich* when no train is standing at the platform (Point 1 above). The space available on the platform also affects the time required for the alighting and boarding process and the time required for all passengers alighting from a train to leave the platform (Point 2).

2. The available platform width where the platform is made narrower by obstacles and facilities. This factor is directly related to the aim of ensuring that passengers do not enter the *Gefahrenbereich* when no train is standing at the platform (Point 1).

3. The functioning of the platform entrance(s). This factor is directly related to

the need to avoid queues forming at stairs and escalators that extend into the *Gefahrenbereich* (Point 1).

4. The functioning of other platform access routes, such as footbridges and subways, and the entrance to the station. This factor is relevant to avoiding delays to transferring passengers (Point 2) and avoiding queues forming on platforms (Point 1).

5. The degree to which it is possible to achieve the required transfer times between connections. This factor involves looking at the station as a whole, and is relevant to preventing delays during changing (Point 2).

The VöV guideline devotes considerable attention to calculating the maximum traffic load of the station. This is based on the number of boarders and alighters per train (including transferring passengers), the percentage of passengers on a train that boards or alights at the station, what use can be made of the line (technically and logistically) and the type of rolling stock. The limiting values for the above factors are in part based on existing standards, including those set out in the SBB handbook mentioned above.

This sub-section ends with a number of case studies. In 2015, SBB commissioned ETH Zurich (the Swiss Federal Institute of Technology in Zurich) to conduct an exploratory study regarding the safety of passengers on platforms [98]. The aim was to provide a basis for determining the minimum width of the safe zone (the *Sicherheitsbereich*). The study was necessitated by the absence of empirical data to underpin the minimum width laid down in the standards. To illustrate this, the authors identified two extremes: on the one hand, the Swiss standards stipulate a maximum pedestrian density on railway platforms of 0.45 persons per square metre [93]. At the other extreme, they note that research from China indicates that pedestrian densities on platforms in Beijing are regularly twice as high, with no major problems. To explain this discrepancy, the authors point out the cultural differences between Asia and Europe, which mean that safety hazards arise in Europe at lower pedestrian densities than in Asia. They also mention the multiple functions of a platform – circulation (walking) and waiting (standing) and the large differences in the distribution of passengers along the platform as factors that make it difficult to compare situations in the two countries. One of the hypotheses to be tested in further study is that whether passengers enter the *Gefahrenbereich* depends on the density of passengers on the platform. Thurau et al. [70] have recently confirmed the existence of such a link on the basis of quantitative research conducted in Switzerland and the Netherlands. At the same time, the researchers point out that other factors also play a role in whether passengers enter the *Gefahrenbereich*.

3.2.4 Generic handbooks

As part of the present study, three publications were identified that have a direct or indirect connection with calculating station capacity: *Railway Stations; Planning, Design and Management* [99], the fifth edition of the *Highway Capacity Manual* (HCM) [100] and the third edition of the *Transit Capacity and Quality of Service Manual* (TCQSM) [101].

Railway Stations; Planning, Design and Management, published by Ross et al. in 2000 [99] describes a method of calculating capacity based on three pillars. In summary, the method is as follows:

1. There are three main operational aims: Avoid congestion in the pedestrian flow. Ensure that the system is resilient to surges in demand during service disruptions. Provide sufficient capacity for an emergency evacuation. These aims match the policy set out by London Underground [87].

2. From a functional point of view, stations are divided into a logical sequence, consisting of the following components: entrance, concourse, horizontal movement, vertical movement, buffer zones, platforms and waiting areas. Entrances connect the station to its surroundings. These are followed by the concourse, where passengers can orientate themselves, obtain information, buy tickets and use any facilities that may be provided. The components associated with horizontal and vertical movement form the link between concourse and platform. Horizontal movement takes place via subways, footbridges and tunnels, while stairs, escalators, ramps and lifts enable vertical movement. Buffer zones in or near horizontal movement components maintain safety near such critical processes as gates, escalators and lifts. Platforms enable passengers to move between station and train. Waiting areas provide places for passengers to wait for their trains away from the platform. This route – or parts of it – appears in the handbooks, guidelines and standards of every country.

3. The authors recommend the setting of maximum pedestrian density and flow levels to ensure the good functioning of a station and the testing of designs against these limits. Like the handbooks, guidelines and standards of the three countries mentioned above, Ross et al. refer back to Fruin's levels of service [36]. They recommend using a combination of experience, common sense and pedestrian simulation models to assess conformity of station designs with requirements.

The *Highway Capacity Manual* (HCM) [100], published in 2010, contains guidelines for calculating the capacity of pedestrian facilities in urban environments. The content of the handbook reflects the work carried out in the 1970s by Pushkarev & Zupan [95] and Fruin [36]. For specific applications, the handbook refers the reader to the specific rules and guidelines that apply. For urban public transport, for instance, it refers to the TCQSM.

The *Transit Capacity and Quality of Service Manual* (TCQSM) [101] defines the pedestrian capacity of a station as the maximum number of people who can occupy or pass through a pedestrian facility or element. A distinction is made between maximum and design capacity. The maximum capacity is defined as the peak load that a facility is physically capable of processing within a given time. The design capacity is defined as the capacity required to handle pedestrian flows under normal peak conditions, plus any extra capacity that may be required to cope with disruptions to train services, special events and evacuations. The design capacity, which will be lower than the maximum capacity, is determined in accordance with the desired level of service. In other words, design capacity is a choice (possibly a matter of policy), whereas maximum capacity is a system characteristic. On the basis of their study on the Washington Metro, based on the TCQSM, Antos et al. [102] conclude that there is no single industry standard governing the design capacity of metro station components.

The TCQSM points out that the level-of-service values in the HCM differ from those of Fruin [36] because of the particular field of application. The LOS values in the HCM are for urban pavements, whereas those drawn up by Fruin apply to public transport facilities. The desired LOS depends in part on the time for which pedestrians are to be exposed to a particular level of crowding. The longer the exposure, the more space is required in order to give a pedestrian the same perceived level of comfort. Where there is a mixture of traffic and waiting functions, the TCQSM recommends using the time-space concept [103] or microscopic pedestrian simulations. Further criteria can be applied, in addition to the LOS. In this connection, the TCQSM describes (1) the ratio of intensity to capacity, (2) passenger walking and dwell times (3) the time to clear a platform and (4) the mean delay caused by queueing. The TCQSM strongly advises against designing for maximum capacity, on the grounds that this will result in an unstable system. While the TCQSM does give examples regarding design capacity, the choice of capacity value is left to the user. The TCQSM also mentions the situation that commonly arises in practice, in which LOS values are specified with no maximum or other duration and/or no mention of the areas to which they apply. This leads to ambiguity in applying the standards. Like the handbooks produced by Network Rail [86] and London Underground [87], the TCQSM emphasizes the importance of providing sufficient space near escalators, stairs and gates in the interests of safety.

From a railway perspective, the TCQSM points out that the dwell time of a train can play an important role in determining the capacity of a line. When headways are short, it is important that passengers arriving on one train can clear the platform before the next train arrives. The time required for the alighting and boarding process often accounts for a significant percentage of total dwell time. At the same time, it is difficult to control this process in practice as it is influenced by a multiplicity of factors, including the number of passengers alighting and boarding, the dimensions and layout of the platform and the capacity of the train doors. The handbook describes four ways of dealing with dwell time. The first, commonly-used method is to use assumptions. The second is to use dwell times recorded during service. This involves using statistical methods and techniques, without considering the passenger processes that take place on the platform. The third method involves combining the first or second method with a standard deviation value to account for the variation in dwell times. In the fourth method, dwell time is estimated on the basis of the passenger processes that take place on the platform and in the train. This is a complex method and requires a sufficient quantity of high-quality input data. That method is covered in the *Rail Transit Capacity* handbook [104] mentioned later in this chapter.

3.2.5 Conclusions

The standards reviewed here indicate that John Fruin's level of service concept from the 1970s (see Section 3.3) forms the basis for dealing with platform crowding in the Netherlands, Switzerland and the United Kingdom, and in the generic handbooks. The aim of these standards is to ensure that sufficient space is provided for the safe execution of all the processes that take place on a platform, concurrently or consecutively, such as circulation, waiting, alighting and boarding. The review described in this section also indicates that it is standard practice to use the peak load (i.e. maximum passenger flow) from one or more trains. However, there are divergences in the way peak load is calculated and in the way the related standards are applied.

The standards and case studies show that researchers and station operators are aware that high or very high densities occur for short periods. However, the standards, guidelines and handbooks differ as to how long it is acceptable for these high density levels to persist. At the same time, there is agreement regarding the pedestrian processes that present the highest degree of risk. All station operators intend their standards to limit: the use by passengers of the zone along the platform edge (the "danger zone"), crowding near platform entrances (especially escalators) and the duration of the alighting and boarding process (because of its effect on train dwell time).

Various evaluation methods are used in the countries and generic handbooks considered. Statistical or dynamic pedestrian models are almost always used when evaluating existing situations or designs. In some cases, these models have been calibrated and validated on the basis of empirical data from the context under investigation. In other instances, generally-accepted model parameters are used. Only one study has been identified that directly evaluates specific situations on the basis of on-site measurements (a recent Swiss/Dutch study). From this, one may conclude that no generally-accepted method currently exists for measuring platform capacity.

3.3 Research on platform capacity

Traditionally, pedestrian traffic and railway operations have been separate fields of research. This section will therefore start by discussing the "pedestrian" and "railway" approaches to platform capacity. In the pedestrian approach, processing pedestrian traffic is central, whereas the railway approach focuses on dealing with railway traffic on the track. Some recent research has combined these two perspectives. This section will therefore conclude with a combined pedestrian/railway perspective.

The present section provides an overview of the research in this area. That part of this study was carried out in a number of stages. The first stage consisted of listing all relevant theses and dissertations. Next, books covering conferences in the field of pedestrian traffic were scanned for relevant articles. The conferences concerned were those of the *Transportation Research Board* (TRB), *Pedestrian and Evacuation Dynamics* (PED) and *Traffic & Granular Flow* (TGF). The bibliographies in the theses, dissertations and conference articles were then used to build as complete as possible an overview of the state of the art in this area. These publications were located via *Google Scholar* and *ResearchGate*. As many older publications (generally speaking, those published prior to the 1990s) were not available online, the author made several visits to the library of Delft University of Technology and the Library of Congress in Washington (USA). Finally, print versions of several older works were purchased online from libraries in the US that were disposing of unwanted items.

3.3.1 The pedestrian perspective

The fundamental diagram (FD) is a common method of calculating the capacity of pedestrian infrastructure [36] [95] [100] [105] [106] [107]. The FD shows the relationship between density (k), flow (q) and speed (u) (see Equation 3.1). The FD assumes that initially, flow (q) will increase with traffic density (k). After a certain density is reached, further increases in density will lead to a reduction in flow. This is the density that corresponds to maximum flow (q_{max}).

$$q = k \cdot u \tag{3.1}$$

Several researchers have estimated an FD for a specific pedestrian route on the basis of empirical data. Figure 3.7 shows fundamental diagrams of flow against density based on the work of Pushkarev & Zupan [95], Buchmüller & Weidmann [106] and Zhang [107]. Appendix C shows the figures for the other FD relationships and all functions. The fundamental diagrams found were estimated on the basis of empirical data for various types of two-way traffic (e.g. In cities, on campuses and at public transport interchanges). Given the diversity of traffic situations, the relationships are not directly comparable. However, Figure 3.7 does clearly show that different values were obtained for capacity (maximum flow), i.e. the maxima of the curves. The lower values are around 1 pedestrian per second per meter width, whereas the upper values are 50% higher. At maximum flow, density is between 1.25 and 2.5 pedestrians per square metre.

Hoogendoorn et al. [108] have recently applied the principle of the fundamental diagram to pedestrian networks, i.e. combinations of multiple routes. The resulting diagram is referred to as a macroscopic fundamental diagram (MFD). The idea behind the MFD is that the number of pedestrians emerging from the network (production) is dependent on the number of pedestrians who are concurrently in the network at any given time (accumulation). As for an FD, the production in an MFD initially increases with accumulation and then falls from a specific point onwards. That point marks the capacity of the network (i.e. maximum production). In a network MFD, the variation in spatial distribution of pedestrians over the network is an important factor. To obtain good results, it is important to know about local bottlenecks that affect the performance of the network. Daamen et al. [109] have confirmed this regarding station platforms. During that study, they applied the MFD principle to platforms, using microscopic pedestrian simulation. That exploratory study showed that the critical bottlenecks on a platform immediately following the arrival of a train do not always occur at the platform exits. Where heavy cross flows occur on a platform, high local densities in the network can reduce the production of the platform as a whole.

In his work carried out in the 1970s, Fruin [36] laid the foundations for the use of the level of service as a design concept for pedestrian intensity. He explained the

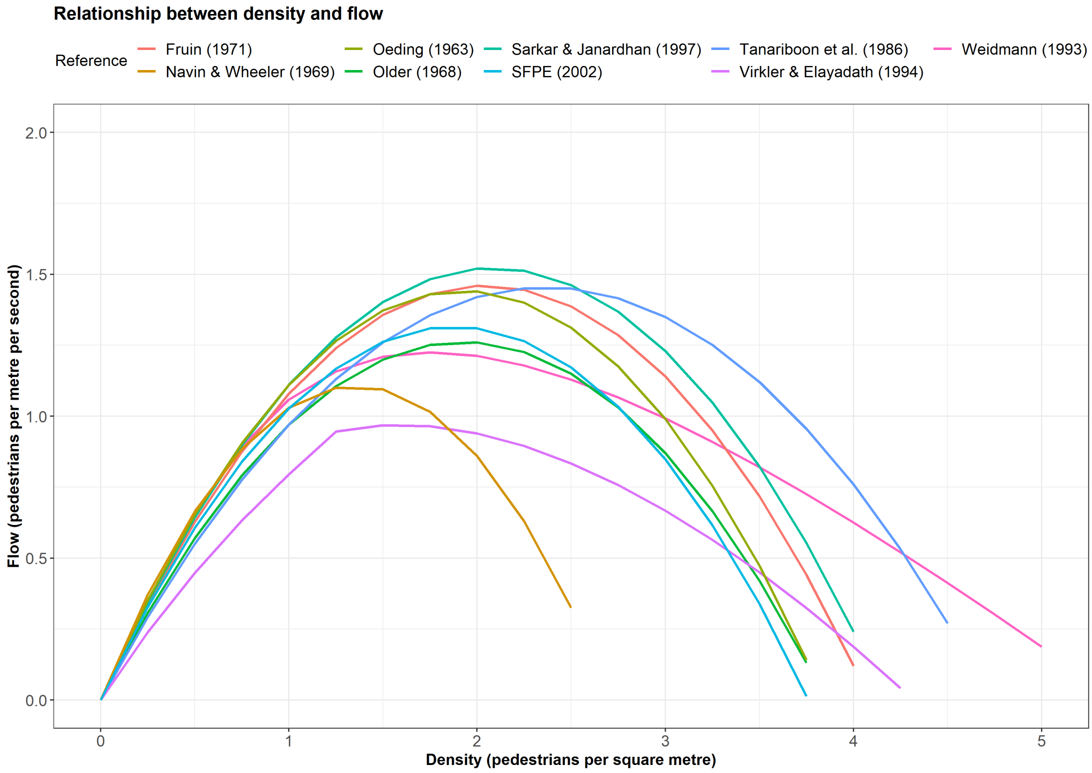


Figure 3.7: Fundamental diagram for pedestrian traffic (flow-density relation)

need for his concept by pointing out that many pedestrian facilities of the time were designed for maximum passenger flow, and that capacity was being defined on that basis. Using the fundamental diagram, Fruin showed that passenger flows that come close to loading a facility to its maximum capacity cause high densities and unstable pedestrian flow. As a result, pedestrians lose much of their freedom of movement and have little choice regarding walking speed, and use of the facility becomes uncomfortable. Fruin maintained that “designing for capacity is designing for congestion”. Appendix C gives the values that correspond to Fruin’s levels of service, along with his qualitative descriptions of each level [36].

A couple of years later, Pushkarev and Zupan [95], in their research on pedestrian space requirements in a generic urban context, defined capacity as “the maximum possible ability to accommodate a flow”. Like Fruin, the researchers point out the undesirable yet common use of pedestrian capacity as a design criterion in the United States during the 1970s. Unlike Fruin, however, they do not propose any numbers for design standards, but simply note that the selection of a particular level of service as a design standard is “a matter of judgment and policy”.

While Fruin’s work [36] is used in all the handbooks, guidelines and standards mentioned above, it was intended to be more generic, in the sense of being applicable to all types of pedestrian facility, from city pavements to public transport interchanges. Having said which, his work is linked to railway stations in a number of ways. For instance, Fruin obtained the primary empirical data for his research from bus and train stations in New York, specifically the Port Authority Bus Terminal and Pennsylvania Station. He also cites examples throughout his work, many of them taken from railway or metro stations. Fruin makes a number of suggestions regarding the design of such pedestrian facilities:

- Facility design should be based on the magnitude and duration of the peaks in pedestrian traffic, paying more attention to shorter peaks than to average peaks over longer periods. A distinction is made between bulk and intermittent processes when examining the arrival patterns of pedestrians at the facility. Pushkarev and Zupan ([95]) refer to the bulk processes as "platoons". Fruin noted that when bulk processes occur, overcrowding of pedestrian facilities is inevitable. This need not lead to bottlenecks, as long as load does not exceed capacity for too long. Fruin suggests that a platform (the part of a station most subject to bulk passenger arrivals) should be so designed that all passengers from a given train can clear the platform before the next train arrives. He also maintains that disruptions to train services do not result in excessively high peaks that last excessively long.

- The levels of service are presented in the form of ranges. Fruin argues that if the pedestrian profile is favourable from a traffic handling point of view, one can design for the lower end of the range. This will result in higher pedestrian densities. Commuters and other workers are cited as examples of favourable pedestrian profiles. If the pedestrian profile is unfavourable, it is better to design for the upper end of the range. Fruin cites passengers with luggage or situations with multiple conflicting pedestrian flows as examples of unfavourable profiles for a railway station.

- He points out the need to balance comfort and space as regards mechanical pedestrian facilities. For instance, he points out that while an escalator enhances comfort for passengers accessing a platform, the same escalator occupies space on the platform, impeding pedestrian traffic on the platform itself and restricting passengers' freedom of movement.

While Fruin regularly points out the importance of time in his design suggestions, it is space that plays the central role in the level-of-service concept. In the 1980s, Fruin worked with Benz to incorporate the time aspect in the design concept [94]. In the time-space concept, the space required for each pedestrian – the inverse of density – is multiplied by the time for which the pedestrian occupies that space. By comparing total footfall with the available time-space, it is possible to decide whether the facility is sufficiently large. The advantage of this method is that other activities can be included in the calculations, in addition to walking and waiting. Initially, the researchers applied this method to corners and intersections in urban pedestrian infrastructure. Later, Benz wrote a handbook [103] for the application of this concept to public transport interchanges. In that publication, he demonstrates the need to choose the space and time for the analysis carefully in order to obtain valid results. Grigoriadou and Braaksma [110] have applied the time-space concept to metro platforms. They point out the double function of a platform – circulation between platform entrance and train on the one hand and bulk queueing while waiting for the train on the other. Circulation requires relatively little time per pedestrian, but requires a relatively large amount of space. A person who is walking occupies a lot of space, but is only at any given point for a short time. Waiting is exactly the opposite. Grigoriadou and Braaksma also show that the headway between trains plays an important role in determining the level of service that all platform users experience.

In her 2004 thesis [105], Daamen presented a microscopic pedestrian simulation model capable of generating information regarding the functioning of pedestrian flows in a public transport facility. At the time, no such model existed. Her model is based on the three main components of a public transport facility: the pedestrian, the pedestrian infrastructure and the public transport system. It is the last of those three components – consisting of a timetable and the characteristics of the trains used – that distinguishes Daamen's model from all other pedestrian models available at the time. As little research had been carried out in this area, Daamen devoted considerable time and attention to studying the creation and capacity of bottlenecks in pedestrian flows. In particular, she investigated the patterns of passenger flow that emerge when pedestrian flow approaches or exceeds the capacity of a component of the infrastructure. She defines the capacity of a pedestrian infrastructure component as the point at which congestion occurs. Daamen based her analyses on microscopic observations conducted during large-scale pedestrian experiments in a laboratory. The results of those experiments were incorporated in the pedestrian simulation model, which was then applied to four case studies. Fruin's levels of service [36] were used to evaluate the results that the model generated. The LOS values were looked at from three angles: the lowest LOS, the length of time for which each LOS applied and the extent to which the simulated pedestrians encountered each LOS. Consideration was also given to walking distances, whether it was possible to achieve a predetermined alighting and boarding time and how long it took for all passengers alighting from a train to clear the platform. Daamen gives no information regarding the combinations of indicators (and the values of those indicators) at which the capacity of a public transport interchange is reached. However, the following conclusions are relevant to calculations of platform capacity:

1. The timetable of the train, including any late running, results in passenger flows through the station that are concentrated in time. The bottlenecks (including local bottlenecks) that result from these peaks in pedestrian traffic can be alleviated by adding pedestrian infrastructure. This raises the level of service. At the same time, adding pedestrian infrastructure may increase the size of the station, thereby increasing walking distances and times.

2. The relationship between the number of platform entrances and the time required for passengers to make the transfer between train and station is non-linear, negative and dependent on the ratio of boarders to alighters. In other words, increasing the number of platform entrances accelerates the transfer process between the train and the station (the concourse or subway). However, the increase in transfer speed is smaller for each additional entrance.

3. In order to apply the pedestrian model successfully, it is essential to have a correct, detailed description of the passenger flows, together with detailed information regarding the functioning of congestion-sensitive components of the infrastructure. The lower the quality and quantity of this information, the more

> assumptions one is obliged to make. These assumptions have a major impact on the results that the model produces, and on the quality of any conclusions based on those results.

Daamen recommends further research to validate the results of her pedestrian experiments in practice. She argues that it is important to find the right balance between simply issuing sound guidelines – which can obviate the need to conduct expensive simulations to assess relatively simple real-life situations – and using pedestrian simulation models where they add value, i.e. for complex situations with multiple interactions between transport interchange components.

Responding to the first of her own recommendations [105], she and Hoogendoorn collected empirical walking speed and density data at Delft station, as part of the validation process for the pedestrian simulation model SimPed [111]. They show that the model corresponds closely to reality, but also point out one effect not included in the model, namely that as a train arrives, passengers walk along the platform in the direction the train is moving, redistributing themselves over the available platform area.

From a flow perspective, capacity can be defined as the density at which flow reaches a maximum, i.e. the top of the curve in the flow diagram (Figure 3.7). Bottlenecks occur when capacity is exceeded [37]. However, the occurrence of bottlenecks in a network does not automatically mean that the capacity of the network has been reached. Hoogendoorn et al. [108] argue that it is certain critical points in a network that determine its capacity. In continuation of this research, Daamen et al. [109] have recently taken a first step towards the application of the MFD to a platform.

In his 2016 thesis, Hänseler [112] presents a hybrid model for determining pedestrian demand and level of service in stations. He developed a new demand model for stations, as no such model existed, and detailed information regarding passenger flows per train are often unavailable. To measure the performance of infrastructure components, he developed a macroscopic assignment model which, by comparison with existing models, can easily be applied to complex infrastructure such as railway stations and delivers results quickly. One important step in Hänseler's research is the modelling of how the timetable influences traffic demand. Train services are the dominant factor determining the distribution of demand over time (arrival and departure times) and space (track utilization), and the number of boarding and alighting passengers per train (the volume of the passenger flows). As a result of these "train-induced pedestrian flows", a station differs markedly from other types of pedestrian facility, such as a shopping street or a stadium, and generic demand models are less capable of describing passenger flows in stations. To validate the model, and its applicability, Hänseler compiled a large dataset from multiple sources, describing pedestrian flows at the central station in Lausanne, Switzerland. On the basis of his research Hänseler recommends collecting more data, which would make it possible to determine the model parameters for a wider range of situations. In 2020, Hänseler et al. [26] developed a pedestrian model with which it is possible to estimate the distribution of passengers within the train, passenger densities on platforms and the use of platform entrances at stations, along an entire rail corridor. The researchers demonstrated that the model correctly simulates real-life (i.e. measured) passenger flows, using a case study for the busy rail corridor between Utrecht and Amsterdam.

3.3.2 The railway perspective

In his 1994 thesis [113], Weidmann developed a model with which it is possible to estimate the duration of the transfer process between vehicle and bus stop and between tram stop and railway station, along with the variation in this parameter. This *Fahrgastwechselzeit* or passenger service time is an important factor for the design and operation of a public transport network. A shorter dwell time results in a faster public transport system. Reducing the variation in dwell time results either in more stable implementation of the timetable, and hence improved punctuality, or else makes it possible to reduce headway, rendering the public transport system faster. Weidmann also points out in the justification for his research that the importance of dwell time for the planning, operation and design of vehicles, stops and stations increases as the public transport system becomes more heavily loaded. He conducted his research on the basis of empirical data gathered in Switzerland and Germany.

Weidmann states that, for instance, S-Bahn trains spend 81% of a trip moving and 19% standing in a station. Almost two thirds of this dwell time is used for the passenger transfer process, with one third devoted to other, passenger-independent processes. Because of the important role that the duration of the passenger transfer process plays in the functioning of the public transport system as a whole, Weidmann has investigated a number of station factors. He highlights the following factors as being of relevance to station capacity:

- The number of train passengers alighting and boarding.
- The way the alighting and boarding process is organized. An alighting and boarding process with two-way traffic at all stages is slower than one that consists of one-way traffic.
- The distribution of alighting and boarding passengers over the doors of the train. Even distribution of passengers produces the fastest alighting and boarding process. The distribution of alighting and boarding passengers over the train doors depends on a large number of closely-interrelated factors, which meant that Weidmann was unable to quantify the impact of each factor. In general, however, he states that the alighting and boarding process takes 40% longer if the passengers are distributed over the train doors in accordance with a triangular distribution than if they are uniformly distributed.
- Capacity restrictions at train doors, and the possibility that the train door itself may be the critical bottleneck determining the duration of the alighting and boarding process. However, the bottleneck may also be located downstream, in the train, in the form of restricted flow in vestibules, in corridors/gangways and on stairs (in the case of double-decker coaches), etc. There may also be capacity restrictions on the platform that slow the alighting and boarding process. This is the case when crowding leads to high densities of pedestrians at train doors, in the train and/or on the platform.

Weidmann argues that the door through which passengers take the longest time to alight and board is the critical door as regards train dwell time. However, he points out that this need not be the most-used door. Where the number of passengers in the train and on the platform is relatively low, less-used doors can become critical owing to natural variations in the alighting and boarding times of individual passengers. Where passenger numbers are relatively high, bottlenecks resulting from capacity restrictions at train doors can result in relatively low door productivity, prompting passengers to move to other doors.

At around the time Weidmann was conducting his research in Europe, Parkinson & Fisher [104] were compiling an inventory in the United States of factors that play a role in "rail transit systems". That research was conducted under the Transit Cooperative Research Program, which formed part of the Transportation Research Board. Their study concluded that train dwell time is the second most important factor determining the minimum headway between trains, the most important being the signalling system and its limitations. The researchers make a distinction between "light rail transit", "rail rapid transit" and "commuter rail". Light rail transit and rail rapid transit (which include such services as metro networks) provide a frequent service, with short headways and separate platforms for each direction. The busiest stations are generally in the centre of the network, and the network crosses city centres. Commuter networks run less frequent services, with relatively long minimum dwell times. The busiest stations are generally those at the extremities of the network, which coincide with city-centre termini.

In her 2003 thesis, Heinz [72] conducted extensive empirical research in Sweden into the relationship between train dwell times and the alighting and boarding process at individual train doors, for metros, regional trains and long-distance trains. The practical motivation for her research was that train simulation models use constant dwell times, which does not correspond to reality. To identify the relevant factors, Heinz looked at the interior of the train near the doors, the width of the doors, the difference in height between platform and coach, passenger characteristics and the distribution of passengers over the platform and the train. She introduces the concept of the "dimensioning door" in connection with the last of these factors. Here, Heinz is referring to the fact that boarding passengers are often distributed unevenly along the platform. As a result, one train door has to handle a relatively large number of passengers, thereby playing a critical role in the duration of the alighting and boarding process of the train as a whole. She also notes that not only the mean dwell time but also the standard deviation of the dwell time is relevant. Using hypothetical probability distributions, Heinz demonstrates that a lower mean with a wide distribution can result in a less punctual service than a higher mean and a smaller distribution. Irregular intervals between trains, with a constant inflow of passengers to stations, can result in greater distribution of dwell times and hence a less stable service. The cumulative effect of delays means that this effect becomes more and more noticeable as the train gets further away from its starting point. Finally, Heinz points out that while a larger number of model parameters would probably result in a more accurate model, it would be necessary to set valid, reliable values for all those parameters. She argues that a simpler model with fewer parameters is better than a more complex model. Her research does not address the relationship between bottlenecks on the platform and train dwell times.

In his standard work on urban public transport, Vuchic [114] – like Weidmann [113], Parkinson & Fisher [104] and Heinz [72] – emphasizes the impact of train dwell time on the functioning of the railway system as a whole. Because of the way that signalling systems work, a stop on a route with the same number of tracks in the station as on the lines leading into it results in an increase in minimum headway. This increased minimum headway leads to a reduction in the capacity of the network. The critical stations in a network are those with the largest minimum headway. Increasing the number of platforms in a station is a common means of compensating for the loss of network capacity that a station causes. Like a number of other researchers mentioned above, Vuchic warns of the risks involved in dimensioning and planning a public transport for capacity. Doing so drastically reduces system speed, leading to increased operating costs and a system that is less attractive to passengers. Furthermore, natural irregularities in operations render them less robust. The alighting and boarding process at critical stations is a major source of irregularities.

3.3.3 The combined perspective

In an overview published in 1998, Mansel et al. [115] describe the factors that must be taken into account for heavily used urban rail transportation. Their publication was prompted by the rapid growth of light rail transit (LRT) in North America, especially in regions with high concentrations of activity. The authors highlight the following factors regarding platform capacity:

1. Departure peaks related to the type and scale of activities near the station, e.g. if the station is located near a sports stadium or a business district. The station must be capable of safely handling the critical peak. The authors see estimating the critical peak as one of the biggest challenges in designing a station.

2. Train cancellations, which mean that the following train has to handle a much larger number of passengers than usual. The researchers speak of planning for two to three times the normal number of passengers, in order to maintain the same level of service as would be possible if no train were to be cancelled.

3. Depending on headway, from a given point onwards dwell time becomes the factor determining the number of services that a line can handle in a given time. Using a moving block signalling system on a system providing a very frequent service causes the system to reach that point earlier, because of the shorter headways on the open line.

4. If escalators are used under very crowded conditions, there is a risk of accidents in the runoff area, as passengers cannot see if there is enough room to move away from the other end of the escalator before they step onto it.

Like Parkinson & Fisher [104] and Vuchic [114], Mansel et al. [115] point out the difference between the ideal and practical design capacity of a rail route. Mansel et al. refer the reader to the work of Parkinson & Fisher [104] as regards the procedure required to take account of practical factors in deriving a practical design capacity from an ideal design capacity.

In 2011, Leurent [116] presented a qualitative framework for identifying capacity bottlenecks in public transport systems. He divides the public transport system into four subsystems: passenger, vehicle, station and line. He then goes on to describe the relationships between the four subsystems. The capacity of the public transport system as a whole depends on the order of its subsystems. Leurent points out the dual nature of the pedestrian function: the traffic function, which makes possible walking and transfer between train and surroundings, and the "storage" function, which enables passengers to wait for their train to arrive. He mentions the short but intense peaks in passenger flows that occur immediately following the arrival of a train.

On the basis of the relationships between the subsystems, Leurent identifies a number of "congestion gears" – factors that increase congestion. These are situations where a heavy load in one subsystem results in a heavy load in another, which then has a retroactive effect on earlier subsystems. When this happens, bottlenecks "escalate", with negative consequences for the capacity of the entire system. For stations, Leurent identifies three congestion gears:

1. An increase in the number of alighting and boarding passengers per train increases the required dwell time, which means that trains cannot run as frequently. This results in a larger number of alighting and boarding passengers per train.

2. High densities on the platform and/or in the vehicle hinder the alighting and boarding process. This causes an increase in the number of passengers on the platform at the same time, further hindering the alighting and boarding process and increasing the dwell time.

3. Intense crowding upstream on a line will be propagated downstream if delays occur as a result of crowding in the train and/or increased numbers of alighters and boarders at stations downstream. Those delays will result in larger numbers of boarders at stations downstream, which again will lead to longer dwell times.

In his 2016 thesis, Srikukenthiran [117] designed a decision-support system for handling service disruptions in a metro network, taking the Toronto metro as a basis. He justified the combining of station and line by pointing out the major impact that passenger flows in the busy main stations can have on the operation of the metro system as a whole if headways are short. He noted that "network" and "station" are two different worlds in research, in the operation of a metro and in the development of decision-support systems, including the commercial aspects.

One important step in his research is the identification and modelling of those elements of a busy station that have the greatest impact on the functioning of the network. The idea behind this is that local bottlenecks in crucial elements of the pedestrian network within a station can increase the dwell time of a train. If the increase is too great, the train will be unable to maintain the required headway and delays will occur because of congestion in the network. This congestion can affect very busy stations, because if the service is irregular, waiting passengers will accumulate on platforms. As far as platforms are concerned, Srikukenthiran identified two factors: 1. Which platform exit passengers choose. On a metro, this is almost always some form of vertical circulation. If passengers have to queue for one or more exits they may form an obstacle for other passengers, making it more difficult for them to move along the platform. As a result, arriving passengers are less evenly distributed over the available exits, and departing passengers are less evenly distributed along the platform. 2. The locations along the platform where waiting passengers (boarders) choose to wait. This is an important factor, because passengers generally do not distribute themselves evenly along a platform or train. As a result, the busiest door is critical to the process whereby passengers move between vehicle and station.

Srikukenthiran's research shows that it is possible to build entrance and waiting location models for the case of Toronto that incorporate these factors, and that these models have a high predictive value (¿ 90%) when compared with the empirical data collected in the context of his study. Application of these models as part of microscopic pedestrian simulations using MassMotion within the decision-support system shows that both factors have a noticeable effect on passenger flows along platforms and on train dwell times. For the case investigated, the researcher showed that a specific platform at a station in the centre of the network formed a weak link in the metro network as regards the processing of service disruptions. In view of the effort required to produce a properly calibrated microscopic simulation model of a station, Srikukenthiran recommends that a method be developed for deciding which stations require only a relatively simple model, and which require a detailed microscopic model.

3.3.4 Conclusions

There is a direct relationship between peak crowding on platforms and the operation of services on a network. However, it is not possible to establish a direct relationship between these peak loads and the system capacity of a platform, as no research has been found that defines the system capacity of a platform, i.e. the point at which the productivity of the platform is at its highest.

Several researchers point out that one should not plan to use the full system capacity of pedestrian systems, such as platforms, as this results in unstable processing of pedestrian traffic and hence in safety hazards. Not knowing the system capacity of a platform need not be a problem, as long as one knows the usable capacity, or "service capacity". There is, however, no scientific consensus on this point.

Some researchers approach service capacity from a pedestrian perspective, looking at safety and comfort. These approaches frequently use John Fruin's level-of-service concept, which involves pedestrian densities and flow rates. Other research looks at the service capacity of a platform from a railway perspective, focusing on train dwell times. The passenger transfer process – alighting and boarding – forms an important part of this. Important factors affecting passenger service time are the number of alighting and boarding passengers and the way they are distributed over the doors of the train. Recent studies have combined these two perspectives. Those studies indicate that platforms with large numbers of alighters and boarders can restrict rail traffic on busy networks because of the dwell times at those platforms. The researchers point out the risk of excessively long dwell times due to excessively long passenger transfer processes resulting in delays on the network, which in turn result in larger numbers of passengers alighting from and boarding the following train, increasing dwell times and delays still further.

Like rail service operators, researchers studying peak loads and system capacity run up against the limited availability of data on passenger flows in stations. Owing to the shortage of data, rules of thumb are often applied (e.g. [99]), or microscopic pedestrian models are used to generate synthetic datasets (e.g. [91] and [83]). However, the quality of the results these models produce depends very much on the quality of input, calibration and validation, and these are largely based on empirical data. Another factor is that pedestrian models have become increasingly complex, which has tended to increase rather than decrease the need for empirical data. In the countries examined, large-scale use of data analysis for stations is a recent phenomenon (e.g. [98] [84] [112] [118]). Given the variations in the empirical data, one may argue that – as for the traditional approach, with relatively little data – a good definition of peak load is essential even if empirical data are available in abundance.

3.4 Defining the passenger capacity of a platform

Despite the lack of an unambiguous definition, it is clear from the literature study that the occurrence of bottlenecks – locations in a station where passenger flow exceeds capacity – is inextricably linked to the concept of capacity. Large numbers of passengers arrive at a station simultaneously as the result of a train service that delivers large numbers of them to and collects them from the station at the same instant. Via the boarders and alighters, the train service sends pulses along the passenger arteries of the station, just as the heart sends pulses through the body's circulatory system. The strongest pulses are felt on the platforms. As a result, it is on platforms that capacity bottlenecks generally occur first. The literature review in this chapter shows that platform capacity is more a "soft" policy choice than a "hard" system characteristic. As far back as the 1970s, Fruin [36] and Pushkarev & Zupan [95] argued that designing and loading a pedestrian system to capacity causes unstable traffic, resulting in safety hazards and a high level of discomfort. With the aid of standards, guidelines and handbooks, station operators in the three countries studied attempt to find a balance between safety and comfort on the one hand, and cost on the other. From a pedestrian perspective, the area near the platform edge and the areas near escalators are considered the most dangerous areas on a platform. From a railway perspective, what matters most are the dwell times of those trains that can have a critical impact on the capacity of a line, together with the stability of these dwell times. The combined perspective addresses the interaction between those two perspectives. In some cases, bottlenecks on the platform and on the line reinforce each other, which may cause both bottlenecks to escalate.

As far as the pedestrian perspective is concerned, station operators in the three countries studied use Fruin's level-of-service concept to manage the balance between safety, comfort and cost. In all cases, station operators maintain a certain margin with respect to that capacity – which is seen as a system characteristic, but of which the exact value is unknown. One complicating factor is that Fruin's method is not unambiguous. Fruin himself recognized this in pointing out that the time element is missing from his level-of-service concept. Furthermore, the choice of aggregation level will affect the results, as there is a risk of averaging away peak loads that are relevant to capacity calculations over space and time.

In recent decades, a number of researchers have pointed out that Fruin's level-of-service concept produces results that are open to multiple interpretations (e.g. [83] [119]). In practice – and in the author's experience – this results in repeated discussions regarding the level of safety and the extent to which the costs of safety-enhancing measures are justified. In the UK, Network Rail and London Underground have attempted to solve this question by assigning peak loads to the standardized levels of service for various elements of a station. Swiss Federal Railways distinguish between shorter and longer peaks. In the Netherlands, specialists link the levels of service to a peak load when applying the standards.

From a railway perspective, critical interactions can occur between platform and line processes, just as they can on a metro system. This occurs whenever headways become shorter and dwell times become longer or less stable because of the larger number of alighters and boarders. In such situations, the processing of passengers on one or a few platforms becomes critical to train operations [117]. However, a number of differences between metro and railway systems mean that the two are not totally comparable. Weidmann [96] mentions differences in the number of doors in a train, and their width, plus differences in the height of the step between platform and train and the use of specific parts of a train for particular sub-populations. The last of these aspects is common in trains, but does not occur in metros. The BAV [93] emphasizes the hazards that arise as a result of the fact that railways carry passenger and freight traffic on the same tracks. In his thesis, Haith [120] points out the differences in speed and the higher average speeds on a mixed rail network. Metro systems also provide more frequent services and enjoy a greater degree of operating stability. Heinz [72] points out that railway trains have fixed dwell times, whereas trains on a metro often leave as soon as all passengers have alighted and boarded, or when the train is full. Furthermore, because of the frequent service, the passenger arrival pattern at a metro station is less dependent on a timetable, and therefore more regular. If passengers are optimally distributed over the trips, the peak load per trip will be less pronounced. In London, it appears that the type of interaction between station and line typical of metro systems is now being observed on parts of the railway network, owing to the sharp increase in passenger numbers of recent years [21]. This is resulting in deteriorating punctuality and line capacity, which can only be addressed by investing in stations and/or new lines. In the Netherlands, this phenomenon seems to be occurring at Schiphol Airport station, where optimizing the stopping position of trains on the platform proved to have a major effect on dwell times [25]. Partly on account of passing freight trains, infrastructure manager ProRail declared a platform at Utrecht Centraal overloaded [5] in 2017, because of excessively high passenger density during peak hours, expressed as a Fruin level of service. In the Swiss city of Basel, there has been discussion as to whether planned expansion of train services can go ahead if the station is insufficiently prepared [121].

On the basis of the above, and of the literature study in this chapter, the passenger capacity of a railway station platform is defined as a situation with one or more of the following characteristics:

1. Immediately following the arrival of a train, **queues form at the escalators** via which passengers leave the platform. As a result, passengers come into conflict

with one another near the escalators, and/or the queues for the escalators lead to passengers regularly walking or standing too close to the platform edge.

2. As a result of crowding, **passengers regularly walk or stand too close to the platform edge** when no train is standing at the platform.

3. As a result of the alighting and boarding process, **train dwell times regularly exceed the time allocated in the timetable**. The platform therefore causes or increases delay to trains as they proceed further along the line. Trains delayed by the longer dwell times may result in overlapping passenger flows on the platform.

In the list above, "regularly" means occurring as part of a pattern, with a causal link to crowding. Coincidental use of the area near the platform edge, or use for other reasons, does not fall under this definition.

Figure 3.8 shows the relationships between the factors mentioned above.

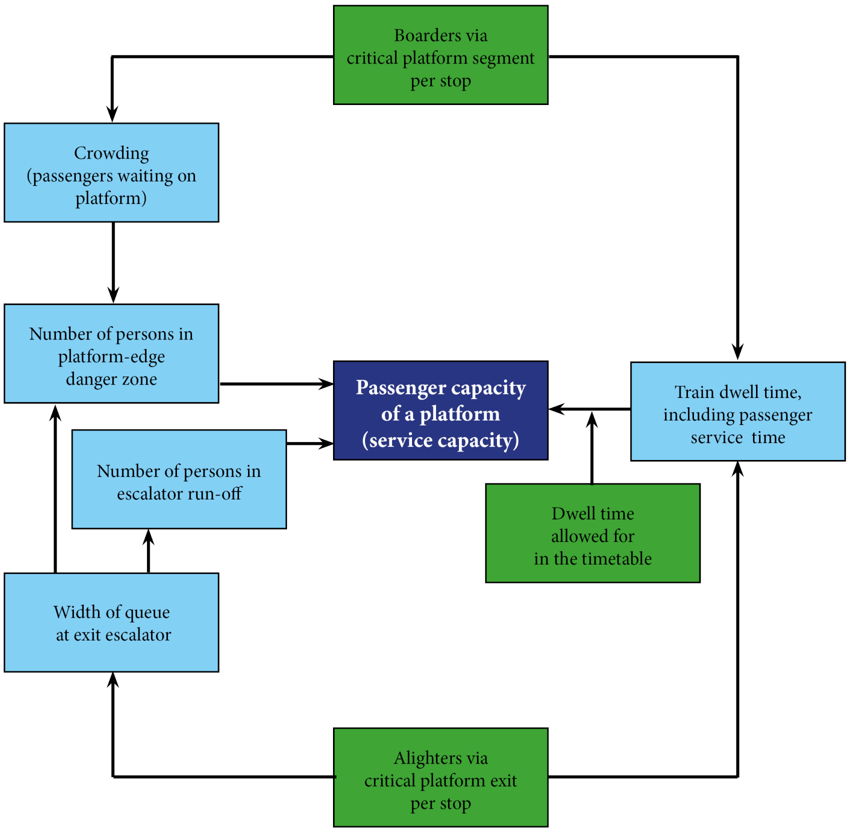


Figure 3.8: Relationships between the limits on the passenger capacity of a platform

3.5 Thematic studies to address research gaps

In Chapter 1, it was pointed out that crowding in trains and stations is receiving increasing attention in the Netherlands. Managers regularly state that the railway network is reaching the limits of its capacity. At some stations, crowd control on platforms is a daily necessity. Increasing platform capacity, as a factor determining line capacity, is one of the major aims of rebuilding work at Amsterdam Centraal, one of the stations handling the largest number of passengers in the Netherlands. Chapter 2 has shown that recent increases in the number of passengers and train arrivals will probably continue. At the same time, it is becoming more difficult and more expensive to add extra platforms or widen existing platforms. The literature study in this chapter has shown that there is no unambiguous, generally-accepted definition of platform capacity, on the basis of which it would be possible to say at what passenger flow rate the system capacity of a platform has been reached. However, this system capacity is only of secondary importance for practical purposes. In practice, any attempt to make full use of the system capacity of a platform will result in safety hazards that could lead to accidents. Furthermore, using a platform to its full system capacity would render dwell times unpredictable, making it difficult for a railway to run a stable timetable. And an unstable timetable can result in safety hazards (or additional hazards) for passengers on platforms, via feedback mechanisms.

In practice, therefore, a normative approach is taken to platform capacity, using what is referred to in this thesis as the “service capacity”. But as for system capacity, it has proved impossible to find any unambiguous, generally-accepted definition of service capacity. It is therefore argued, on the basis of the literature study in this chapter, that the service capacity of a platform (in terms of the number of passengers) has been reached if one or more of three situations arises. These situations will be studied further in the remainder of this thesis. For each situation, the following hypotheses are postulated on the basis of the literature study:

1. Chapter 5: As a result of queues forming at an exit escalator immediately following the arrival of a train, passengers stand or walk too close to the platform edge, and/or passengers in the queue for the exit escalator wait in the run-off from the incoming escalator.

2. Chapter 6: As a result of crowding on the platform, passengers stand or walk too close to the edge.

3. Chapter 7: As a result of the number of alighting and boarding passengers, trains regularly depart with a delay, or with more delay.

Investigation of each topic starts with an in-depth literature study, for which the literature study in the present chapter serves as a starting point. As part of this in-depth literature study, concepts and boundaries will be discussed in more detail. Research for each topic will use the extensive sources of empirical data collected by NS in recent years. The next chapter, Chapter 4, describes those sources and the processing of the data selected for this research.

Chapter 4

Data sources, data preparation and datasets

A train stop, or arrival, forms the unit of observation for all the thematic studies in this thesis. A stop consists of the train stopping at the platform, passengers alighting and boarding and the train departing. To compare arrivals systematically between the subtopics in this thesis, data available within NS Stations have been used. The two most important data sources were pedestrian sensors (SMART Station) and the OV-chipkaart smart-card system (ROCKT Station). These sources were developed in parallel with the research for this thesis, under the supervision of the author. The other two sources are TRENTO, which logs train movements on the track and in stations, and publicly-available weather data from the KNMI – the Dutch meteorological office.

Because data from existing sources were used (i.e. secondary data), this research was shaped in part by the data available. The most important data for the first two thematic studies – on queues at escalators and pedestrians close to the platform edge – are those that describe the positions of individuals on the platform. These trajectory data were generated by the newest generation of pedestrian sensors (SMART Station), which were installed on the platforms of a limited number of stations. For the third thematic study – on passenger-dependent dwell time – use was made of ROCKT Station, from which the number of boarders and alighters for each NS arrival were derived. Using this data source, as many arrivals as possible were compared, under different conditions (e.g. different platform characteristics, train types and weather).

A period of at least one year was analysed for all the thematic studies, to ensure maximum diversity in the stops described by the data. Discussion of the results will include consideration of the limitations that data availability imposes (regarding the general applicability of the results, for instance).

The present chapter is structured as follows. The next section, Section 4.1, gives a general description of the data sources: SMART Station, ROCKT Station, TRENTO and KNMI weather data. As SMART Station and ROCKT Station were developed in parallel with the research for this thesis, the process of developing these sources and the accuracy of the data they generate will be discussed briefly. Section 4.2 describes the three platforms at Amsterdam Zuid and Utrecht Centraal that feature in the first two thematic studies. Section 4.3 describes the manner in which the datasets containing per-arrival trajectory data were created, and how they were enhanced using the information required for this study concerning pedestrian traffic on the platform, train traffic at the platform and/or weather conditions. The chapter concludes with an overview of the number of observations per research topic (Section 4.4).

4.1 Data sources

Four data sources were used for this thesis. 1. The SMART Station measuring system, which NS Stations uses to measure pedestrian flows in stations and on platforms. 2. ROCKT Station. This source is based on a combination of check-in and check-out data from the OV-chipkaart and traffic data from the rail network. 3. TRENTO, which contains data concerning train movements and the composition (length and rolling stock) of each train. 4. Publicly-available weather data from the KNMI.

4.1.1 SMART Station

SMART Station is a system containing pedestrian data from railway stations that was developed by NS Stations between 2010 and 2016 [27] [122] [123]. Experience had shown that pedestrian models often provided insufficiently accurate (synthetic) data concerning passenger flows in a station. This was partly because the empirical passenger flow data were not available that would have made it possible to calibrate and validate such models. At the time, no standard solutions were available that were suitable for measuring passenger flows in railway stations. NS Stations, together with a number of knowledge and technology partners, therefore developed the SMART Station concept [124]. This concept resolved three major problems regarding the measuring of pedestrian flow and locations at railway stations.

1. **Accuracy**: The accuracy of measurements of large pedestrian flows over a large area (see [118] for instance). It was found that a combination of sensor types often gave a better picture of pedestrian flows than one type alone. Furthermore, test installations using counting sensors revealed that measurements with these devices were less accurate at high pedestrian intensities (approximately 30 persons per metre per minute or more) and in the case of cross-flows (i.e. two or more directions). Both of these situations are typical of pedestrian flows in stations [23].

2. **Privacy**: The Dutch privacy legislation that applied in 2010 allowed far more flexibility in the use of Bluetooth and WiFi tracking in public areas than does the current EU General Data Protection Regulation. While the legislation in force when SMART Station was being developed was less strict, NS Stations had decided on a strict application of the “privacy by design” principle. This basically meant that as little (potentially) personally-sensitive data was to be captured as possible, and that when such data was acquired, it was to be anonymized as quickly as possible. In addition, there were maximum retention periods for measurement data and measures were taken as regards procurement, organization and culture (see [125] for further information).

3. **Cost**: Complexity in terms of technology, operation and regulatory compliance makes it expensive to use pedestrian sensors in a railway station. For instance, station stations may be as high as 10 m (e.g. the concourse at Utrecht Centraal) and as low as 3 m or less (e.g. subways at Amsterdam Centraal). It is only possible to install and maintain the sensors at night, as the passenger flows during the day make it impossible to create safe working areas. Specific requirements apply on platforms because of the adjacent track (train movements) and overhead line (risk of electrocution).

SMART Station uses a combination of pedestrian sensor types to build up a comprehensive picture of passenger flows on stations (see Figure 4.1). These are divided into sensors for counting and tracking. Counting sensors count all pedestrians detected in a floor field or on a counting line at specific locations within a station. The newest generation of counting sensors also detect whether or not a train is standing at the platform.

Counting sensors perform local measurements, while tracking sensors cover larger areas. Tracking sensors measure the distribution of passenger flows over time and space by detecting the Bluetooth and/or WiFi signals emitted by devices that pedestrians are carrying. Observations from tracking sensors at multiple locations are combined to establish walking routes and times. However, tracking sensors only detect 10% to 25% of pedestrians [122] [123]. By combining the counting data for all pedestrians at a specific location with the tracking data for a percentage of pedestrians over a greater area, it is possible to reconstruct a complete picture of the passenger flows, static locations and time spent in the station.

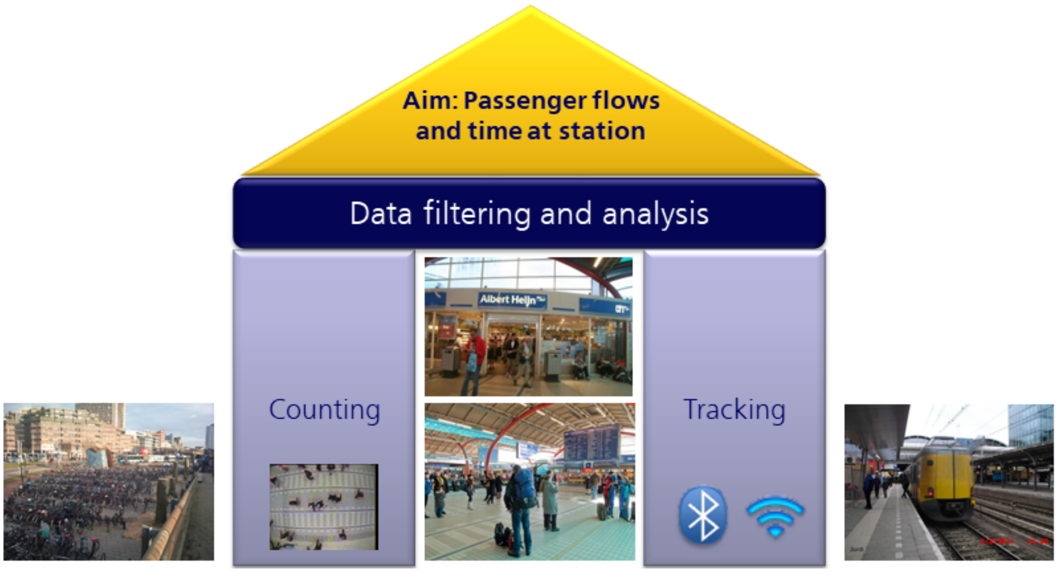


Figure 4.1: SMART Station concept (figure by author in [125])

The design of a measuring point depends on the purpose of the measurements. A combination of sensors is selected that balances data accuracy, the privacy of station users and the cost for NS Stations. See Appendix D for a list of “SMART Stations”, with descriptions of sensor types and the purposes of the measurements.

Since SMART Station was delivered in 2016, there have been three major developments regarding the use of sensors:

1. Since 2017, the counting sensors used have been capable not only of counting the number of persons passing a counting line or occupying a floor field, but also of recording the walking routes (trajectories) of pedestrians within the area they cover. These trajectory data from the SMART Station counting sensors on the platforms at Amsterdam Zuid and Utrecht Centraal form the empirical basis for the sub-topics covered in Chapters 5 and 6.

2. Bluetooth tracking was phased out in 2018, as it had become possible to obtain sufficient data from WiFi tracking. Phasing out Bluetooth tracking reflected the privacy by design principle whereby no more data is collected than is necessary to achieve the aim.

3. At the end of 2020, WiFi tracking was also phased out, partly because ROCKT Station was by then sufficiently developed that most of the data needed could be generated using ROCKT. WiFi tracking had been used primarily to identify walking routes between platforms and station entrances, plus time spent at the station. It became possible to derive this information from the OV-chipkaart data, once (a) ROCKT Station made it possible to work out from that data which passengers had arrived on which train, (b) it became possible to extract the platform on which each train had arrived from the platform traffic data and (c) the OV-chipkaart readers (and clusters of readers) could be linked to station entrances.

The trajectory data (see Appendix E, Table E.1) describe the walking routes of individual pedestrians in a floor field (*sensor_id*) using a unique i.d. number (*tracked_object*), the spatial coordinates (*x_pos* and *y_pos*) and the time the measurement was recorded (*timestampms*). These data are recorded 10 times per second. The time of measurement is expressed in milliseconds, and saved in UNIX Epoch format. The spatial coordinates describe the position of the pedestrian's head. The i.d. number is a unique number that is allocated to a pedestrian the first time they are detected. The train detection data (see Table E.2) are event-based. In this instance, that means that the sensor registers an event whenever the situation at the platform changes from "train" (1) to "no train" (0) or vice-versa. The sensors do not detect train type or length. The data are saved in comma-separated text format and processed using the statistics software R [126].

To verify the accuracy of the sensor data, the author carried out experiments on the platforms at Amsterdam Zuid. Figure 4.2 gives an impression of the results of 3 of the 72 experiments. A test person was asked to walk along a predefined straight line through the measurement area, parallel to the platform edge, from left to right in Figure 4.2. The points in the figure correspond to the measurements recorded for each test person, at 0.1-second intervals. The position of the line along the axis was calculated using locally estimated scatterplot smoothing (LOESS). This line was taken as the ground truth for the trajectory of the test persons. The grey strip indicates a bandwidth of 10 cm either side of the LOESS line.

The data clearly show the typical body sway of a pedestrian. It also became apparent that Test Person 1 deviated from the predefined route after about 12.5 m (at

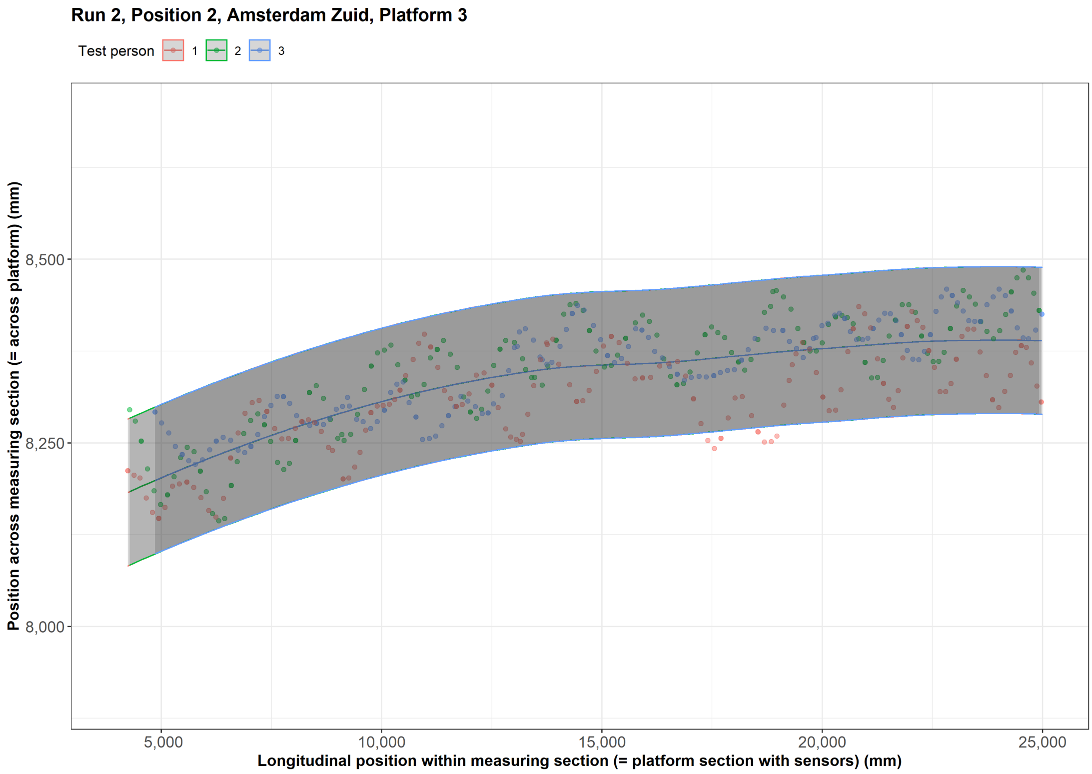


Figure 4.2: Analysis sample, precision of trajectory data, based on test for Amsterdam Zuid (figure from Run 2, Position 2, Platform 3, from [27] (formatting modified))

17,500 mm on the x-axis). This was confirmed by the video of the experiment. From these experiments, it was concluded that the position and number trajectory data from the sensors deviate by no more than a few centimetres from the real-life situation at regularly-observed pedestrian densities. The experiments also showed that the identification of unique pedestrians and the continuity of the walking routes recorded were of good quality (see [27] for more information).

4.1.2 ROCKT Station

ROCKT stands for "Reizen met de Ov-Chipkaart Koppelen aan Treinen" (linking OV-chipkaart journeys with trains). The word "Station" hints at the aim, which is to investigate passenger flows at stations for each train, between entrance, platform and train. ROCKT Station is designed to measure the number of alighters, boarders and transferring passengers for each train as accurately as possible, and then to indicate the walking routes of these passengers and the length of time they spend at the station. The idea of ROCKT Station is based on the results of NS' Aurora projects, which were carried out between 2009 and 2013 [127], with the aim of accurately predicting the number of passengers using a specific service between two stations. ROCKT Station was developed in order to accurately determine the number of passengers during a stop.

ROCKT Station was developed in three phases starting in 2012, under the leadership of the author, working with specialists inside and outside NS. Proof-of-concept tests were conducted in 2013 and 2014. Figure 4.3 shows an example of the first results of the proof-of-concept. That figure shows the cumulative distribution of the dwell time of transferring passengers at Deventer station on a number of days during December 2012. Deventer forms the intersection between trains on the east-west Amersfoort-Hengelo line and those on the north-south Zwolle-Arnhem route. The timetable changed on the second Sunday in December, which meant that on some of the days the 2012 timetable was in force, and on others the 2013 timetable. Under the 2013 timetable, the trains on the north-south route arrived 15 minutes later. Figure 4.3 shows that this 15-minute difference is clearly visible in the ROCKT data. Following a positive evaluation, a fully-functional prototype of ROCKT Station was developed in 2015–2016. The prototype was then integrated into NS data production systems in 2018.

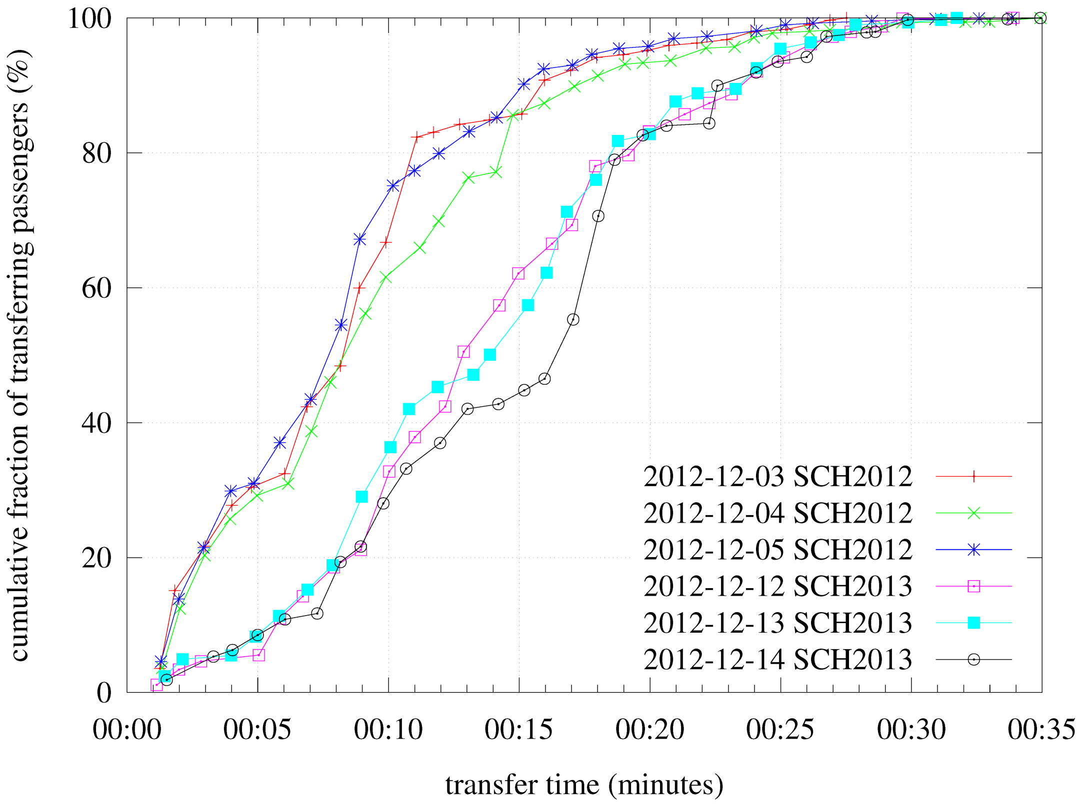


Figure 4.3: Dwell times for transferring passengers, Deventer station, December 2012 (from [84])

ROCKT Station is based on OV-chipkaart check-in and check-out transactions, with OV-chipkaart train journeys accounting for approximately 90% of the 1.3 million journeys that take place on an average working day. This equates to an average of approximately 2.3 million OV-chipkaart transactions per working day, or 750 million to 800 million transactions per year (in 2019).

The combination of a check-in and a check-out corresponds to one journey between two stations. These data are combined with data from four other sources, to obtain a complete picture of passenger flows for each train arrival.

1. Arrival time, departure time and platform (see the explanation concerning TRENTO for further information).

2. Where the validators are located. In practice, validators are clustered at station entrances. This means that station entrance usage can be determined from cluster usage.

3. OV-chipkaart scans carried out by conductors on trains. When a conductor scans a card, the train and service number are also recorded. It is therefore certain that this group of passengers has used this particular service.

4. Manual passenger counts on board trains.

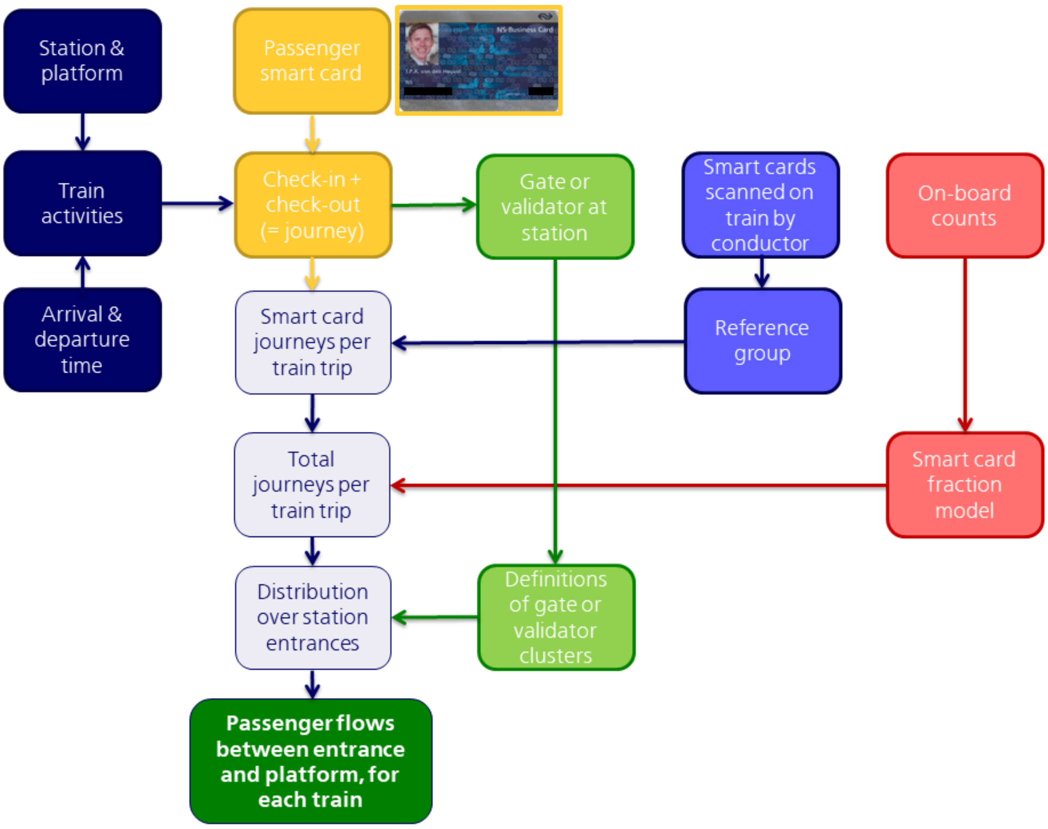


Figure 4.4: ROCKT Station concept

In general terms, check-in and check-out combinations (i.e. journeys) are combined with the other four data sources as follows (see Figure 4.4): A passenger checks in at station X at time A. They then check out at station Y at time B. When they do so, the time and the scanner i.d. are recorded. A search is then made of all trains (i.e. services) between times A and B that the passenger could reasonably have used to travel from X to Y. For many journeys, only one service is possible, so the journey can immediately be linked with that service. For some connections between two stations, it would often be possible for a passenger to undertake the journey using any one of several different services. This occurs, for instance, when two trains depart in the same direction in quick succession (e.g. on the Gouda-Utrecht route). Furthermore, some passengers check in relatively far in advance of the departure of their train at station A, or check out relatively long after arrival at station B. Here again, a journey could have been undertaken using any one of several trains. In such cases, the journey is distributed over the possible services using a probability distribution based on the probability that a specific possible service has been used.

That distribution is regularly re-calibrated using data from the OV-chipkaart scans carried out by conductors on the trains. The choice of train is obviously unambiguous in the case of the passengers concerned. Finally, journeys undertaken using the OV-chipkaart are extrapolated to match the total number of journeys. This is undertaken using the manual passenger counts that are regularly carried out on board trains [127]. In addition to the number of passengers on the train, those counts include the date and the train number. The privacy-sensitive element of linking data from different sources within ROCKT Station is carried out automatically within NS' OV-chipkaart data systems, which are subject to strict rules regarding access and data processing. The author of this thesis does not have access to those systems. For this research, the only data used were the aggregated output data from the OV-chipkaart data systems (see Appendix E, Table E.3).

There are no other data sources with variables and units comparable with those of ROCKT Station that could serve as a basis for verifying the accuracy of the ROCKT Station data. As a result, it is only possible to assess the accuracy of ROCKT data indirectly. The manager of ROCKT Station at NS Stations carries out regular quality assessments of the output data generated by the intermediate stages of the algorithm. Experience shows that three indicators give a reliable picture of the quality of the output data:

1. The **time** that elapses between the arrival of a train at a station and the moment at which alighters check out at the OV-chipkaart validators. The vast majority of alighters leave the station within a few minutes of their trains arriving. If ROCKT mis-assigns journeys to train services, a second check-out peak for a service will occur at around the time the next train from the same origin station arrives (e.g. 15 minutes later if there are four trains per hour on the route).

2. As mentioned above, the cards of a percentage of passengers are scanned during their journey. The scan data is used to determine the correlation between (a) the actual number of **cards scanned by the conductor** and (b) the number of cards that should be scanned according to the probability of a card being scanned that ROCKT Station calculates. This probability is calculated for a given service by dividing the number of journeys that the conductor records by the total number of journeys undertaken using one single journey option. It is assumed that the number of passengers confirmed as having taken a given journey option is representative of all passengers who have used a specific service.

3. The number of check-in and check-out combinations (i.e. journeys) for which **no possible train** was found. Where there are disruptions to train services and or/engineering works, ROCKT Station is frequently unable to assign journeys to train services, as passengers will have completed part of the journey by bus.

These replacement bus services are not included in the datasets, so ROCKT finds no route options for some journeys.

To supplement the standard quality control checks, the ROCKT Station output data used for this thesis were compared with count data from OV-chipkaart gates. Figure 4.5 shows an example for Leiden Centraal (12 September 2019). The red diamonds show the number of check-outs recorded at the gates. Check-outs were recorded per 15-minute period during peak times (07:00 hrs–09:00 hrs) and per 60-minute period otherwise. The blue dots indicate the number of passengers alighting from each train according to ROCKT Station. Each dot corresponds to one train arrival. The figure clearly shows that the two data sources give the same picture. One can therefore conclude that ROCKT gives an accurate indication of the passenger flow associated with each arrival.

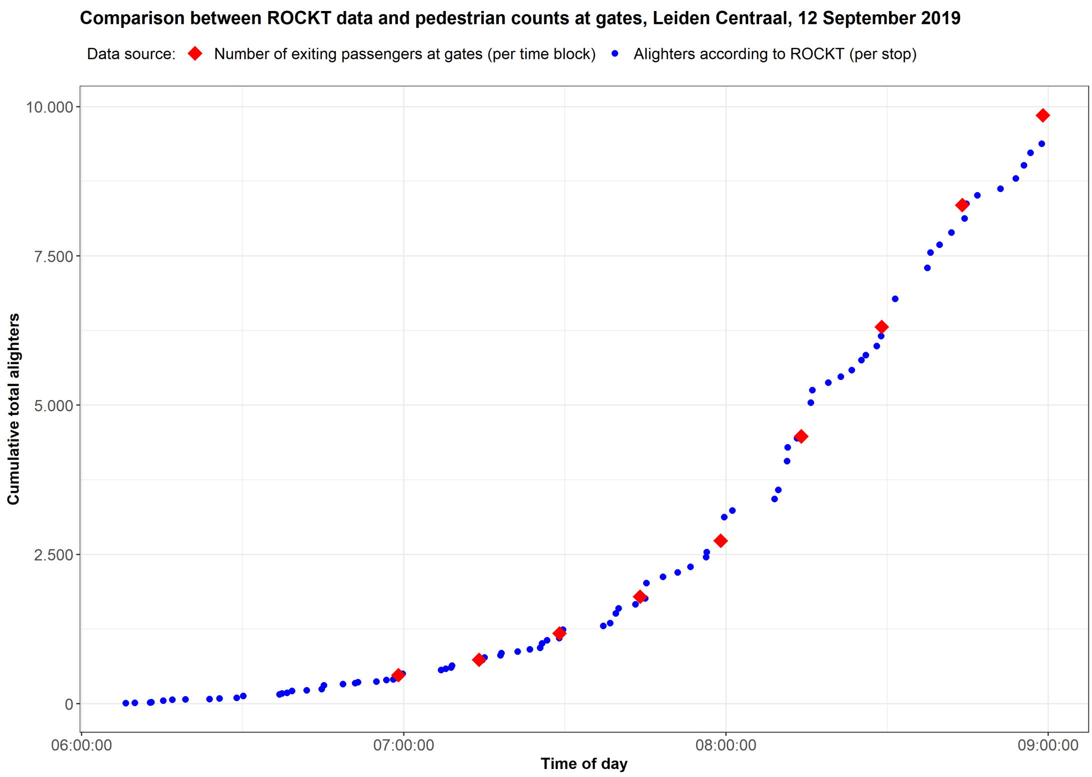


Figure 4.5: Example analysis of precision of ROCKT data on basis of comparison with gate data

4.1.3 TRENTO

The NS TRENTO database combines types of train traffic data.

- Data from the ProRail traffic control systems. These data from TROTS (*Trein Observatie & Tracking Systeem*) record the presence of a train in a track section [128]. In addition to the track section number, train number and the time at which the train entered and exited the section, the signal aspect is also logged. From the signal aspect, it is possible to deduce whether a stop was prolonged by a signal at danger, (e.g. because of a conflicting train movement) or for another reason.

- Planned arrival and departure times. By comparing these data with the actual times, it is possible to calculate delays in arrival and departure.
- Train consist, i.e. type and length.

A TRENTO dataset contains the data from all of the approximately 5,500 journeys by NS trains that occur on an average working day, which equates to approximately 14.5 million stops per year (in 2019). Tables E.4, E.5, E.6 and E.7 in Appendix E show a sample of the TRENTO data used for this research.

Using the TRENTO arrival and departure times, it is possible to see not only when a train arrived and departed but also how long it remained at the platform. For stations with pedestrian sensors, this information is also available from the train detection data generated by the SMART sensors. Comparing the two sources reveals that they give slightly different arrival and departure times. This results in a difference of approximately 10% in calculated dwell time. The discrepancy stems from the different ways in which the two systems record arrivals and departures. In TRENTO, the trigger for an arrival is the moment at which the train occupies the platform track section. This occurs as soon as the train enters the section. Departures are recorded in an analogous fashion. TRENTO corrects these track-occupancy times for braking and acceleration, and for the position of the platform within the track section. This correction process generates a start and end time for the stop, from which the dwell time can be calculated. A SMART Station sensor registers the presence of a train in its measurement area. The start time is the time at which the train enters the measurement area and the end time is the time at which it leaves it. Like the TRENTO system, SMART Station records an occupancy time that is longer than the actual dwell time.

The differences between the two sources are small, and they are also consistent. Because calculations are carried out using the difference between arrival and departure time, it is reasonable to assume that the discrepancy between the arrival and departure times recorded by the two systems will have no effect on the results of this study.

4.1.4 Weather

Certain analyses made use of publicly-available weather data published by the KNMI (the Dutch meteorological office) [129], with data from each weather station aggregated over a full day. The data used were those that indicate the amount of precipitation, its duration and the number of hours of sun. The closest weather station to each railway station was identified using the latitude and longitude coordinates of railway and weather stations. Table F.1 in Appendix F lists the weather stations used to determine the weather conditions at each railway station.

4.2 Stations equipped with SMART Station

Figure 4.6 lists the stations equipped with SMART Station sensors and the periods for which they were in use at each station. Appendix D lists the sensor types used in each area of the stations concerned.

The first two thematic studies – on queues at escalators and pedestrians close to the platform edge – used data describing the positions of individuals on the platform. Only the latest generation of pedestrian sensors generates this type of trajectory data. Appendix D shows that during this research, that type of sensor was only in use at Utrecht Centraal, Amsterdam Zuid and Schiphol Airport. Because Schiphol Airport station serves an international airport, many railway passengers using the station have luggage with them. The trajectory data from Schiphol Airport was not used for the thematic studies in this thesis, as the sensors do not record luggage (see [27]) and the quantity of luggage varies during the course of a day (see [130]). Excluding Schiphol Airport ensured that the results could not be distorted by the presence of an unknown quantity of luggage.

For two of the three sub-topics in this thesis, trajectory data were therefore used that were generated by the SMART Station pedestrian sensors on platforms at Amsterdam Zuid [131] [132] and Utrecht Centraal [133]. These sensors were operational on both stations from March/April 2017. The trajectory data used for this study cover the period from April 2017 up to and including May 2018. This section explains the position of these stations in the Dutch railway network, the layout of the platforms and the measurement area covered by the sensors.

4.2.1 Amsterdam Zuid

In 2019, Amsterdam Zuid occupied seventh place in terms of passenger numbers per average weekday, handling approximately 70,000 passengers (boarders and alighters). The number of passengers using the station is increasing very rapidly: approximately 10–20% (year on year) between 2016 and 2019. 28 trains arrive at this station per hour, from Utrecht Centraal, Amersfoort and Almere Centrum to the east, and from Schiphol Airport and Leiden Centraal to the south-west. See Figure 4.7.

The two platforms at Amsterdam Zuid (see Figure 4.8) are approximately 9 m wide and are located on an embankment (at Level +1). The three entrances – Zuidplein, Mahlerplein and Parnassusweg – are at surface level. A subway (the Minervapassage) runs under the platforms near the lifts, linking the platforms to the Zuidplein and Mahlerplein entrances. During peak hours, some 80% of passengers use the Minervapassage to reach the platforms. The Parnassusweg entrance lies at the western end of the platform (the Schiphol/Leiden end) and forms a direct connection between the platform and the outside. During peak hours, some 20% of passengers use this entrance.

The following features of Amsterdam Zuid are relevant to this study:

1. The SMART Station sensors are set up to measure pedestrian flows at the escalators, as crowding regularly occurs at these locations. The measurement area covers the full width of the platform (9 m) and is approximately 30 m long. As

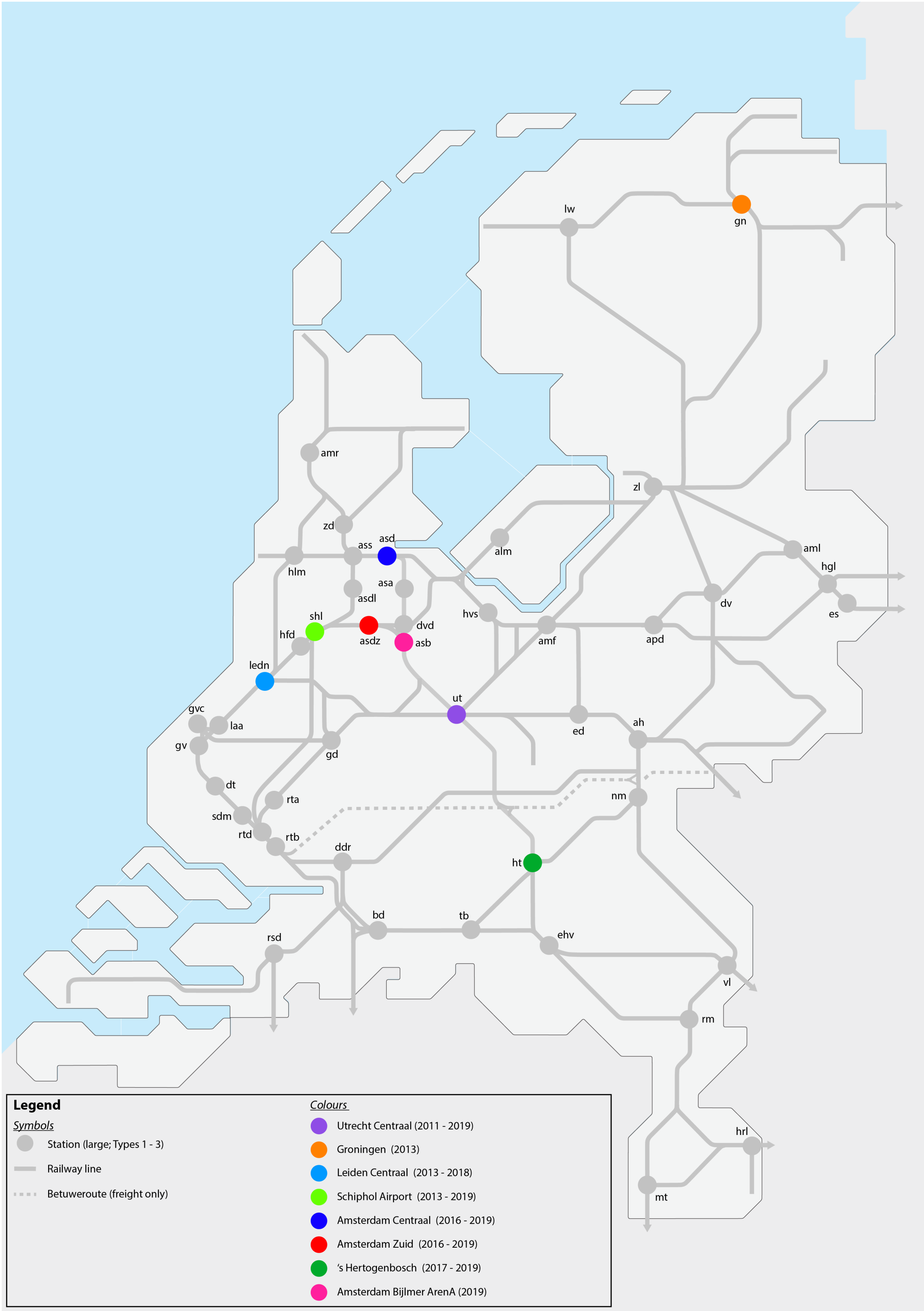


Figure 4.6: Stations in the Netherlands that were equipped with SMART Station between 2011 and 2019

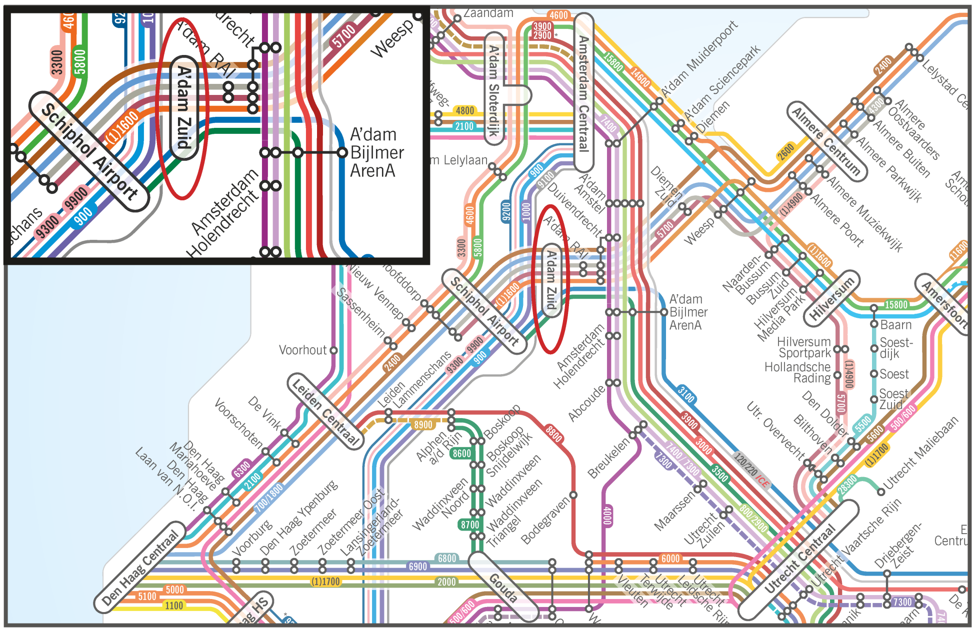


Figure 4.7: Amsterdam Zuid – position in rail network

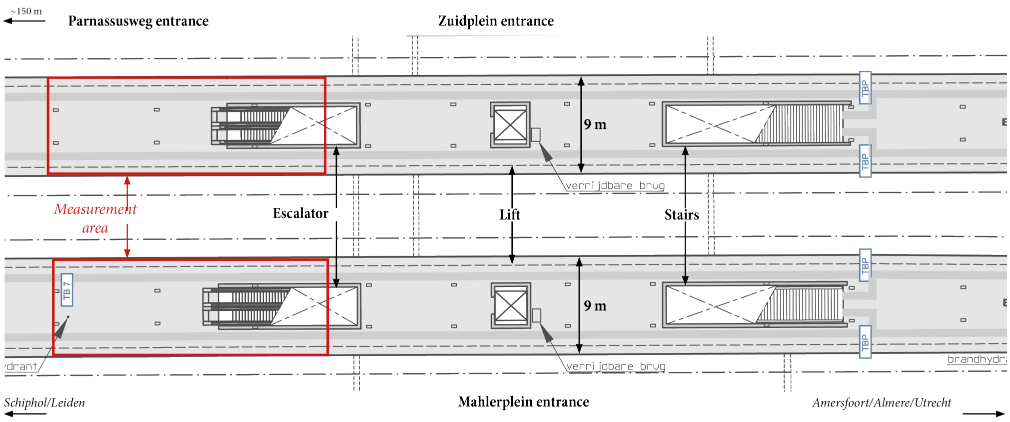


Figure 4.8: Amsterdam Zuid – plan view of platforms

a result, it also covers those areas of the platform between the escalators and the platform edge.

2. The platforms of this station are very heavily used [7]. A wide range of crowding levels therefore occurs, i.e. platforms are sometimes very busy and sometimes very quiet. This wide range of crowding levels leads one to expect a wide range of queues to occur.

3. There is an empty space approximately 20 m long leading up to each escalator (see Figure 4.9). The only items located in this space are a number of slender columns supporting the platform canopy, and a railing approximately 1.5 m long forming a divider between the two escalators of each up and down pair. As the columns are slender, one can expect them to have little effect on the shapes of

queues. The queue will therefore be determined primarily by passenger dynamics, rather than by platform layout. The divider at the escalators is a relevant feature, because it restricts the width of the queue over the first few metres of its length, as measured from the escalator.

4. The dimensions and layout of the two platforms are virtually identical in the areas surrounding the escalators. However, the stopping positions of trains relative to the escalators, and the numbers of passengers per train, are not the same on the two platforms. As a result, the passenger flows on the two platforms are different. This station therefore makes it possible to study two situations in parallel and compare the results.

5. All types of train – long or short – stop adjacent to the escalator.

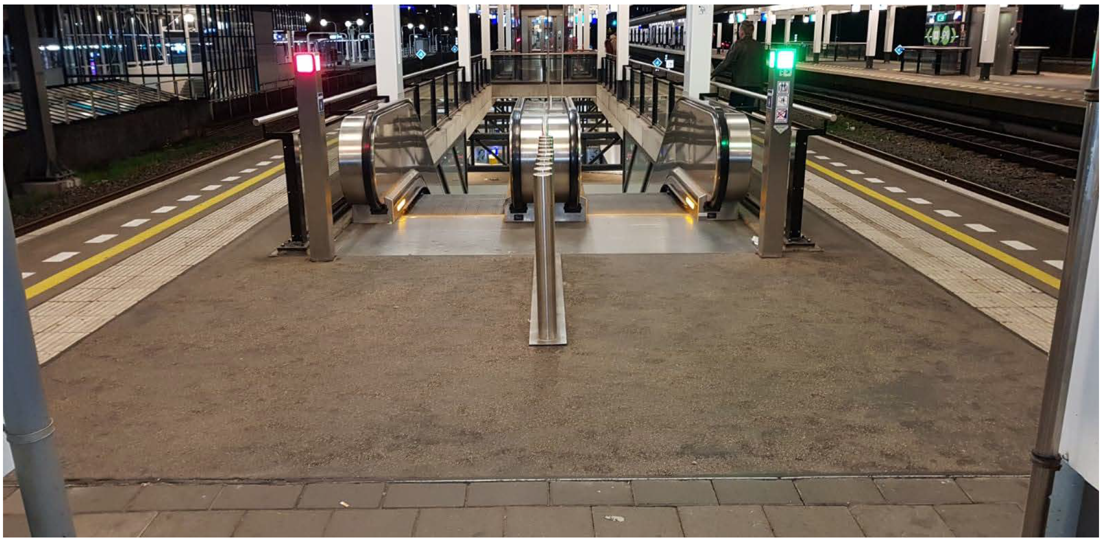


Figure 4.9: Amsterdam Zuid, Platform 3-4 – front view of escalator (Photo: Jeroen van den Heuvel)

4.2.2 Utrecht Centraal

In 2019, Utrecht Centraal occupied first place in terms of passenger numbers per average weekday, with approximately 205,000 passengers (boarders and alighters) arriving and departing via 16 platforms. The platform at Utrecht Centraal selected for this study (Platform 5, which occupies one side of an island platform) is one of the busiest in the station, handling over 20,000 passengers per average weekday; this corresponds to 10% of all passengers using Utrecht Centraal. The trains that stop at this platform come from the directions of Arnhem/Nijmegen and ’s-Hertogenbosch, and depart towards Amsterdam Centraal and Amsterdam Zuid/Schiphol Airport (see Figure A.1b). Five trains arrive at Platform 5 per hour: four domestic Intercity services and one ICE from Frankfurt via Arnhem, which continues to Amsterdam Centraal.

Figure 4.11a shows the layout of the platform. The platform is approximately 430 m long, making it long enough to accommodate a complete ICE consisting of two

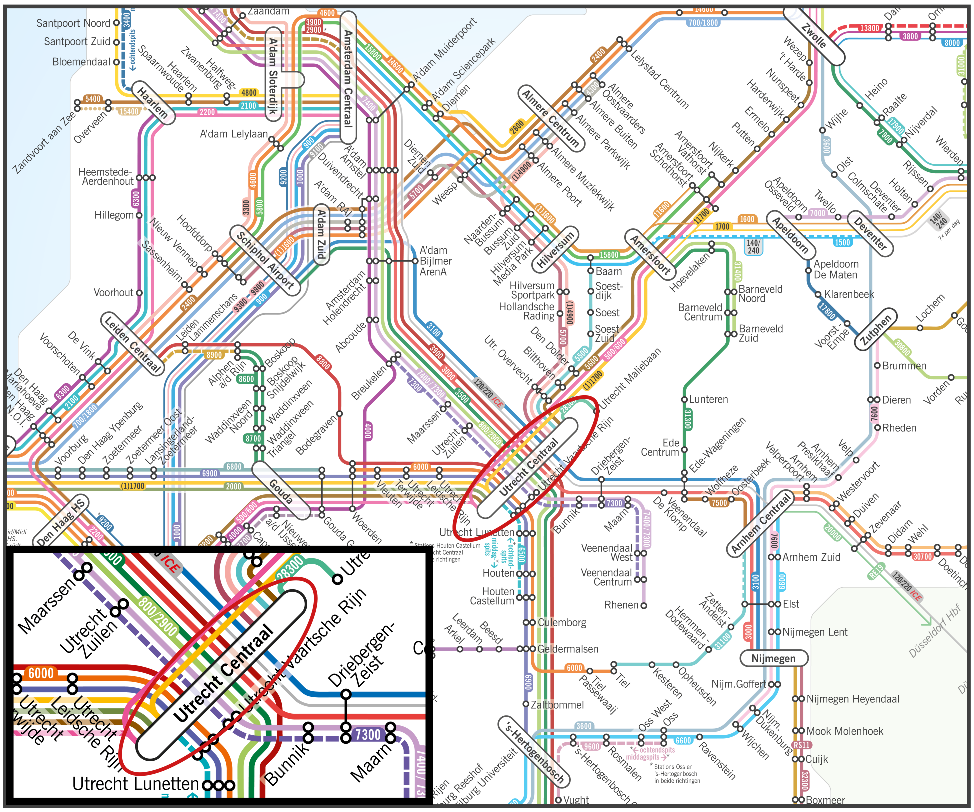


Figure 4.10: Utrecht Centraal – position in the rail network

train sets. Domestic train services at this platform are generally operated using VIRM double-decker stock. These trains can consist of 12 coaches, making them 330 m long, but in practice are generally much shorter: between 4 and 10 coaches (110 m to 270 m). The shortest, four-coach trains come to a halt entirely under the station concourse. Access to and egress from the platform is via one lift, two escalators and four sets of stairs. Two sets of stairs lead up to the concourse and two lead down to the two subways under the tracks. Those subways (the Noordertunnel and the Middentunnel) lead to station entrances. In practice, 70% of passengers use the stairs and escalators between the platform and the concourse. The following features of Utrecht Centraal are relevant to this study:

1. The platform is heavily used [5]. A wide range of crowding levels therefore occurs, i.e. the platform is sometimes very busy but there are often quieter periods similar to those that occur on less heavily-used stations.

2. As this platform is sufficiently wide along most of its length, all users can choose where they walk or stand. Concentrations of passengers are therefore the result of space and dimensions at specific platform sections in combination with the choices that pedestrians make – as individuals and collectively – and do not result from any general lack of space.

3. Because the platform becomes so crowded (see [5]), the pedestrian sensors are set up in such a way as to measure passenger flows over a considerable length of

the platform. Figure 4.11b shows a close-up of the measurement area indicated in Figure 4.11a. The measurement area is 125 m long and 3 m wide, covering the area between the platform entrances and the edge of the platform. This is the zone in which intensive crowding occurs; compare the photos in Figures 4.11d and 4.11c. This relatively long measurement area makes it possible to measure the distribution of passengers both along and across the platform. The measurement area along the platform edge covers a surface of approximately 375 m^2. The pedestrian flows in the floor fields at the stairs and escalators are also measured.

4. The entire platform – and hence also the measurement area – is under cover. Weather will therefore have much less effect on the walking and standing behaviour of passengers on this platform than would be expected at stations in the open air. This reduces the influence of factors external to this study that could affect the distribution of passengers on the platform and hence the results of analyses.

5. Trains stop at almost all points along the measurement area (see the blue line in Figure 4.11b).

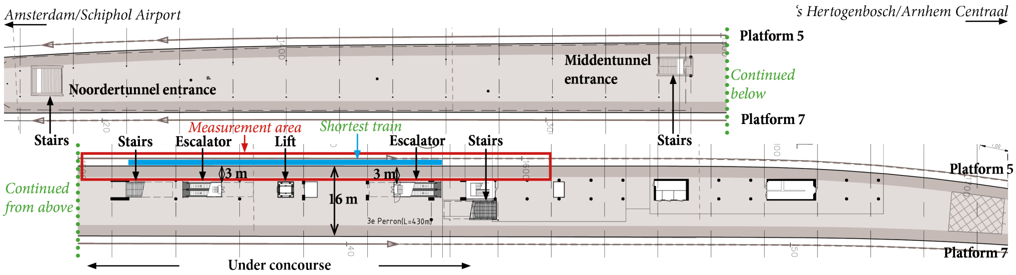
4.3 Preparation and enhancement of trajectory data

The aggregation level for the TRENTO and ROCKT data is the train stop, with combinations of train number and date forming unique identifiers. This is not the case for the SMART Station data describing pedestrian traffic on the platform. In preparation for this study, data subsets were extracted from the daily files for each measurement area and stop. Basis files were then created for this study by aggregating and supplementing those subsets. This section describes how this was achieved.

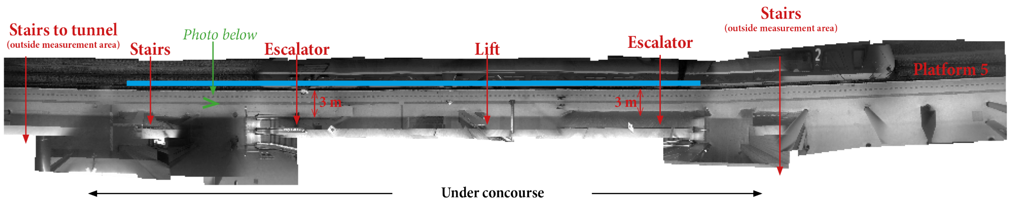
Table 4.1 below lists the types of pre-processing to which the trajectory data were subjected and the thematic studies for which each type of pre-processing was used.

Pre-processing	**Section**	**Queue**	**Platform edge**
Chapter	*4*	*5*	*6*
Datasets per stop	4.3.1	Yes	Yes
Position	4.3.2	Yes	Yes
Pedestrian type	4.3.3	Yes	No
Speed	4.3.4	Validation only	Yes
Distance from platform edge	4.3.5	Yes	Yes
Density	4.3.6	Weidmann	Fruin

Table 4.1: Preparation and enhancement of trajectory data



(a) Plan view of platform, showing layout



(b) Enlarged view of measurement area

(c) Empty platform, 10 November 2020, 06:44 hrs

(d) Full platform, 11 October 2018, 08:21 hrs

Figure 4.11: Situation at Utrecht Centraal, Platform 5 (Photos: Jeroen van den Heuvel)

4.3.1 Datasets per stop

The sensor data available for this study covered the period 1 March 2017 to 30 May 2018. Recording commenced on 1 March 2017 and data analysis for this thesis began on 30 May 2018.

The measurement data cover a period of over a year and three locations. As a result, there were several terabytes of raw trajectory data. To make it possible to process these data, separate files were created, each containing the trajectory data for one day on one platform. Each daily file contains approximately 1 to 2 GB of data in the form of 10 to 30 million lines, representing all trajectories in a specific measurement area on a specific date.

The volume of data was reduced by filtering on the time periods around the arrival and departure of trains, using the TRENTO data. For each train (identified by its train number), those data give the arrival time, departure time and platform number. Using these data, those trajectories were extracted from the daily files for each measurement area that lay between the arrival and departure times of an individual train. A margin was applied, to ensure that observations relevant to this study were not filtered out. The data was then saved, using a separate file for each unique treinID, which consisted of the date and the train number. Figure 4.12 shows this procedure in schematic form.

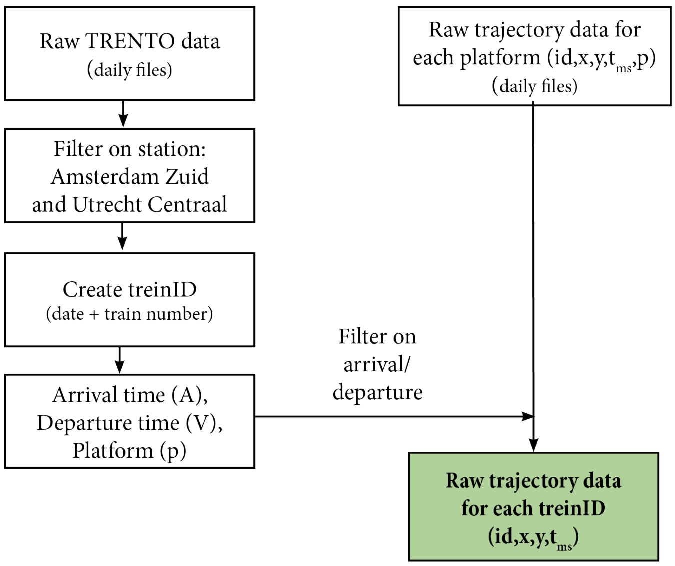


Figure 4.12: Trajectory data process for each stop

4.3.2 Positions of pedestrians

The pedestrian sensors on the stations at Amsterdam Zuid and Utrecht Centraal generate trajectory data giving the position of every pedestrian in the measurement area on a millimetre scale, at 0.1-second intervals. Figure 4.13 shows the example of Utrecht Centraal, Platform 5, before the arrival of Train 3024 on 6 April 2017. The dots show the positions of all pedestrians in the measurement area for one measurement, on x and y axes. To make the situation clearer, the points are superimposed on a photo taken by the sensor cameras.

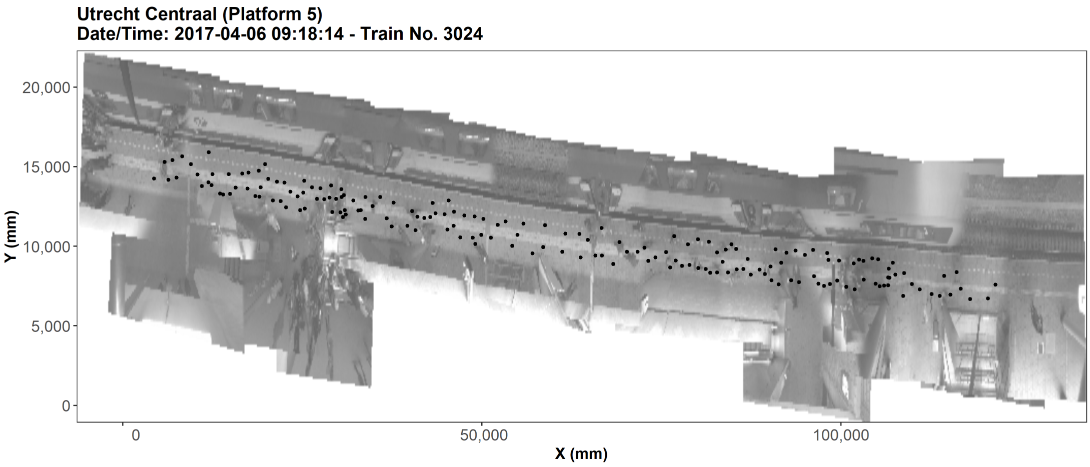


Figure 4.13: Graphical representation of trajectory data: example

Earlier research by Van den Heuvel et al. [27] has shown the error in measuring the positions of the pedestrians to be very small. However, this study did reveal a limited number of discontinuities in the unique i.d. numbers allocated to the pedestrians recorded. This can happen, for instance, where signs are installed in the sensor measurement zone, as the sensors are mounted higher than the signs. In such instances there will be a small gap in the measurement area, resulting in a pedestrian being allocated a new i.d. number.

The sensors do not measure the dimensions of the pedestrians. This means that one must take account of pedestrian dimensions when interpreting the data. This study uses data from research by Buchmüller and Weidmann [106]. Figure 4.14 is taken from that work and indicates that the researchers used a body ellipse of 50 cm x 60 cm. This means that in any given situation, the dimensions of a pedestrian depend on their orientation. However, the present research also involves observing stationary pedestrians, whose orientation is unknown. For this study, therefore, a 60 cm x 60 cm body ellipse (i.e. a circle) was used when interpreting the data and results. In certain cases, this can cause an interpretation error of approximately 5 cm. The perimeter of a stationary pedestrian facing along a line parallel to the edge of the platform is 5 cm closer to the platform edge than it would be if they were standing at the same point but facing along a line perpendicular to the platform edge. According to the data, however, the pedestrian is standing at the same location in both cases. As this error is of the same order of magnitude as the maximum measurement error for the position of the pedestrian, it has been assumed for the purposes of this study that the difference can safely be ignored.

To limit the quantity of data to be processed for this study, the pedestrian position data has been aggregated from the original level of 0.1 s to 1.0 s, by calculating the mean position of each pedestrian over a one-second period. Given the high degree of accuracy with which the sensors measure position (see Chapters 5 and 6), it is assumed that this aggregation will have no impact on the results of the present study.

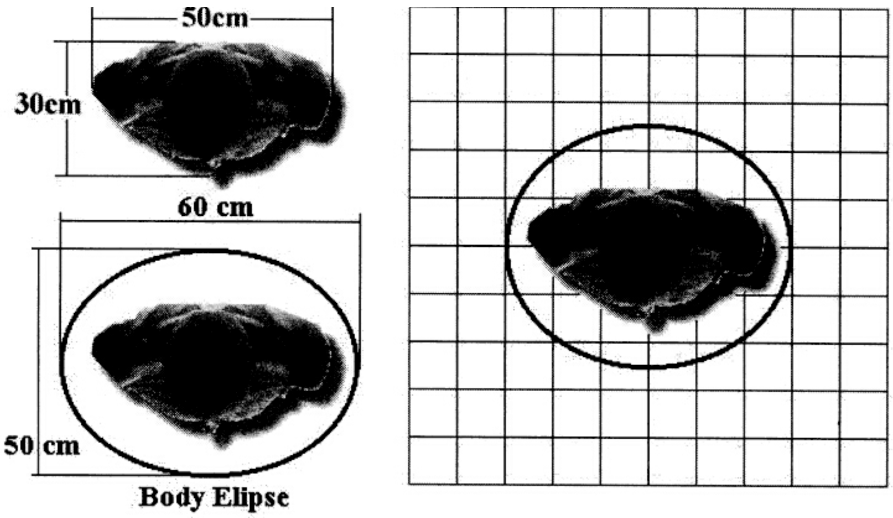


Figure 4.14: Dimensions of a pedestrian, based on Buchmüller and Helbing [106]

4.3.3 Types of pedestrian

For the sub-topic on queue formation at escalators (see Chapter 5), all pedestrians in a dataset were grouped by the locations within the measurement area at which they were recorded for the first time and for the last time. This processing was carried out for each escalator (see Figure 4.15 for an example taken from Platform 1-2 at Amsterdam Zuid).

The groups were as follows:

- **Outgoers** Pedestrians who were last recorded in the orange zone, or were only recorded in that zone. These are passengers who arrived by train and left the platform via the exit escalator (alighters).

- **Incomers** Pedestrians who were first recorded in the orange zone, or were only recorded in that zone. These are passengers who reached the platform via the arriving escalator and subsequently boarded the train (boarders).

- **Passers-by** Pedestrians who are first or last recorded in the red, green or blue zone, and are not recorded in the orange zone. The red zone is on the Platform 1 side, the green zone is on the Platform 2 side and the blue zone lies between the escalator and the Parnassusweg entrance. For these purposes, passers-by are passengers who walk between the areas of the platform located to the east and west of the measurement area. Most of these are either boarders coming from the Parnassusweg entrance or alighters walking towards it.

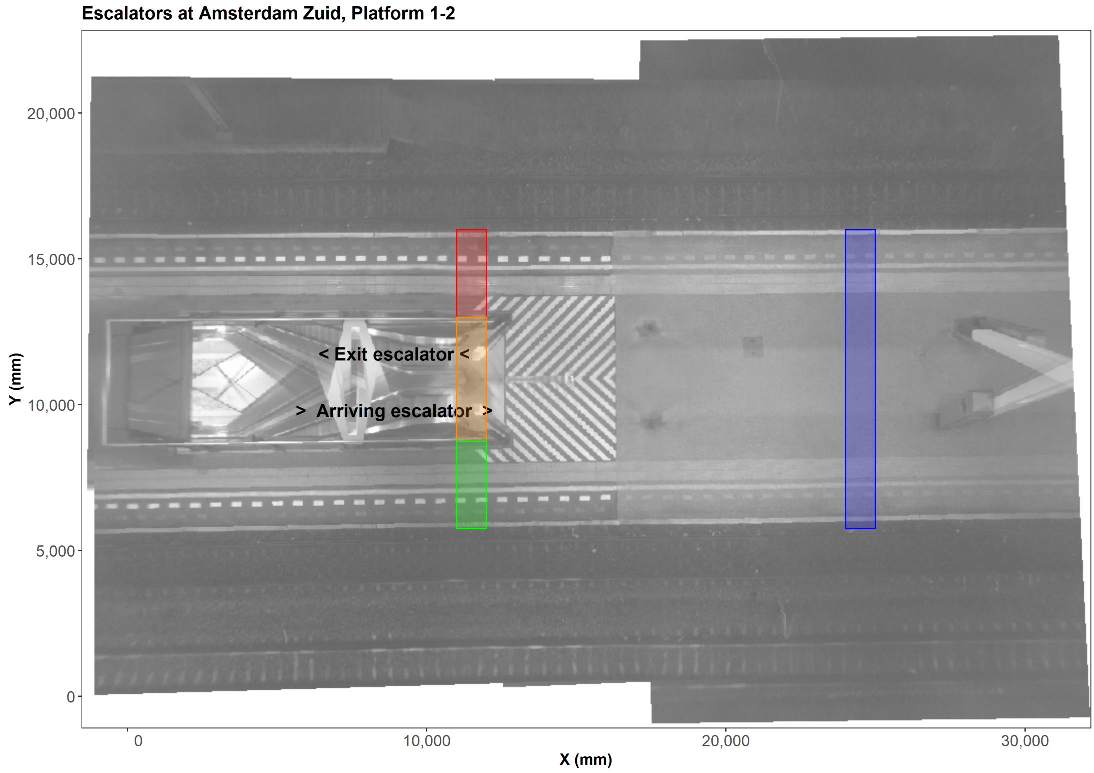


Figure 4.15: Floor fields used to assign pedestrians to groups

- **Others** All pedestrians who do not fit into one of the above categories. These include people who arrive on the platform via the arriving escalator and then leave it via the exit escalator (because they are on the wrong platform, or because they are meeting or saying goodbye to a passenger) and those who walk back and forth between the eastern and western areas of the platform (e.g. personnel). The data show that "Others" account for less than 1%. This group was not included in the study.

For the sub-topic on distance to platform edge (Chapter 6), a distinction has been made between passengers who were recorded in the buffer zone along the platform edge before the arrival of the train and those who were not.

4.3.4 Walking speed

For each pedestrian i, Equation 4.1 was used to calculate the instantaneous walking speed at time t (in hh:mm:ss), on the basis of the distance covered during the first observation (at hh:mm:00) and the last (at hh:mm:59) within each second.

$$v_{i;t} = \sqrt{\left(\frac{\Delta x_{i;t}}{\Delta t_t}\right)^2 + \left(\frac{\Delta y_{i;t}}{\Delta t_t}\right)^2} \tag{4.1}$$

4.3.5 Distance of pedestrians from platform edge

The distance between each pedestrian and the platform edge (or edges, in the case of Amsterdam Zuid) at any given moment is calculated from the coordinates of the platform edge (see Figure 4.16). Like the trajectory data, the coordinates are accurate to the nearest millimetre.

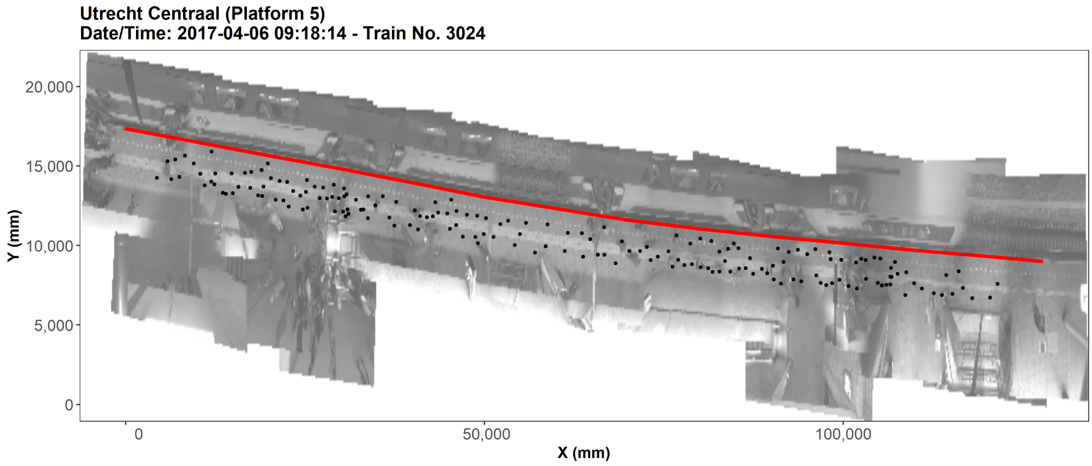


Figure 4.16: Graphical representation of trajectory data with platform edge: example

The distance d between each pedestrian i and the edge P of Platform sp at time t is given by Equation 4.2, where j represents the coordinates of the platform edge (x,y). This produces approximately 125,000 values for Utrecht Centraal (with a measurement area approximately 125 m long) and approximately 30,000 for each side of the platform at Amsterdam Zuid (with a measurement area approximately 30 m long).

$$d_{i;t} = \min_{j \in P_{sp}} \sqrt{(x_{i;t} - x_{P_{sp};j})^2 + (y_{i;t} - y_{P_{sp};j})^2} \tag{4.2}$$

4.3.6 Pedestrian density

Pedestrian crowding can be expressed in several ways. The classic method according to Fruin [36] calculates density by dividing the number of passengers in a floor field by the area of the field. This method requires the floor fields to be defined in advance, and generates a mean density for the floor field. The disadvantage of this method is that if the floor fields are large, with the pedestrians distributed unevenly, there will be large differences between mean density and the density in the vicinity of a given pedestrian and/or the density experienced by the pedestrians and to which they adapt their behaviour. If the floor fields are very small an allocation problem arises, because it is unclear to which floor field a given pedestrian should be allocated.

As an alternative to the classic method for determining density, Liddle et al. [134] propose a density calculation method based on a Voronoi diagram. This method uses the area available to each pedestrian, calculated from their position relative to other pedestrians. One major disadvantage of the Voronoi diagram is the manner in which pedestrians at the edge of the diagram are handled. Unless precautions are taken, pedestrians at the edges appear to have more space than they would have in practice, and density is underestimated at the edges. The researchers resolve this problem by placing virtual pedestrians outside the Voronoi diagram and by setting a maximum size for the cells within it.

In their overview article, Duives et al. [135] assess nine methods of quantifying pedestrian crowding. The researchers based their assessment on the quality of the fundamental diagrams that the various methods generated from a given empirical dataset. In so doing, they investigated not only traditional ways of expressing crowding in persons per *square* metre but also less common ways of expressing crowding, based on the distances between pedestrians in *linear* metres. According to the researchers, five of the nine methods reproduce empirical pedestrian crowding accurately. Of the measurements based on density (persons per square metre) these were the X-T method, the exponentially weighted distance method (see [136]) and the Voronoi diagram (see [134]). The only measure of crowding based on spacing (in linear metres) that gives good results is that which involves measuring minimum distance while taking account of the direction in which the pedestrian is facing. Quantitatively speaking, the X-T method and the Voronoi diagram produce the best results. The researchers therefore conclude that the the Voronoi diagram and the X-T method best reproduce the fundamental diagram. At the same time, they point out that each method has its advantages and disadvantages, and that there is no single "best" method.

The method using minimum distance between pedestrians while taking account of the direction in which each person is facing was rejected for this study, as the data available do not indicate the direction in which a pedestrian is facing. The density-based Voronoi diagram was rejected, as platforms have many edges. These include the platform edge, stairs, lifts, escalators, stairwells and obstacles. Those edges would render implementation of that method highly complex. Implementation of the X-T method is also technically complex. That method was therefore rejected. Two crowding measures were pre-selected for the sub-topics in the present thesis:

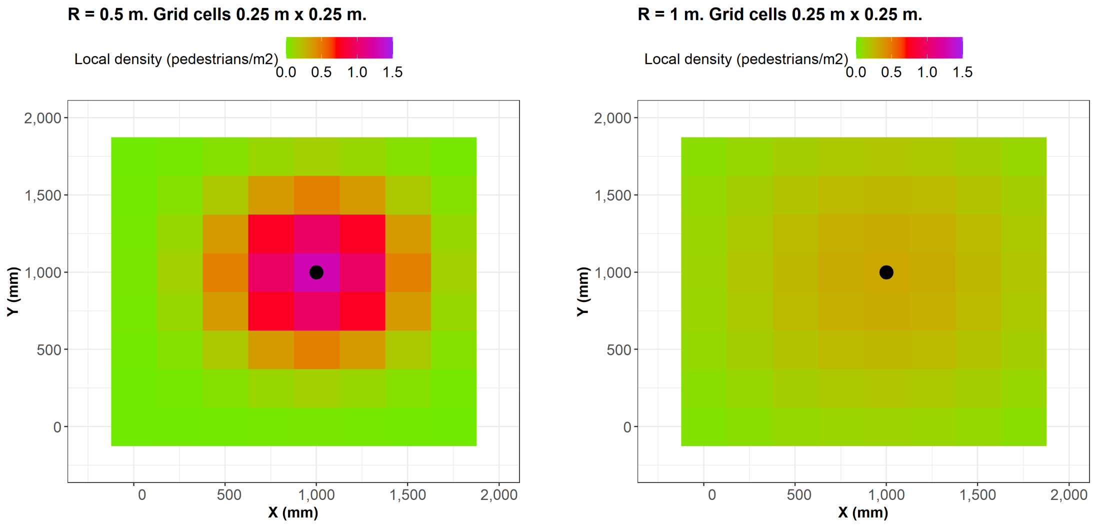
- **Classic density (Fruin)**. This method has two advantages. 1. It is easy to use and computing times are short, even with large numbers of pedestrians. 2. The "Fruin" density corresponds to that used in the standards applied in practice (see Chapter 3). This makes it possible to compare the results of this study with those standards. The most significant disadvantage of the classic density method is that the results depend on the size of the floor fields used. For the sub-topic in Chapter 6, this disadvantage was minimized by repeating the analyses with floor fields of various sizes.

- **The exponentially weighted distance method (the "Helbing" method)**. The greatest advantage of this method is that one does not need to know the shape of the floor fields in advance. This makes it possible to study situations in which the distribution of crowding or the shape of queues is not known in advance. The computing time required is a disadvantage, but that was overcome for the purposes of the present study by using a powerful PC. A further important disadvantage is that at low densities this method underestimates the density experienced by the pedestrian. For the sub-topic in Chapter 5, validation was performed to assess whether this would affect the results.

The classic density method results in a mean density for a floor field [36]. For a floor field vl at time t, density is calculated by dividing the number of pedestrians I in the floor field by the area A of the floor field (see Equation 4.3).

$$\rho_{t;vl} = \frac{I_{t;vl}}{A_{vl}} \tag{4.3}$$

The exponentially weighted distance method produces a local density [137] Local density for platform location $\vec{r} = (x, y)$ at time t is given by Equation 4.4, where $\vec{r}_i(t)$ is the position of pedestrian i within the measurement area. For each pedestrian i, this function applies a normal distribution to the relative distance between the pedestrian and a position on the platform $\vec{r}$ for which the local density $\rho_{t;vl}$ is calculated. The greater the distance between the pedestrian and the location for which the density is to be calculated, the smaller the contribution of that pedestrian to the density at that location. The local density for a given location $\vec{r}$ is derived from the sum of the density contributions of all pedestrians i in the measurement area.



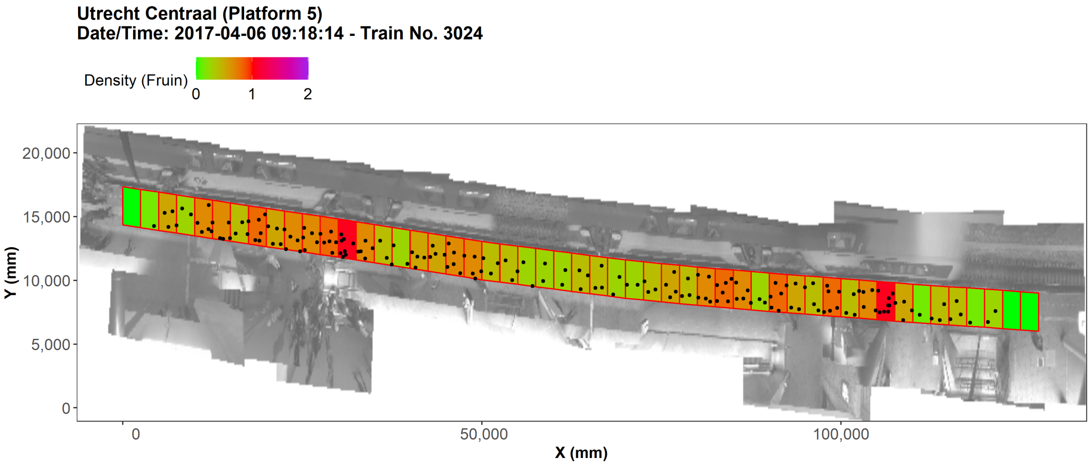
(a) R = 0.5 m (b) R = 1.0 m

Figure 4.17: Local density for one pedestrian at different values of scale factor R

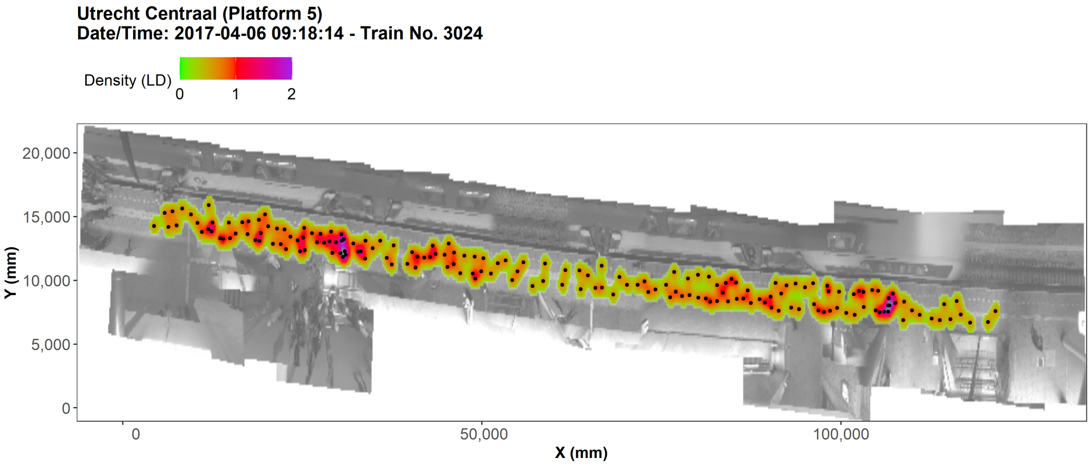
$$\rho(\vec{r}, t) = \Sigma \frac{e^{(-\|\vec{r}_i(t) - \vec{r}\|^2)}}{\pi R^2} \tag{4.4}$$

One of the important factors in this method is the scale parameter R, which determines the characteristics of the normal distribution (see Figure 4.17 for an example). The value of R is chosen on the basis of the purpose of the analysis and the granularity of the measurement area. On the basis of the work of Seitz [138] and Köster [136], a scale factor R of 0.7 m was applied when using the local density method to investigate queueing at escalators (see Chapter 5). A grid with cell dimensions of 0.25 m x 0.25 m was used.

To illustrate the differences, Figure 4.18 shows the results of applying the two methods to the data from Train 3024, 6 April 2017, Utrecht Centraal, Platform 5. For the classic density method, the measurement area was divided into segments of



(a) Fruin method



(b) Helbing method

Figure 4.18: Graphical representation of the dataset for Train 3024, 6 April 2017, Utrecht Centraal

2.5 m along the platform. Comparison of the two methods clearly shows that the Fruin method results in lower density peaks than the Helbing method. This is because the Fruin method averages local densities away over the whole floor field. Nonetheless, both methods show the same areas as being more crowded or less so.

4.4 Datasets

The following hypotheses were formulated in Chapter 3 on the basis of a literature study:

1. Chapter 5: As a result of queues forming at an exit escalator immediately following the arrival of a train, passengers stand or walk too close to the platform edge, and/or passengers in the queue for the exit escalator wait in the run-off from the incoming escalator.

2. Chapter 6: As a result of crowding on the platform, passengers stand or walk too close to the edge.

3. Chapter 7: As a result of the number of alighting and boarding passengers, the actual dwell times of trains exceed the time allowed for in the timetable.

The present chapter describes how the datasets for each stop that were used for this study were generated from the raw data. The periods for which each type of raw data was available were as follows:

- Trajectory data from sensors: 1 March 2017 to 30 May 2018.
- ROCKT data, based on OV-chipkaart and TRENTO data: 10 December 2017 to 8 December 2018.
- TRENTO data: 1 March 2017 to 8 December 2018.
- KNMI weather data: 10 December 2017 to 8 December 2018.

Table 4.2 lists the number of stops in the datasets used for each thematic study. These stops, or train arrivals, form the unit of observation for all the thematic studies in this thesis.

Station(s)	**Platform**	**Queue**	**Platform edge**	**Dwell time**
Chapter		*(Chapter 5)*	*(Chapter 6)*	*(Chapter 7)*
Amsterdam Zuid	1-2	5,995	3,732	
	3-4	10,082	6,314	
Utrecht Centraal	5	15,174	7,761	
297 stations	All	14,442,801	14,442,801	14,442,801

Table 4.2: Number of stops per sub-topic

Chapter 5

Escalator queues as obstacles

This chapter describes the results of research on the obstacles created by queues at escalators. In Chapter 3, this was identified as the first limitation on the service capacity of a platform (see Figure 5.1). This chapter focuses on the following hypothesis: *As a result of queues forming at an exit escalator immediately following the arrival of a train, passengers stand or walk too close to the platform edge, and/or passengers in the queue for the exit escalator wait in the run-off from the arriving escalator*

The literature study in this chapter indicates that we are more or less at the beginning of developing our knowledge of this domain. The present study will therefore attempt to establish aggregated relationships between crowding on the one hand and the size, width and obstacle effect of a queue on the other. This research uses the large quantity of trajectory data available for Amsterdam Zuid and Utrecht Centraal stations. From this study, it transpires that the number of persons in a queue is a good predictor of its size, but not its width. It is also concluded that the obstacle created by a queue causes passers-by to walk round it, and that if the queue is wide, they will walk close/too close to the platform edge. Queues for exit escalators regularly encroach on the run-off areas of arriving escalators.

The structure of this chapter is as follows: Section 5.1 gives an overview of existing research, examining definitions and classifications of queues, queue modelling and measurement and the effects of queues on traffic. On the basis of that overview, Section 5.2 sets out the definition of a queue that will be used for the present study. Section 5.3 describes the research methodology, defining and analysing the queue and rendering it measurable. Methodology, definition and analysis are then reviewed, to verify that together they generate valid results. Section 5.4 presents the results, discussing the size and width of queues, together with their role as an obstacle. The chapter ends with conclusions (Section 5.5), points for discussion (Section 5.6) and recommendations (Section 5.7).

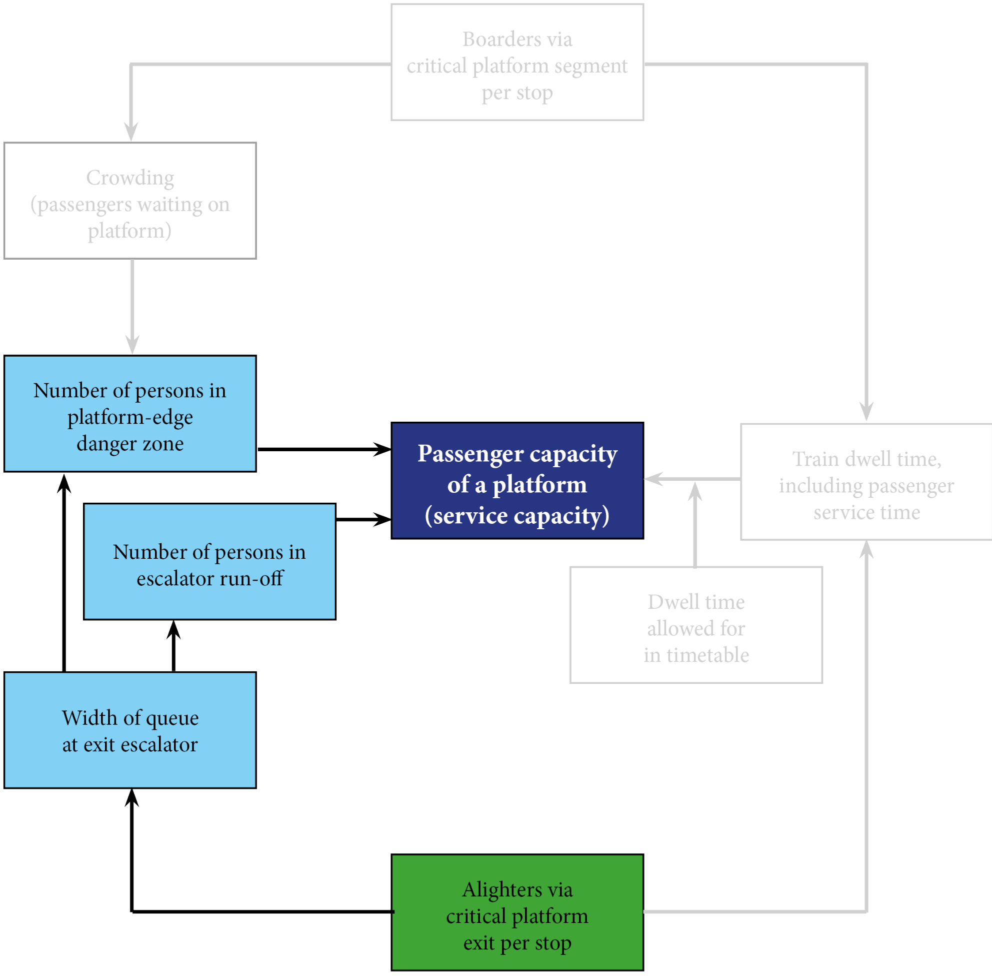


Figure 5.1: The topic in the context of platform capacity

5.1 Literature study

This section reviews the existing literature on queueing. Sub-section 5.1.1 provides an overview of definitions and classifications of queues. Sub-section 5.1.2 then describes various ways of measuring and modelling queues. The third and final sub-section (5.1.3) explains the consequences a queue can have for pedestrians who do not join it (the individual perspective) and for the functioning of the passenger network (a network perspective). Sub-section 5.1.4 concludes this section with a number of conclusions.

5.1.1 Definitions and classifications

Dictionaries give various definitions of a queue. For a queue of people, Merriam-Webster has ”*a waiting line especially of persons or vehicles*” [139]. The Cambridge Dictionary gives ”*a line of people, usually standing or in cars, waiting for something*” [140]. Oxford Dictionary: ”*a line or sequence of people or vehicles awaiting their turn to be attended to or to proceed*” [141]. According to all three of these definitions, a queue has (1) a spatial component (it forms a *line*), (2) a temporal component (*waiting*) and (3) a cause (*something* or *their turn*).

The first research on pedestrian queueing identified for this study dates from the 1960s. Mann [142] studied the sociological aspects of queueing for tickets at Australian Football games. He defines a queue as “a line of persons waiting in turn to be served, according to order of arrival.” This is the “first come, first served” principle, also known as a linear queue. Mann maintains that a queue forms “when a large number of people gather together and priority of service has value.”

In his 1970s standard work *Pedestrian Planning and Design* [36], Fruin defines a queue as any form of waiting undertaken by pedestrians at more or less the same place for a period of time. He distinguishes between two types of queue: the linear queue, in which pedestrians are served in a accordance with the “first come, first served” principle and the undisciplined or bulk queue, consisting of a mass of people. In the case of bulk queues, Fruin makes a further distinction between those with and without internal circulation. Queues with internal circulation incorporate sufficient space for pedestrians to move through them. Fruin cites the example of a metro or railway platform where passengers are waiting for their train. Queues without internal circulation – such as the queue for an escalator – do not have enough space for movement within them. Okazaki and Matsushita [143] divide queues into three categories. 1. Single linear queues, such as those for services in stations and shops. 2. Parallel linear queues, e.g. at entrances to platforms, theatres or museums. 3. Queues at the doors of vehicles, e.g. in front of lifts or at bus stops, or on a platform when a train arrives.

Fruin [36] does not go into detail regarding the size of queues for escalators. He refers his readers to classic queue theory as it has developed since the beginning of the 20th century. That theory focuses on three aspects of queue systems: 1. The time for which users must wait before reaching a server. 2. The number of people in the queue and/or in the system (total number of queues and servers). 3. The time for which a server is not used [144]. In this context, a “server” can be anything – a ticket window, a machine in a factory or (more recently) an internet node. Applications of queue theory to queues of people ignore the dynamics within the queue and the spatial structure around it. Classic queue theory almost always assumes one or more linear queues of constant density.

According to Helbing [145], however, this assumption of constant density is not valid for pedestrians. He ascribes the irregular density of a linear queue to the dynamic equilibrium between the desire to make progress and the desire to maintain a certain distance from the person in front. He suggests that the first factor becomes more important to an individual pedestrian as their waiting time increases. As a result, higher densities occur in the part of the queue closest to the bottleneck. However, Heibing provides no empirical evidence to support his claim.

In recent decades, the classic queue model has been expanded to include interaction between the people in the queue, in the work of Arita [146], Yanagisawa et al. [147] and Arita and Schadschneider [148] [149]. This interaction leads to variations in density over the length of the queue. But despite expanding to reflect interaction, classic queue theory as applied to pedestrians is still restricted to linear queues. As a result, it takes no account of variations in density over the width of the queue such as occur in bulk queues at escalators, etc.

Although her large-scale laboratory experiments involving a narrow opening focus on pedestrian dynamics in and immediately adjacent to the bottleneck, Daamen [105] gives a global account of what happens in the queue for this narrow opening. She observes that some people join the end of the queue, whereas others walk around and join the queue near the bottleneck, but does not quantify this phenomenon. Without going into further detail, Daamen mentions a number of factors that determine the length and width of a queue. In accordance with standard practice in classic queue theory, in later research she models queues at escalators in public transport nodes as single, first-in/first-out queues for servers. Where queues intrude into walking areas, Daamen takes the obstruction caused by the queue into account by including the persons waiting in calculations of level of service on the basis of pedestrian density in the walking area concerned. This research ignores the form of the queue, because of the macroscopic approach taken to queues at bottlenecks.

Kneidl [150] also mentions the relevance of queue shape. According to her, queues fulfil two conditions: 1. People are arriving at a rate higher than the capacity of the server (e.g. service point or bottleneck) to process them. 2. A semi-ordered queue forms, in which people do not push. Kneidl makes an explicit distinction between this and situations involving uncontrolled pushing or jostling. She states that queues can take a number of forms, and that the form of a queue for a bottleneck depends in part on the angle to the bottleneck from which people arrive at the queue. Kneidl goes into no further detail regarding the form of queues.

In their study on the capacity of escalators at London Underground stations [151], Davis and Dutta investigate the dynamics at the approaches to escalators. The researchers make a distinction between crush queues and orderly queues: Crush queues are wider and shorter, whereas orderly queues are longer and narrower. The researchers maintain that the shape of the queue is determined by the tendency of users to organize themselves *before* reaching the escalator in accordance with their intended behaviour once *on* it – standing (on the right) or walking (on the left). If there is sufficient space in the approach to the escalator, passengers organize themselves before reaching the run-on, and orderly queues form. If there is not enough space, passengers with the two different intentions are mixed together, and a crush queue is formed. This distinction between the two types of bulk queue is possibly less applicable to the situation in the Netherlands. While the British "Please stand on the right" principle is promoted at Dutch stations [152] [153], passengers would appear to be less inclined to follow it in the Netherlands than in the UK [154]. No research was identified on this point.

5.1.2 Measuring and modelling queues

Because the VISSIM microscopic simulation model – based on Helbing and Molnar's 1995 social force model – was unable to accurately reproduce linear queues for cinema tickets, Kim et al. [155] expanded the model to include a module for waiting processes at servers. The queues in question are of the ordered, linear type. Liao en Liu [156] extended a queue model originally developed for evacuation studies (the cellular automata model), to cover servers at urban transit stations such as ticket sales points and fare gates, plus nonpayment areas. In their case study, the model creates both straight and curved linear queues. Yanagisawa et al. [157] used a similar method to study the differences between various types of linear queue. They compared the mean waiting times in parallel and forked queues at servers, such as checkouts, vending machines and cash machines. Zheng et al. [158] studied the creation of linear queues in metro stations, at ticket windows and baggage inspections, using a microscopic simulation model. The idea behind their work is that a queue is dynamic, its characteristics being determined by the preferences of those waiting and the form and length of the queue.

Berrou et al. [159] claim that microscopic models should be ideal for predicting queue shape. In particular, they mention situations with densities of more than 1.5 to 2 persons per square metre, such as queues for stairs and escalators. Fundamental diagrams showing the macroscopic relation between flow and density underestimate density. This implies that a macroscopic approach will over-estimate the size of a queue. At the same time, the researchers state that it is not possible to improve the microscopic models owing to a lack of empirical data. Schadschneider and Seyfried [160] come to the same conclusion.

In their model of the behaviour of agents in high-density situations, Pelechano et al. [161] reproduce a realistic queue shape at bottlenecks by assigning to the agents specific parameters that apply when an agent has to wait in a high-density situation. They do not go into further details regarding those parameters, and nor do they explain how they compared those parameters and/or the results of the model with empirical data.

In their study on the modelling of queue formation at bottlenecks, Köster and Zönnchen [162] state that most microscopic pedestrian models generate mushroom-shaped queues at bottlenecks (see [138] for example). This is the result of a high level of competition between the agents in the model, with large numbers of them attempting to reach the bottleneck (and hence the front of the queue) by pushing or creeping past others. On the basis of research by Liddle et al. [134] and Dietrich and Köster [163], the researchers maintain that self-organized queues are often cone-shaped. In their model, Köster and Zönnchen reproduce cone-shaped queues by assigning cooperative, rather than competitive behaviour to the agents, and modifying the utility function of the queue model. In later research [164] Köster and Zönnchen distinguish between controlled and self-organized queues, and between queues with and without spatial constraints. In their model, they assign an explicit cooperative or competitive behaviour parameter to the agents. The most representative queue forms (i.e. cone-shaped) were obtained when the agents alternated between cooperative and competitive behaviour, sometimes joining the back of the queue but sometimes attempting to get ahead of others.

(a) Mushroom [138] (b) Cone [163]

Figure 5.2: Forms of queues in pedestrian models

5.1.3 Consequences of queues

Queues do not only affect those in them and the service for which they are waiting. They can also have consequences for pedestrians who do not wish to use the service for which the queue has formed. In the context of traffic management, these consequences are sometimes referred to as “spillback effects” [37].

The UK’s *Rail Safety and Standards Board* [39] states that escalators are one of the most hazardous locations on a railway station. A queue in the run-on of one escalator forming an obstacle in the run-off of an escalator moving in the opposite direction is one of the hazards. The RSSB publication does not investigate the underlying dynamics involved, and nor does it make any connection with accident statistics. Working on the basis of an analysis performed using Transport for London’s *Pedestrian Environment Review System*, Cynk et al. [65] have established that conflicting passenger flows near platform entrances (which often take the form of stairs or escalators) are among the factors that most often lead to hazardous situations. They mention the dangers that occur when queueing and obstruction of flows cause pushing and/or queueing towards the platform edge. Like the RSSB study, this study does not investigate the underlying dynamics. Yamada et al. [54] mention these risks, but state explicitly that they fall outside the scope of their study.

A study conducted at Amsterdam Centraal [82] found that after crowded trains arrive, the queues for some escalators can occupy almost the full width of the platform. The researchers noted that queues can prevent passengers from passing the queue for a crowded exit to access the next one. In research conducted at Utrecht Centraal, Van den Heuvel et al. [123] and Voskamp [23] show that a certain percentage of passengers are prepared to walk to the next exit. This percentage increases with the waiting time for the preferred route. Davis and Dutta observed the same effect on the London Underground [151].

5.1.4 Conclusions

In this study, queueing on platforms at escalators and stairs is seen as a consequence of limited platform exit capacity in combination with the nature of the arrival process, in which trains deliver large numbers of passengers to a platform in a short space of time. These are clearly what Fruin refers to as bulk queues [36]. However, most existing research focuses on ordered queues, such as those for sales processes. Even the definitions in widely-used dictionaries use the word “line” to describe a queue.

The limited research on bulk queues that was identified during this literature study uses microscopic pedestrian models. It is known, however, that these models are not yet capable of accurately simulating queues at bottlenecks such as escalators. Many models generate mushroom-shaped queues, whereas in reality, the queues are cone-shaped. In one single instance, researchers carried out qualitative validation, to discover whether the form of queue in the model corresponded to reality. A number of researchers have cited a lack of empirical data as one of the barriers to better describing bulk queues.

Existing research on railway stations focuses primarily on the side-effects of queues at platform entrances, especially escalators. The hazards that result from these spillback effects are cited in the standards of various countries (see Chapter 3), but with no empirical background. Recent research on the route choice behaviour of passengers at stations has also shown that some passengers have to walk round the queue at a particular platform exit. That research does not look at whether passengers are prepared to enter the zone along the edge of the platform to achieve this and if so, to what extent.

It is therefore apparent that we are more or less at the beginning of research into the form of bulk queues at escalators on railway platforms. The remainder of the present chapter will focus on the systematic, quantitative study of this type of queue and the extent to which such queueing causes obstacles on the platform. To achieve this, it is first necessary to find ways of measuring queues. The next section will formulate a definition, on the basis of the literature.

5.2 Definition and conceptual model

On the basis of the literature study, it will be assumed for the purposes of this thesis that a queue meets the following criteria:

1. It is caused by a flow of passengers which, for a limited period, exceeds the capacity of a bottleneck (e.g. an escalator). As a result, passengers wishing to move through the bottleneck must await their turn (see [35], [140], [144] and [150]). The arrival of more passengers than can immediately be discharged is a common occurrence at stations, as trains deposit large numbers of passengers on the platforms at the same time (see [36], [112] and [151]). This means that queueing at stairs and escalators serving as platform exits can be linked to the arrival of trains at the platform (i.e. there is a causal link).

2. The queue consists of more than one pedestrian, and there is interaction between the pedestrians. This follows automatically from the preceding point, and is analogous, at least in part, to definitions of the term “crowd” found in other research on pedestrian traffic. See for instance [137] and [165].

3. The queue is unordered and non-linear (see [36], [105], [134], [150], [162] and [164]).

4. For a certain uninterrupted period, the queue is sited at a specific geometric location, upstream of an escalator (see [36], [151], [162] and [164]). This means

that there is a more or less continuous pedestrian load in the area where the queue occurs.

5. The queue forms an obstacle for pedestrians, including those who do not wish to use the escalator at which it has formed (see [39], [65] and [82]). In line with Fruin's levels of service, internal circulation within the queue is not possible, because of the high density of pedestrians [36]. Pedestrians wishing to get past the queue must walk round it.

On the basis of the above definition, it is possible to say where on the platform a queue has formed in the vicinity of an escalator, from which train the passengers come (using its ID as a unit of observation) and at what moment this happens (i.e. what the trigger was). We also know how many people are in the queue and what conditions they experience (e.g. density and duration). This involves the following concepts:

1. The number of persons in the queue (n).
2. The size of the queue, expressed as the area it occupies (a).
3. The mean density of the queue, expressed as the ratio between the number of persons in the queue and its size ($\bar{\rho}$)
4. The width of the queue (b), measured towards the edge of the platform (b_1) and the run-off from the arriving escalator (b_2).
5. The distance from the platform edge of:
   (a) People passing the queue
   (b) People in the queue
6. People in the queue who are standing in the run-off of the arriving escalator
7. The walking speed of each person (v)

The conceptual model in Figure 5.3 shows the relationships between the concepts, together with the following research questions:

1. To what extent does the size of a queue at an exit escalator increase with the number of people in the queue?
2. To what extent does the width of a queue at an exit escalator increase with the size of the queue?
3. Does the obstacle formed by the broader queue lead to any or all of the following?
   (a) People in the queue stand too close to the platform edge.
   (b) People in the queue stand in the run-off from the arriving escalator.
   (c) People wishing to get past the queue walk too close to the platform edge.

Previous research does not enable one to express a quantified expectation regarding the answer to any of these questions in advance.

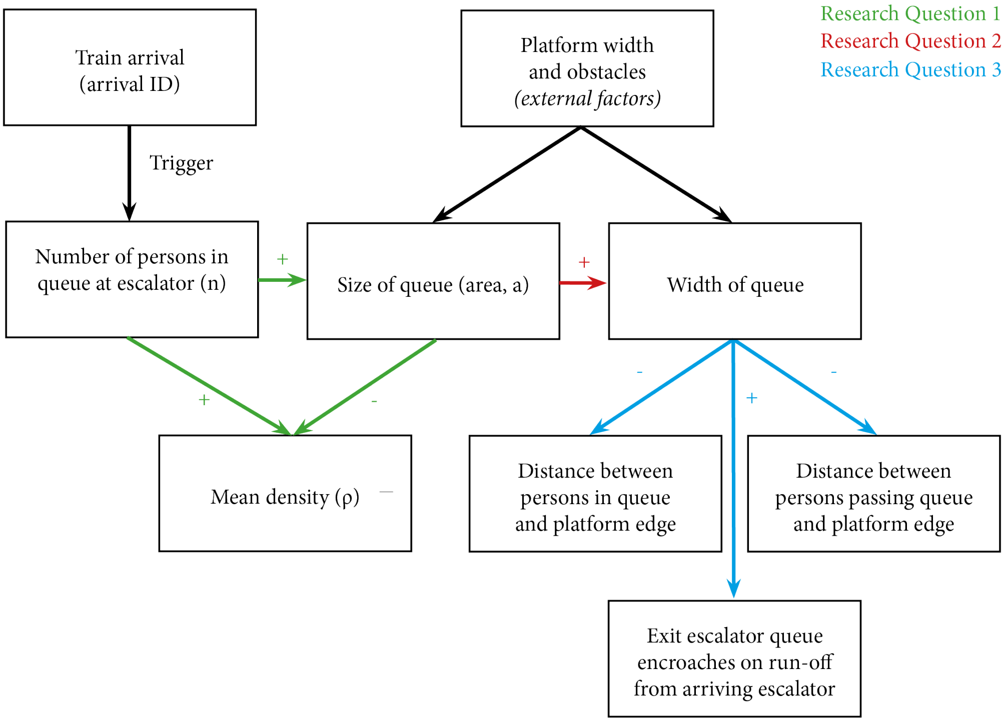


Figure 5.3: Conceptual model

5.3 Research methodology

The conceptual model describes the relationships between the number of persons in a queue at an escalator, the size and width of the queue and the acts of waiting and walking close to the platform edge as a result of the queue. No quantitative information regarding these relationships was found in any existing research. The present study will therefore investigate the aggregated relationships between these factors. The dataset used for this study contains trajectory data at the microscopic level, making it possible to study queues at any aggregation level. The datasets are large (see Section 4.4), describing pedestrian flows for thousands of situations in the measurement area immediately following train arrivals, including the formation of queues at escalators. Comparing these queues in a systematic manner makes it possible to answer the three research questions and to quantify the corresponding relationships. The analysis methodology and data will be explained in the following sub-sections.

5.3.1 Cases and data

Measuring data from Utrecht Centraal and Amsterdam Zuid were suitable for this part of the study. Those data describe pedestrian flows for two escalators on one platform in the case of Utrecht Centraal and two escalators on two platforms at Amsterdam Zuid. The measurement areas for all four escalators (i.e. at both stations) were large enough to measure the entire queue. There are three important differences between the situation at Amsterdam Zuid and that at Utrecht Centraal, which are seen as external factors with respect to this study, and which have been taken into account in interpreting the results.

- At Amsterdam Zuid, there is a divider on the platform between the arriving and exit escalators (see Sub-section 4.2.1). This limits the extent to which the queue for the exit escalator can expand sideways into the run-off from the arriving escalator. The platform at Utrecht Centraal does not have a divider.

- The run-ons for both escalators at Utrecht Centraal are limited by the adjacent stairs. The passenger flows from both sides of the platform towards the escalator therefore take the form of S-curves. At Amsterdam Zuid, the approach to both escalators is virtually obstacle-free, so the passenger flows from both sides of the platform constitute straight lines.

- The Platform 5 side of the platform island at Utrecht Centraal is approximately 0.5 m wider than the platforms at Amsterdam Zuid.

Section 4.4 describes the data available for this part of the study. The table below lists the subset of that data that was actually used. This dataset includes only those train arrivals that resulted in a queue in at least one grid cell. See Section 4.3.6 for more information.

Station	**Plat.**	**Escalator**	**n**
Amsterdam Zuid	1-2	West	5,902
	3-4	West	10,052
Utrecht Centraal	5	North	13,681
		South	12,115

Table 5.1: Number of observations (arrivals, n) per case

5.3.2 Analysis method

The research questions were answered using regression analysis. This method is ideally suited, both because of the large quantity of data per case and because of the aim, which was to study the development of queues at an aggregated level, where the queue is dependent on the number of people in it. To verify the validity of the results, the following tests were applied [166] [167]:

1. There is a relationship between the independent variable – the number of persons in the queue (n_{ID}) per arrival (ID) and the dependent variable Y, which in the case of this study was the area of the queue (a) and its width (b).

2. The dependent variable Y – the area (a) or width (b) of the queue – is a continuous variable.

3. The observations in the dataset are independent of each other. In other words, there is no statistical relationship between queues A and B in the dataset to which the regression is being applied. If that were to be the case, autocorrelation would occur and the regression analysis would give a distorted picture.

4. The residuals (estimates of ε) are normally distributed and display the same variation for all independent values.

Two types of linear regression were used for this study. The first was standard linear regression as per Equation 5.1, in which the relationship between the dependent variable Y and the independent variable n is linear (β_1 constant). As no queue can form in the absence of persons, constant β_0 is assumed to be 0. The second type of regression is a transformed variant, in which both the dependent variable Y and the independent variable n are transformed using a natural logarithm (see Equation 5.2). The reason for using this transformation is that a dimension might increase more slowly as the independent variable increases (see Figure 5.4). Because of this transformation, β_0 in Equation 5.2 takes the value e^0 (=1).

$$Y_{ID} = \beta_0 + \beta_1 n_{ID} + \varepsilon_{ID} \tag{5.1}$$

$$Y_{ID} = \beta_0 {n_{ID}}^{\beta_1} + \varepsilon_{ID} \tag{5.2}$$

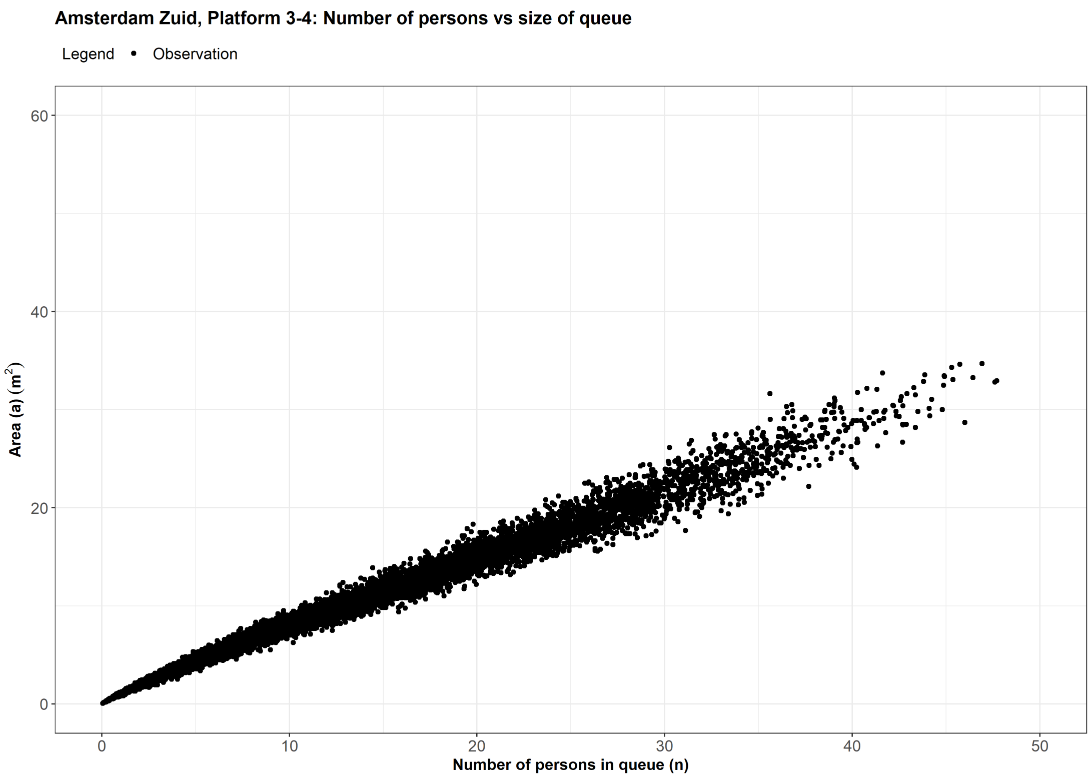


Figure 5.4: Scatter plot of queues at Amsterdam Zuid, Platform 3-4

This study uses the value and significance of β_1, together with the goodness of fit, to verify compliance with the first criterion. A low value for β_1 indicates that the independent variable has little influence on the dependent variable. In such a case, the number of people in the queue would not be relevant to its characteristics. If the estimated value of β_1 is not significant, it is not possible to use regression analysis to determine the effect on the dependent variable. In such a case, an independent variable not included in the model may be playing a role, or else not all conditions for the use of linear regression have been met. Goodness of fit is assessed by visual inspection of the scatter plot on which the regression line is drawn. In addition, the mean absolute error (MAE) is taken into account. This is the mean difference between the predicted and observed values of the independent variable, obtained by summing the differences recorded for each observation and dividing this total by the number of observations. The smaller the MAE, the better the estimated regression function matches the empirical data.

To find out where and when a queue is present following the arrival of a train, the relevant part of the measurement area is divided into segments, in the form of a grid. Small segments were used for the present study, to ensure that the dependent variable is approximately continuous (Criterion 2). For this study, we wish to know whether a queue at an escalator forms an obstacle for other pedestrians. Pedestrian density was therefore chosen as an indicator of the degree to which it is possible to walk through a queue. Because density must be determined for small segments, and the shape of the queue is not known in advance, pedestrian density was determined using Helbing's method (see Sub-section 4.3.6). As in Helbing et al. [137] and Köster and Zönnchen [162], a grid of 25 cm by 25 cm cells was used.

A poor fit (see Criterion 1) may be the result of the stochastic nature of queue formation. Real-life queues look similar but are never identical, because pedestrians do not stand in exactly the same positions at the same instant during the creation and dispersion of two queues. The smaller the segments used for analysis, the greater the risk that any relationships will be hidden by variability in the development of the queue. For the present study, this was resolved by repeating the regression analysis with an aggregate of the dependent variable if the fit obtained by regression analysis with the disaggregated data was too poor. The grid remained constant for the aggregation.

In accordance with the first criterion in the definition of a queue (see Section 5.2), a queue will first grow following the arrival of a train (if enough passengers alight) and will then shrink. As a result, queues are similar to each other at the various points in time during which alighting passengers are being processed, and from a methodological point of view the datasets for each arrival must be seen as time sequences. This can lead to autocorrelation, because the form of a queue at time $t+x$ depends on the form of the same queue at time t. The duration of the correlation (x) is not known beforehand, because it is the queue formation process itself that is being studied. The author's qualitative observations on site indicate that one cannot exclude the possibility of correlation between queue shapes linked to a given train arrival lasting for an extended period, i.e. the possibility that x is large. To verify compliance with Criterion 3, one single moment at which a queue occurred was selected for each arrival. To maximize the variation in queue size within the sample, the instant was selected at which each queue was at its largest, i.e. comprised the largest number of exiting passengers. If this maximum size was attained at more than one instant, one of those instants was selected at random.

Finally, to verify compliance with Criterion 4, each regression model was examined to see whether the residuals were normally distributed. This verification was conducted by means of the widely-used Shapiro-Wilk test of normality [166]. Because of the large number of observations for each case, this test was not applied to the entire dataset for each case in a single operation. The reason for this is that with very large samples, this test – like many other statistical tests – becomes sensitive to small numbers of observations that cause a deviation from normal distribution. With smaller samples, such a deviation would not result in rejection of the null hypothesis. To avoid this problem, the Shapiro-Wilk test was applied to a random sample of 500 observations taken from the dataset. In selecting observations for this sample, weighting was used to ensure that all values of the independent variable were equally represented. This procedure was repeated 500 times for each dataset, following which the mean significance parameter $\bar{p}$ was calculated. The residuals are deemed to be normally distributed if $\bar{p}$ is greater than 0.05 (= 95% significance).

Figure 5.4 gives a first indication that the residuals of a regression model do not have the same variation (Criteria 4). The scatter plot appears to become broader as the number of persons in the queue increases. This problem was resolved by applying a weighting to the regression in accordance with Equation 5.3. The weighting factors ω_n were determined using a linear regression with the absolute values of the residuals of the dependent variable as the dependent variable, and the estimated values of the dependent variable as the independent variable [167]. Because weighting factors were used, and bearing in mind Criterion 1, it should be pointed out that the widely-used coefficient of determination (*adjusted*) R^2 was not used to measure the fit of the regression line. The reason for this is that when weighting factors are used, the coefficient of determination does not give a valid measure of fit.

$$\omega_n = \frac{1}{\sigma_i^2} \tag{5.3}$$

5.3.3 Queue boundaries

For each stop in the dataset, those cells in the measurement area were identified in which queueing was occurring at any given time (see Figure 5.5).

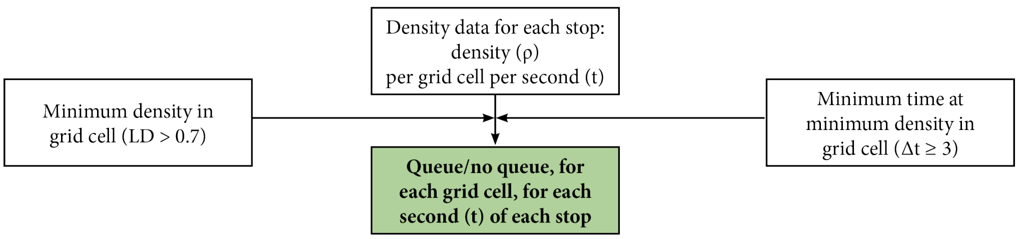


Figure 5.5: Application of the definition of a queue to each grid cell for each second of each stop

To verify compliance with the fourth and fifth criteria in the definition of a queue (see Section 5.2), an assessment was made as to whether each grid cell fulfilled the following two conditions:

1. Density is greater than 0.7 pedestrians per square metre. This determines whether or not it is possible to walk through the queue, and corresponds to the lower of the values found in the following two sources:

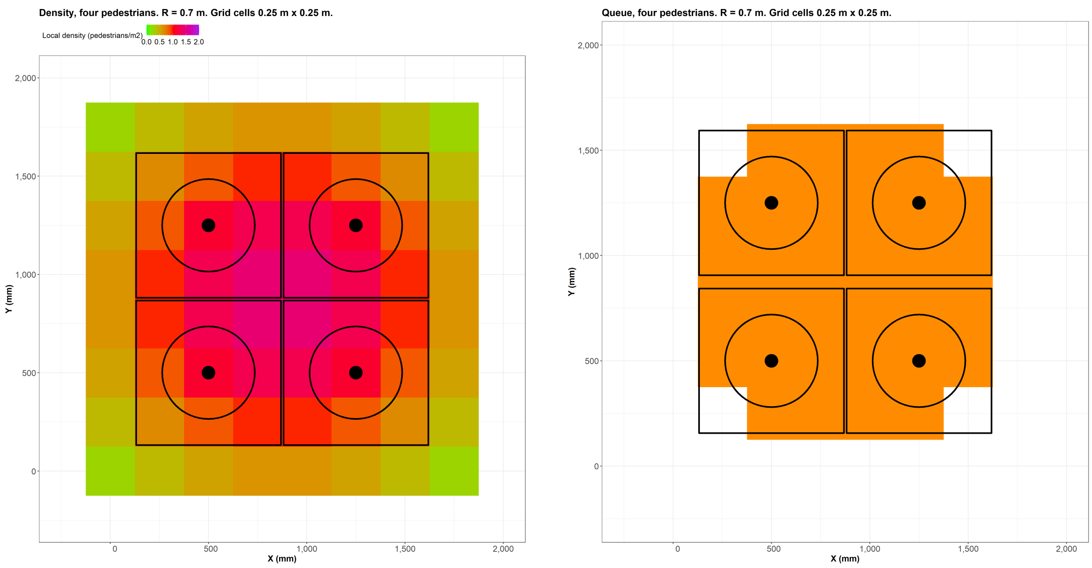
   (a) For each level of service, Fruin [36] describes the nature of pedestrian flow that will occur along a walkway. According to Fruin, fluid flow still occurs at LOS C, but cross and reverse flows are difficult. From LOS D onwards, the number of conflicts with other pedestrians is so great that fluid flow and cross and reverse flows are virtually impossible. The boundary between LOS C and LOS D lies at 15 square feet per person, which equates to 0.7 persons per square metre.

   (b) According to Weidmann's LOS concept, the transition between being able and unable to cross a pedestrian flow occurs between LOS E and LOS F [96]. This equates to 0.75 pedestrians per square metre.

2. The density per grid cell exceeds the limit of 0.7 pedestrians per square metre for 3 consecutive seconds or more. The author's qualitative observations indicate that pedestrians who wish to pass or join the queue begin to anticipate its development as they approach. The criterion of 3 consecutive seconds takes account of this potential anticipation. The thought behind this is that both Fruin's and Weidmann's levels of service indicate that if a high level of density lasts for more than 3 seconds at a given location, internal circulation will not be possible. If density only reaches high levels for short periods at one location, one cannot exclude the possibility that internal circulation may occur. Under those circumstances, it is also possible that a group of pedestrians passes through the measurement area.

As in Köster and Zönnchen's research on queues at bottlenecks [162], grid cell dimensions of 0.25 m by 0.25 m were used, and a value of 0.7 m was used for the scale parameter R in Equation 4.4. The figure below (Figure 5.6) shows the results of using these values in combination with the first condition mentioned above, with four pedestrians in the measurement area. Pedestrians are indicated as circles with a diameter of 0.6 m. The 1.2 m by 1.2 m square shows the area per person at a density of 0.7 persons per square metre. Figure 5.6a shows density and Figure 5.6b shows the grid cells in which queueing is occurring, with "queueing" defined as a density of 0.7 persons per square metre or greater. The second figure shows clearly that the combination of the chosen grid cell dimensions, the scale parameter R and the choice of density criterion accurately reproduces the cells in which queueing occurs.

As an example, Figure 5.7 shows the development of a queue following the arrival of Train 1827 at Amsterdam Zuid on 3 March 2017, on the basis of the above parameters.



(a) Density (b) Queue

Figure 5.6: Density and existence of queueing, for four pedestrians, with R = 0.7 m and grid dimensions of 0.25 m by 0.25 m

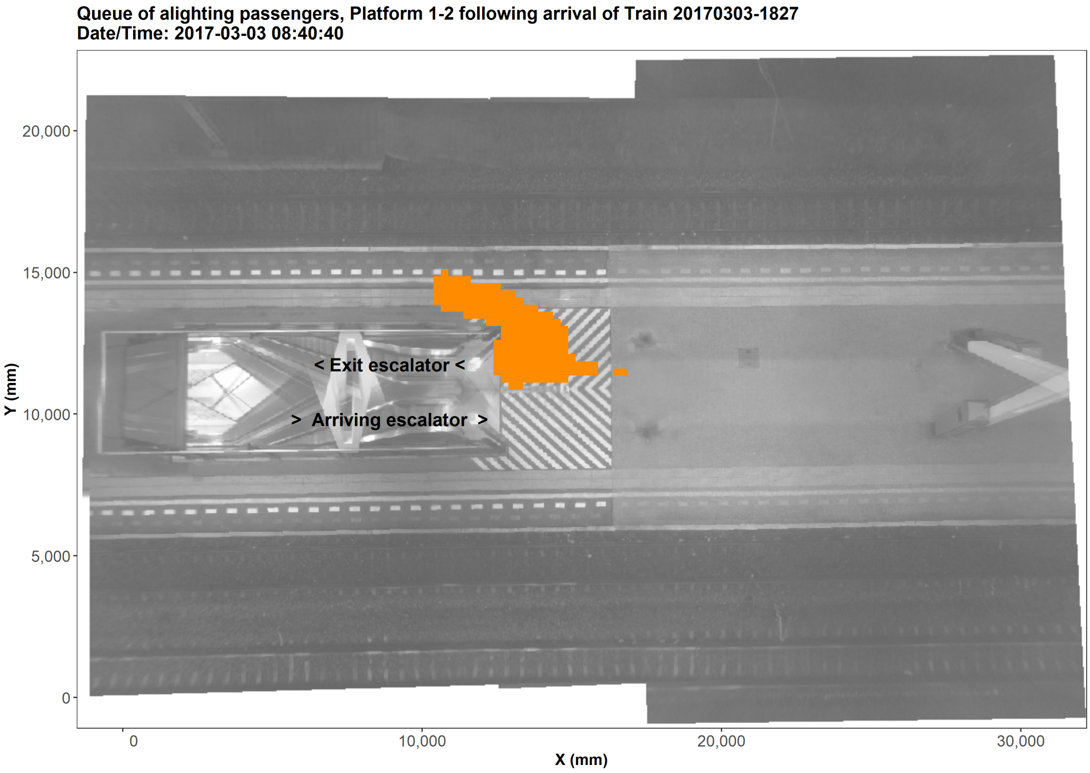
5.3.4 Validation

The final step in the preparatory part of the study was to verify that a queue with these parameters, in combination with the trajectory data, gave a good picture of the queue. As no other source was available that could have been used to validate the formation of the queue (a "ground truth"), qualitative validation was carried out, using the enhanced trajectory data plus two pedestrian dynamics that are characteristic of queues. The first part of the validation process was to see whether pedestrians in the queue moved more slowly than those outside it. The second test was whether the form of the queue changed when pedestrians joined it. Changes in shape were detected by observing the grid cells that become orange when the criteria for the existence of a queue are met (see Figure 5.7)

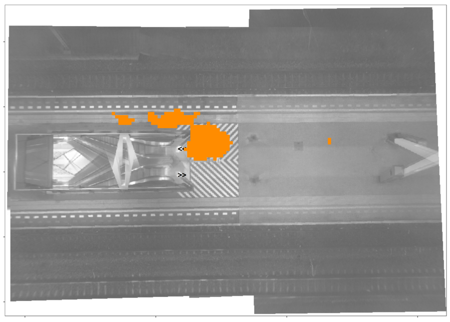
As an example, for Train 1827 on 3 March 2017 (20170303-1827), Figure 5.8 shows the position and speed of each pedestrian who is about to leave the platform via the escalator, superimposed on the queue from Figure 5.7. Using a format similar to that of Figure 5.8, a series of images (one per second) in Figure G.1 in Appendix G shows the queue during the period when it was at its largest. This is the period 08:41:15 to 08:41:30, with the maximum number of persons being observed at 08:41:17. Figures 5.8 and G.1 (Appendix G) show the following:

1. Pedestrians moving towards the queue are walking relatively fast (e.g. those indicated by a circle in Figures G.1h to G.1p).

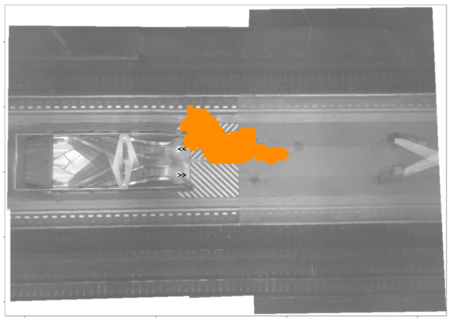
2. People near the queue are moving more slowly (e.g. the individual indicated by a triangle in Figures G.1a to G.1o). Initially, this person is moving along the edge of the queue at a speed of approximately 1 m/s, whereas the people in the queue are virtually stationary. The individual joins the queue in Figure G.1e, and from that time onwards their speed is the same as that of others in the queue.



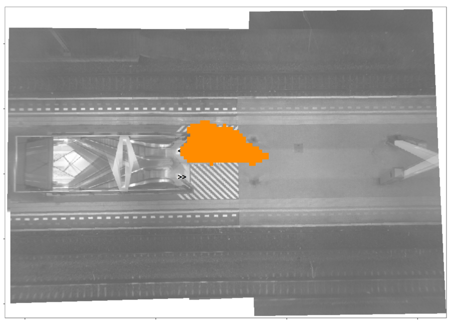
(a) 08:40:40



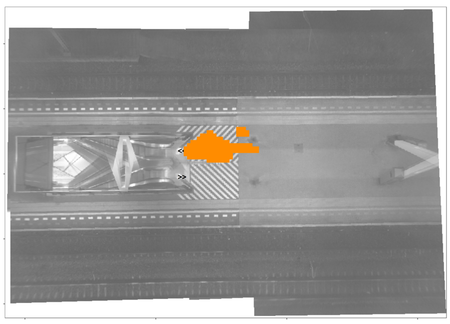
(b) 08:40:55



(c) 08:41:17 (critical)



(d) 08:41:25



(e) 08:41:40

Figure 5.7: Queue formation, descending (exiting) pedestrians, following the arrival of Train 20170303-1827 at Amsterdam Zuid, Platform 1-2 (critical queue at 08:41:17)

Figure 5.8: Queue validation, descending (exiting) pedestrians, following the arrival of Train 20170303-1827 at Amsterdam Zuid, Platform 1-2, 08:41:17

The person indicated by a square is another example. They walk past part of the queue and then join it on the Platform 1 side. Their speed also falls sharply when they join the queue, which occurs in Figure G.1i.

3. The form of the queue changes when additional pedestrians join it. This is apparent from a comparison of Figures G.1h and G.1i. In the images up to and including Figure G.1h, the person indicated by a square is approaching the queue but has not yet entered the area defined as a queue (the area marked in orange). One second later (in Figure G.1i) they have entered that area.

4. People in the queue are moving slowly. All the images clearly show that speeds in the queue do not exceed approximately 0.5 m/s. It is also clear that pedestrians do not often come to a complete halt, and that when they do it is only for a short time.

5. Some persons arriving at the back of the queue (i.e. the end furthest from the bottleneck) do not joint it immediately. For instance, the person indicated by a diamond approaches the rear of the queue at a comparatively high speed up until Figure G.1k. From 08:41:26 onwards, they follow the queue at a certain distance (Figures G.1l to G.1p). They are therefore (correctly) not included in the queue.

6. The figure reveals a discontinuity in the i.d. number of one pedestrian. This individual is indicated by a cross. At 08:41:22 (Figure G.1h) they are shown in grey,

indicating that their speed is unknown. From 08:41:23 (Figures G.1i to G.1p), their speed is known. The reason for this is that the i.d. number for the pedestrian indicated by a cross appears in the dataset for the first time at 08:41:22. At that point they are already well inside the queue, so they were probably present earlier, with a different i.d. This is therefore a measuring error(see [27]). Despite the discontinuity in their i.d. number, the person has been followed continuously. As a result, this type of measuring error has no effect on the queue sizes and widths recorded for this study.

On the basis of the above, it is concluded that the definition of a queue adopted for this study functions in a satisfactory manner for Train 20170303-1827 in combination with the data and with the pre-processing carried out on it. There is a degree of uncertainty as regards the exact moment at which a person joins a queue (point 3), as this is a continuous rather than a discrete process. Furthermore, not all pedestrians join the queue, and they certainly do not all join it at the rear (point 5). As long as the same method is used for all analyses, it is reasonable to assume that no methodological errors will occur as a result of comparing two queues that are not comparable. In this case, measuring errors (point 5) only affect speed measurements for the individual concerned. That indicator is used purely for validation, and not for determining the size of the queue.

Using the data from 20 randomly-selected arrivals at Amsterdam Zuid, Platform 1-2, the author has created animations similar to Figure G.1 in Appendix G. These animations give a result similar to that seen in the images of Train 20170303-1827.

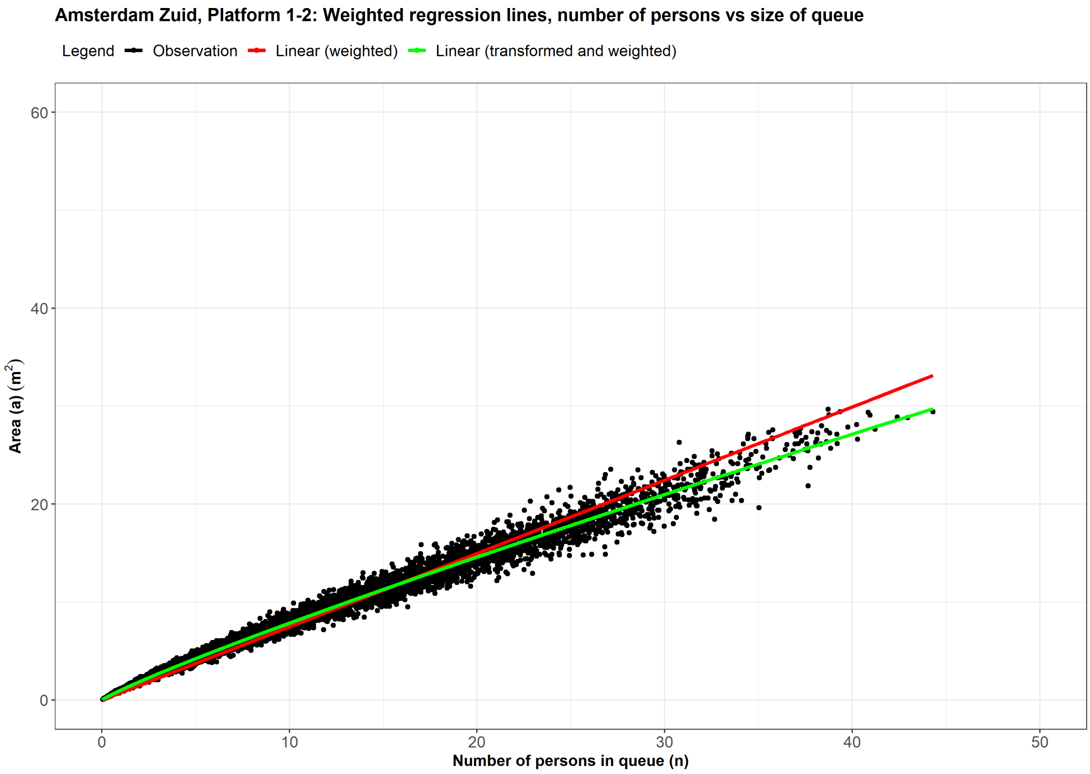
5.4 Results

The results of this part of the research will be described in three sections. 1. The extent to which the size of a queue (i.e. its area) is influenced by the number of people in it (Research Question 1). 2. The extent to which the width of a queue is influenced by the number of people in it (Research Question 2). 3. The extent to which a queue forms an obstacle for people who wish to join it or pass it (Research Question 3, and the reason for conducting this part of the study).

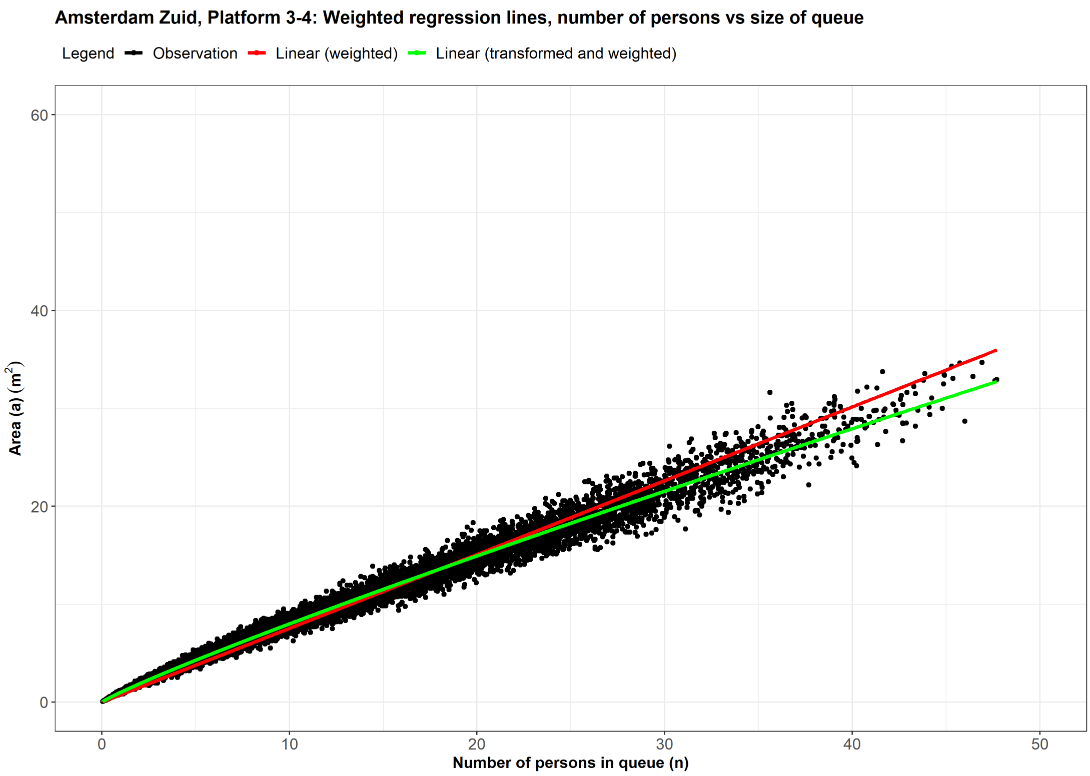
5.4.1 Question 1: Queue size

Figure 5.9 shows the results of a regression analysis in which the size (a) of the queue associated with each train at the critical point in time is plotted against the number of persons in the queue (n). To control for external factors (obstacles, and differences in platform width), the figure distinguishes between Platforms 1-2 (Figure 5.9a) and 3-4 (Figure 5.9b) at Amsterdam Zuid, and the north (Figure 5.9c) and south (Figure 5.9d) escalators on Platform 5 at Utrecht Centraal.

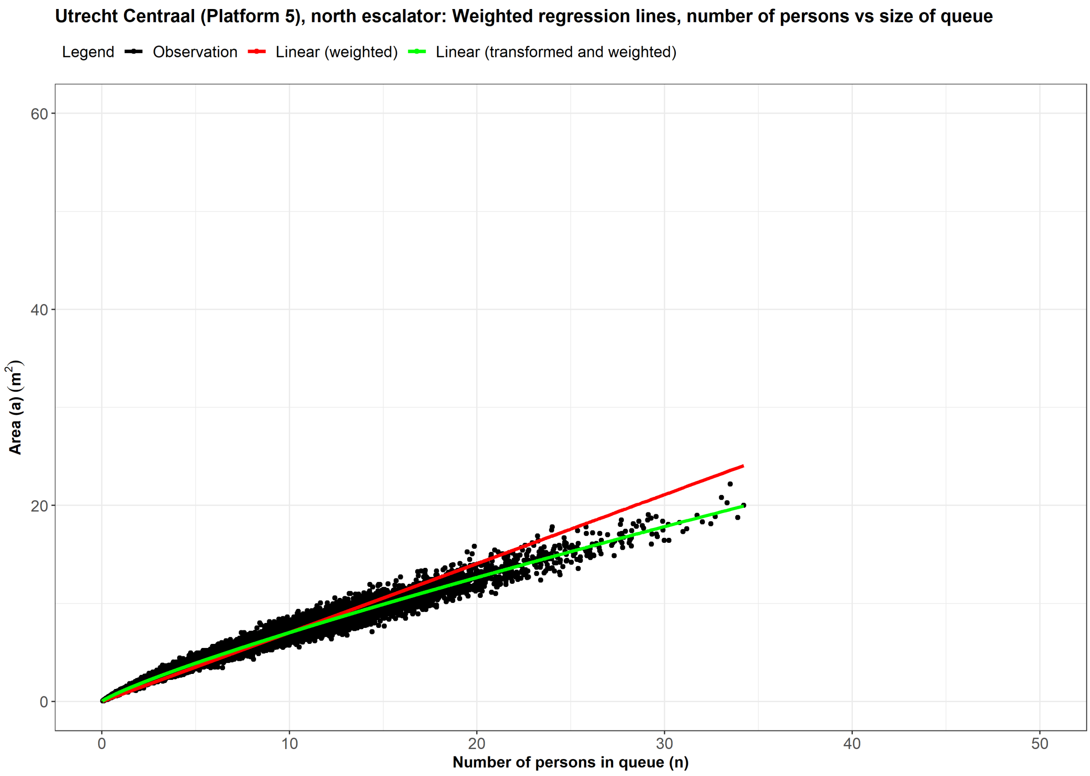
Regression lines were estimated for all scatter plots, on the basis of Equations 5.1 and 5.2. The parameters used are shown in Table 5.2. The table shows that only the transformed model meets the criterion of normal distribution and equal variation for the residuals (Criterion 4). Whether weighting factors are needed is less clear. For



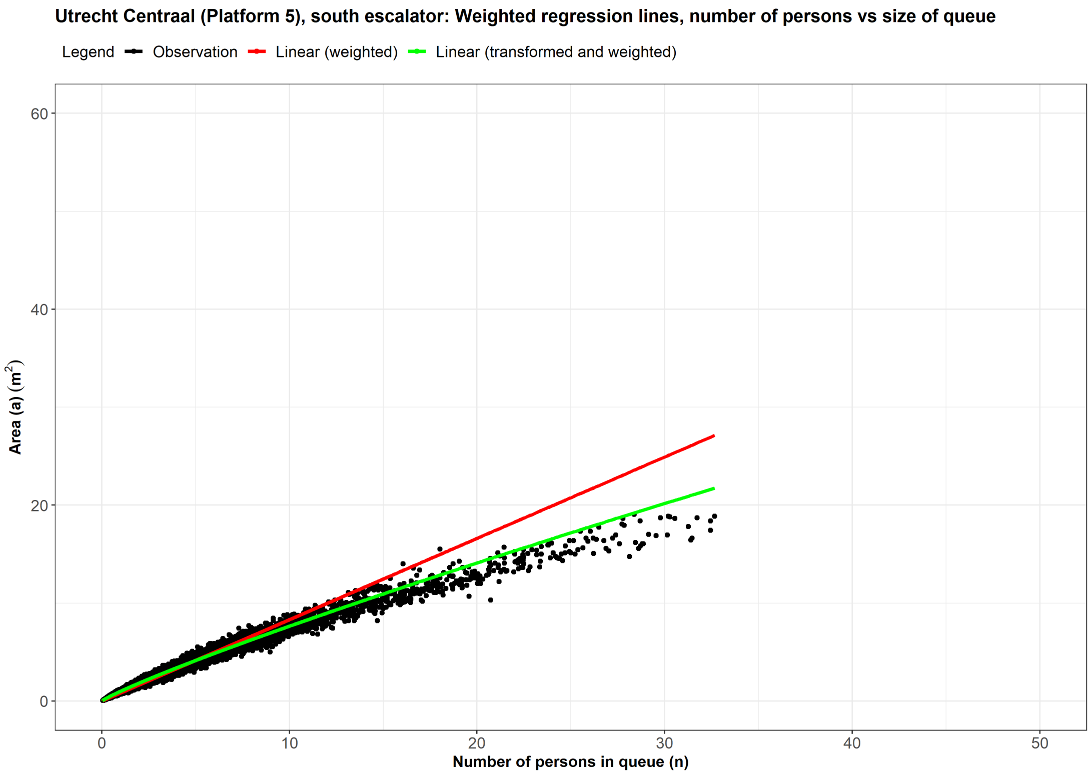
(a) Platform 1-2 (Amsterdam Zuid)



(b) Platform 3-4 (Amsterdam Zuid)



(c) North escalator (Platform 5, Utrecht Centraal)



(d) South escalator (Platform 5, Utrecht Centraal)

Figure 5.9: Regression analysis for relation between queue size and number of persons in queue

Amsterdam Zuid, both models meet the fourth criterion. For Utrecht Centraal, the model without weighting meets the criterion for the south escalator whereas the model with weighting meets the fourth criterion when applied to the north escalator. The estimate for β_1 lies in the range 0.85–0.90 for all models, and is therefore comparable. The MAE calculated from the residuals is of the order of magnitude of 0.8. The low value confirms that the regression function fits the observed values well.

Station	Plat.	Escalator	n_{max}	Model (W)	β_1 (p)	P_{sw}	MAE
Amsterdam Zuid	1-2	West	44	5.1	.73 (0)	0	.77
				5.1 W	.75 (0)	0	.81
				5.2	.90 (0)	.12	.79
				5.2 W	.89 (0)	.13	.80
	3-4	West	48	5.1	.74 (0)	0	.78
				5.1 W	.75 (0)	0	.82
				5.2	.90 (0)	.24	.79
				5.2 W	.90 (0)	.28	.80
Utrecht Centraal	5	North	34	5.1	.68 (0)	0	.79
				5.1 W	.70 (0)	0	.82
				5.2	.85 (0)	.03	.77
				5.2 W	.85 (0)	.23	.78
		South	33	5.1	.73 (0)	0	.68
				5.1 W	.83 (0)	0	.79
				5.2	.89 (0)	.11	.77
				5.2 W	.88 (0)	0	.77

Table 5.2: Parameters for the regression models of queue size as a function of number of persons in the queue (W = weighting applied as per Equation 5.3)

This analysis implies that none of the operational differences between platforms (such as train type, train length, platform, stopping position, number of passengers per train and distribution of passengers within the train) play a determining role in the size of a queue at an escalator prior to the moment at which it reaches its maximum area. The number of persons in the queue is a good predictor of queue area. The fact that the regression function is a straight line indicates that the mean density of a queue is virtually unaffected by the number of persons in it. Density is of the order of 1.4 persons per square metre, which corresponds to Fruin LOS E for a walkway [36].

5.4.2 Question 2: Queue width

For this study, queue width is defined by two dimensions (see Figure 5.10). b_1 is the width measured towards the adjacent platform side (Platform 1 in the case of Platform 1-2 and Platform 3 in the case of Platform 3-4). b_2 is the width measured towards the longitudinal axis of the platform and the pedestrian flow in the opposition direction.

In a manner similar to Figures 5.4 and 5.9, Figure 5.11 shows the scatter plots for the two width dimensions of the queues on Platform 1-2 at Amsterdam Zuid. These diagrams clearly show that a regression analysis does not yield a fit (Criterion 1). Fur-

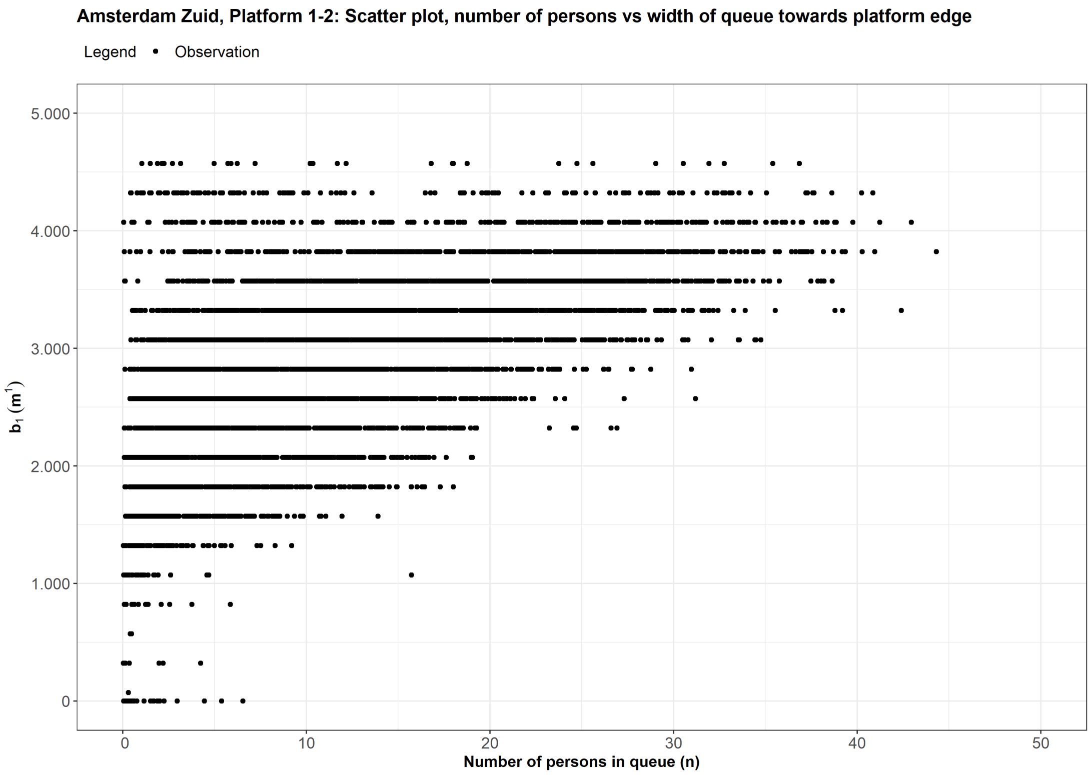
Figure 5.10: Queue width following the arrival of Train 1827 on Platform 1-2 on 3 March 2017

thermore, the criterion of equal variation for the residuals (Criterion 4) is not fulfilled. The diagrams for the other cases paint a similar picture. Stratifying train arrivals by type and length makes no difference. The same applies to the other locations.

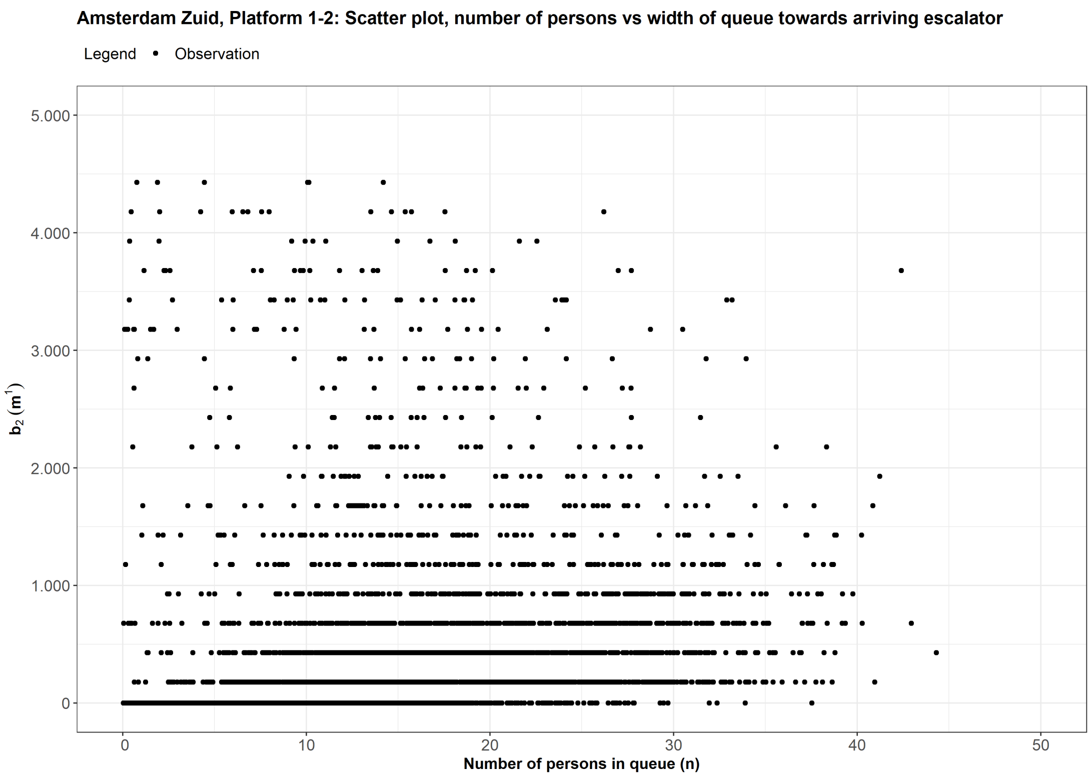
The dynamic nature of queue growth and shrinkage may explain why the area of a queue can be predicted by the number of persons in it but its dimensions cannot. Qualitative observation of several queues (similar to that shown in Figure 5.7) indicates that at some points a queue expands and contracts more widthways and at other times more lengthways. These dynamics are probably related to the direction from which people join the queue and the behaviour – including following behaviour – of individuals within it. The direction(s) from which people join the queue depend(s) on the exact locations of the train doors relative to the escalator and the distribution of alighting passengers along the train. Both factors vary considerably from one train to another.

To reduce the influence on the analysis of the dynamics of the expansion and shrinkage of the queue, the queues were aggregated using a probabilistic approach. This involved grouping all the queues according to the number of persons they comprised. Then, for each group, the probability was calculated, for at least 20 observations of a queue being present at each cell of the grid in the measurement area at the critical moment. By assuming a minimum value for this probability, it is then possible to determine the dimensions of the queue ”feather” in the same manner as before (see Figure 5.10).

Figure 5.12, for Amsterdam Zuid, Platform 1-2, shows that the probability of a

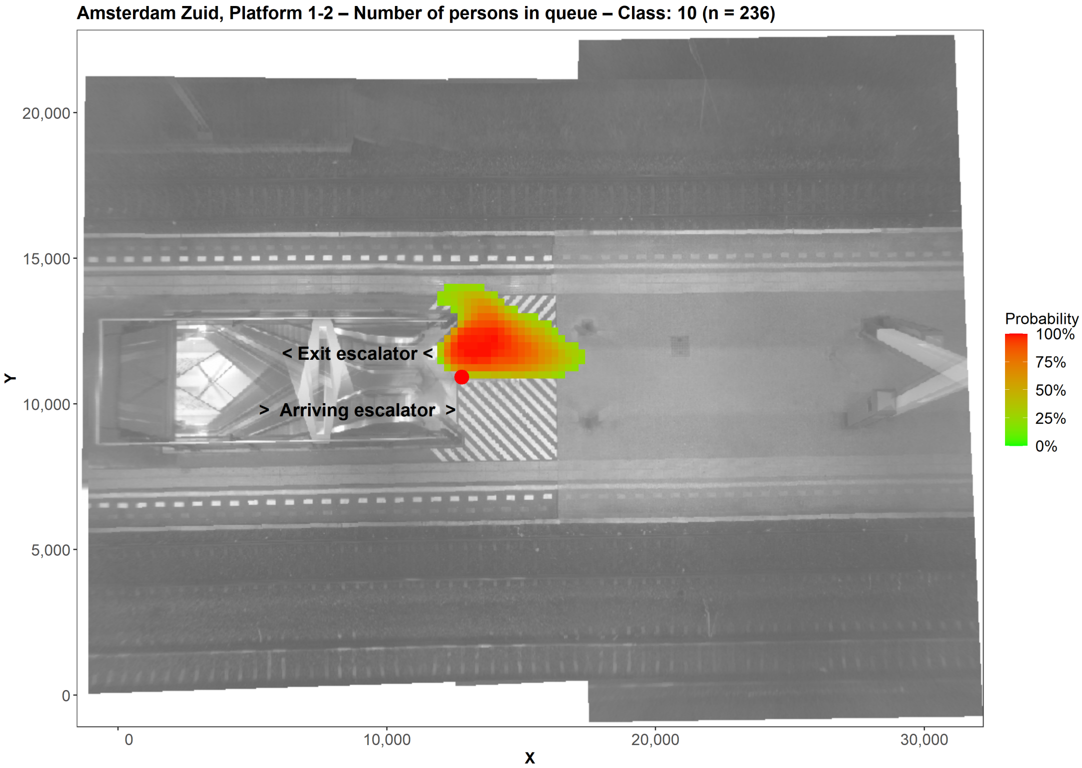


(a) Towards platform edge (b_1)

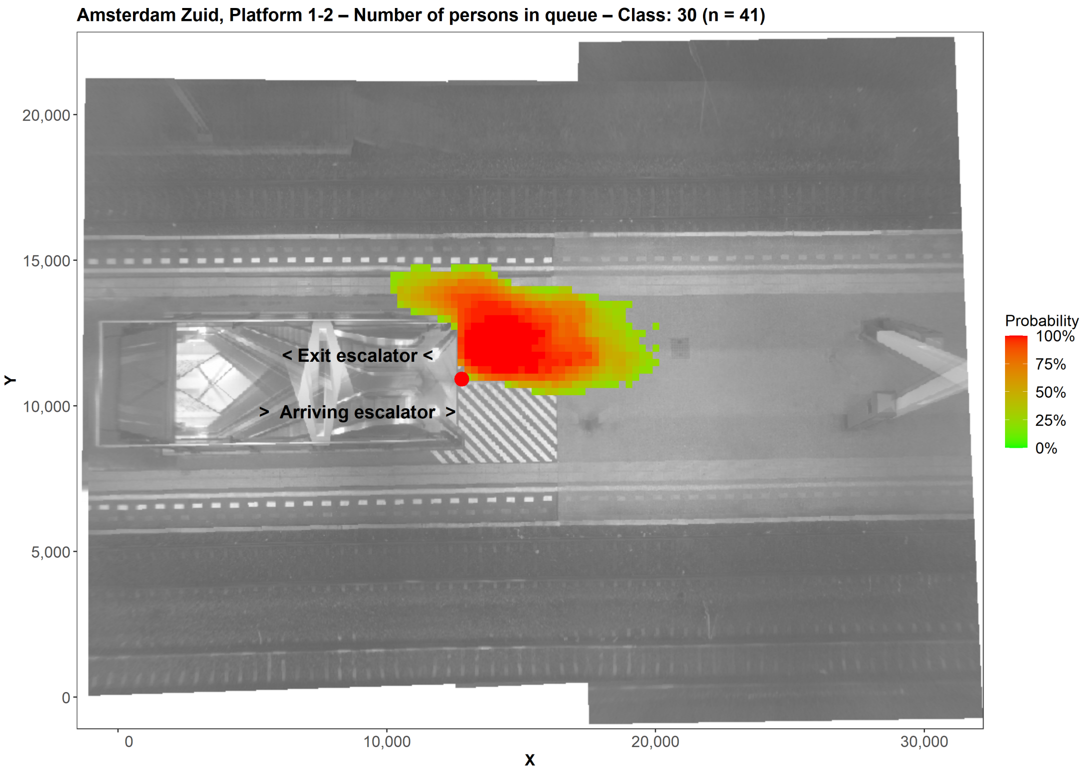


(b) Towards arriving escalator (b_2)

Figure 5.11: Scatter plots for queue width as a function of number of persons in queue, Amsterdam Zuid, Platform 1-2



(a) Number of persons in queue = 10



(b) Number of persons in queue = 30

Figure 5.12: Queue development: probabilistic approach per group of number of persons in queue

queue in the centre of the feather (shown in red) is 100% or very nearly so. That area is in line with the run-on for the exit escalator. The core of the queue expands as the queue grows. Outside the core (the area in green), the picture is less clear-cut. In some cases, the queue lengthens in the direction directly away from the escalator. In other cases, it becomes wider, and in still others it curls around the escalator on the side nearest the track. This confirms the suspicion that the number of people in a queue is not the only factor determining its shape. The situation at the other locations is comparable.

5.4.3 Question 3: Queues as obstacles

This study was motivated by the risks that can arise if people get too close to the platform edge because of a queue (b_1) or enter the run-off from an escalator moving in the opposite direction (b_2).

Figure 5.13 illustrates this for a person walking along the platform edge (Train 1827, 3 March 2017). That figure shows the queue at 08:41:20, combined with the trajectory and speed of a passer-by between 08:41:00 and 08:41:30. A passer-by is defined as a person who does not use either escalator, but walks past the escalators from one side of the measurement area to the other, in either direction (see Section 4.3). In the case of Figure 5.13, the person concerned very probably alighted from the train to the left of the escalator (as seen in the figure) and walked along the platform to the Parnassusweg station entrance at the right-hand end (see Figure 4.8). Figure 5.13 clearly shows the obstacle created by the queue. The passer-by slows down, moves closer to the platform edge to pass the queue, and then speeds up and moves away from the edge.

Figure 5.14 combines all the queue "feathers" from Figure 5.12 for each escalator, using the probabilistic approach applied in Research Question 2. The horizontal axis shows the number of persons in the queue (referred to as the "class" in Figure 5.12), with the escalator located at 0. The vertical axis shows the maximum probability of all grid cells for each Y value. This Y value represents the position of the row of grid cells relative to the platform edge(s), the line(s) indicating the buffer zone(s) along the platform edge and the axis between the exit escalator where the queue has formed and the arriving escalator (moving in the opposite direction). The figure also shows the minimum width that a passer-by requires in order to pass a queue without entering the buffer zone.

It is clear from all cases that the probability of wider queues at the exit escalator increases with the number of persons in the queue. On both platforms at Amsterdam Zuid, there is a substantial (25%) probability that passers-by will have to walk along the buffer zone in order to pass the queue if it contains 20 or more persons. If the queue comprises 30 to 35 persons or more, that probability approaches 100%. This effect does not occur at Utrecht Centraal, probably on account of two differences between the situation there and that obtaining at Amsterdam Zuid: 1. The queues at Utrecht Centraal are smaller, as they contain fewer people (see Figure 5.9). 2. The run-on and run-off areas for the escalators at Utrecht Centraal are delimited by obstacles. This reduces the number of directions from which people can approach the escalators.

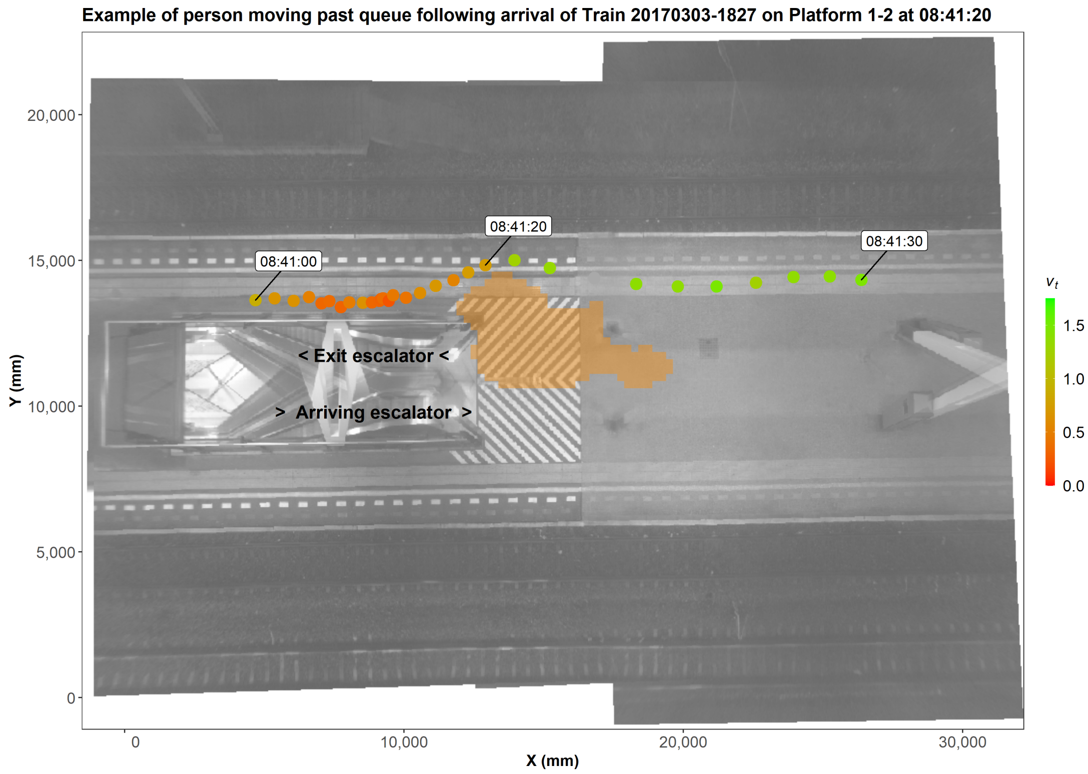
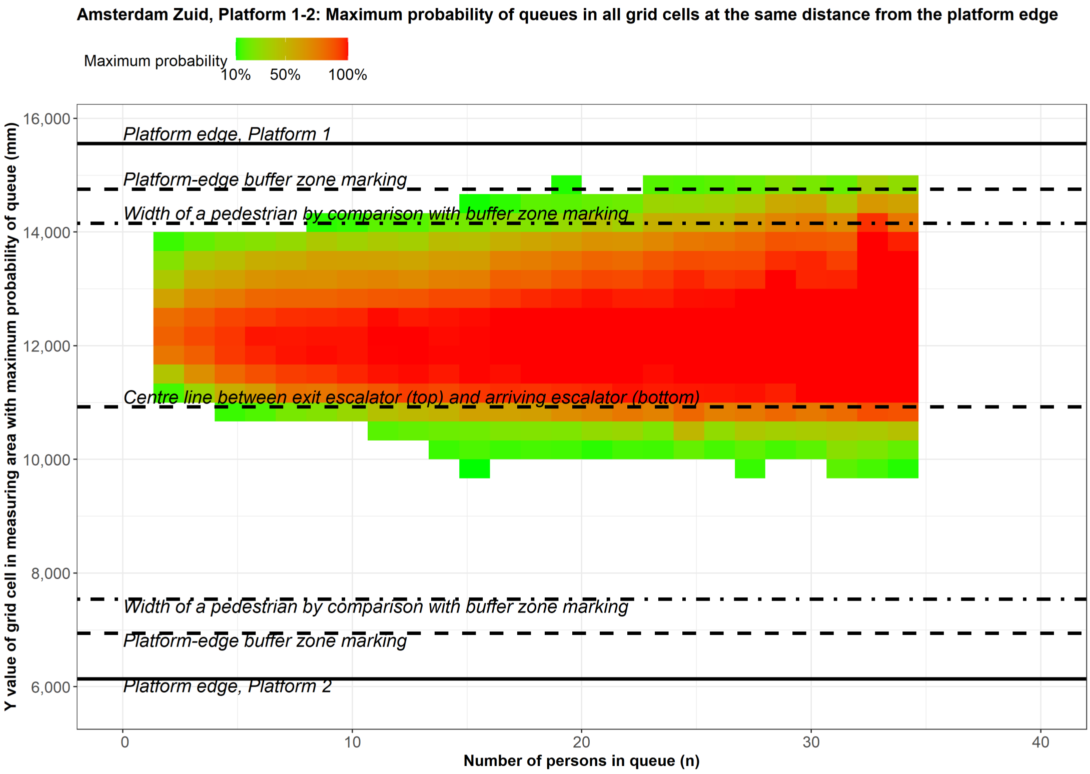


Figure 5.13: Passer-by moving past a queue following the arrival of a train on Platform 1-2

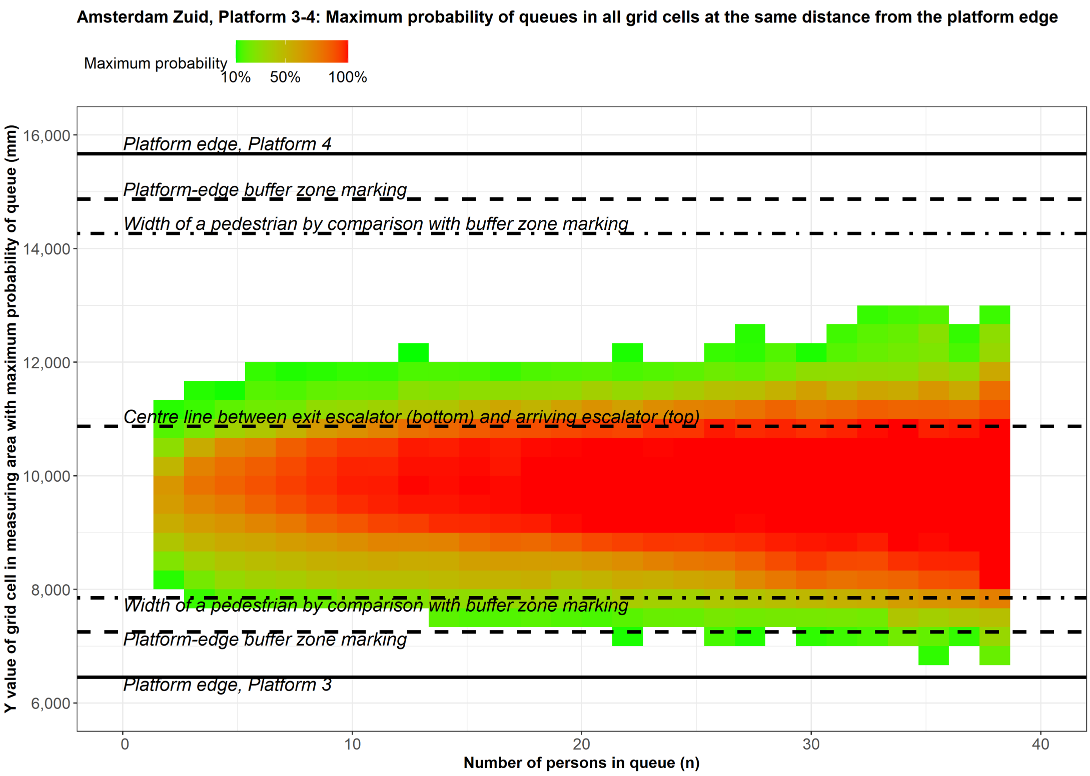
The probability of a queue encroaching upon the run-off zone of the arriving escalator at Amsterdam Zuid is low, on both platforms. It is probable that the presence of a divider plays a role in this (see Sub-section 4.2.1). At Utrecht Centraal, however, queues containing 15 or more persons encroach on the run-off zone from the arriving escalator relatively often.

To obtain an indication as to whether passers-by walk closer to the platform edge because of the obstacle created by a queue, trajectory data for each arrival at Amsterdam Zuid, Platform 1, were used to identify all persons passing between the escalator and the platform edge who walked past the queue when it was at its widest (= the critical moment in Research Question 2). The distance between each passer-by and the platform edge was then measured at the time when the queue was at its widest. The dimensions of a pedestrian were taken into account (see Section 4.3). This was done for a 20-second period, starting 10 seconds before the critical moment and ending 10 seconds after it.

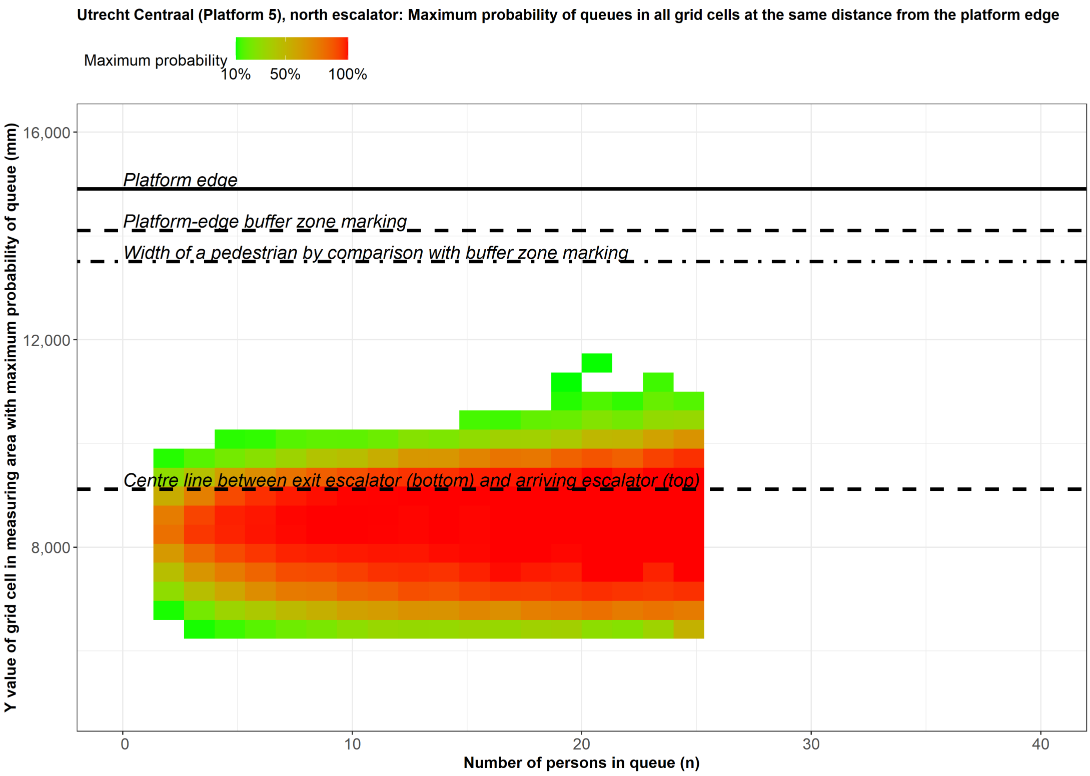
The distances between the individual passers-by and the platform edge were then plotted against the b_1 dimensions of the queues. Because a grid was used, the dimensions were grouped into 250 mm steps. Only groups comprising at least 20 observations were used, to avoid any distortion that could result from a low number of observations per group. The results are shown in Figure 5.15. From that figure, it is clear that the median distance between passers-by and the platform edge reduces as the width of the queue (b_1) at the critical moment increases. This effect is observed for queue widths of up to approximately 3.5 m. After stabilizing, the distance from



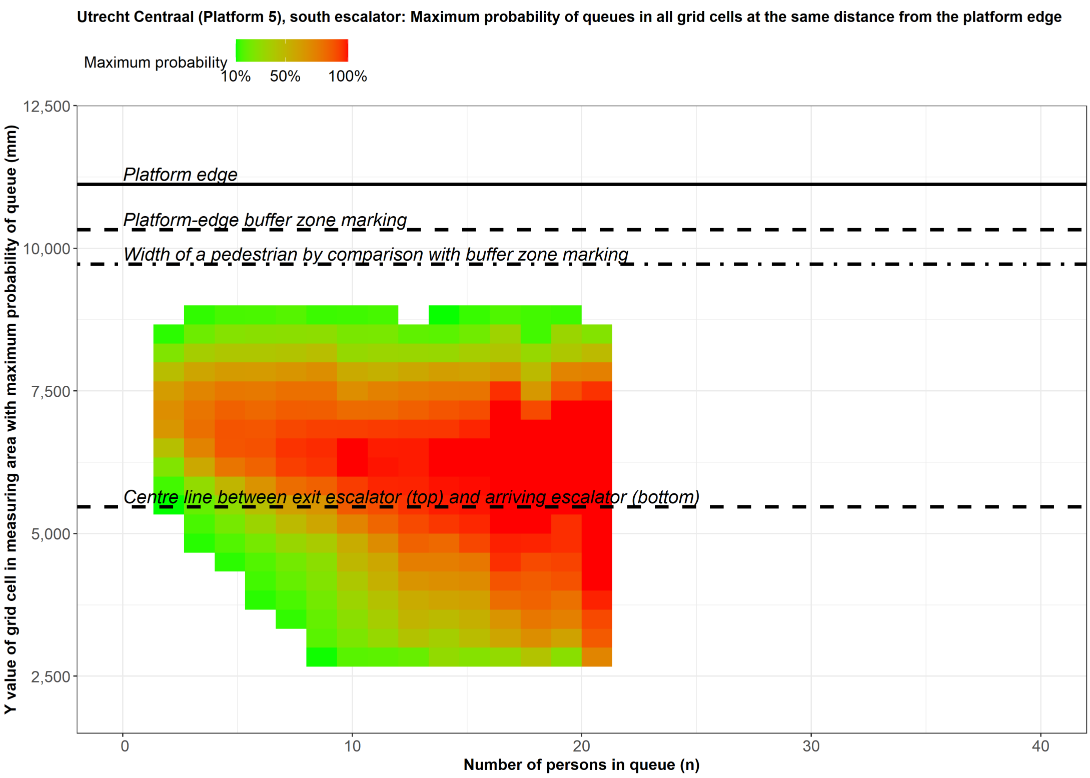
(a) Platform 1-2, Amsterdam Zuid



(b) Platform 3-4, Amsterdam Zuid



(c) Platform 5, Utrecht Centraal – north escalator



(d) Platform 5, Utrecht Centraal – south escalator

Figure 5.14: Probability of queues that form an obstacle

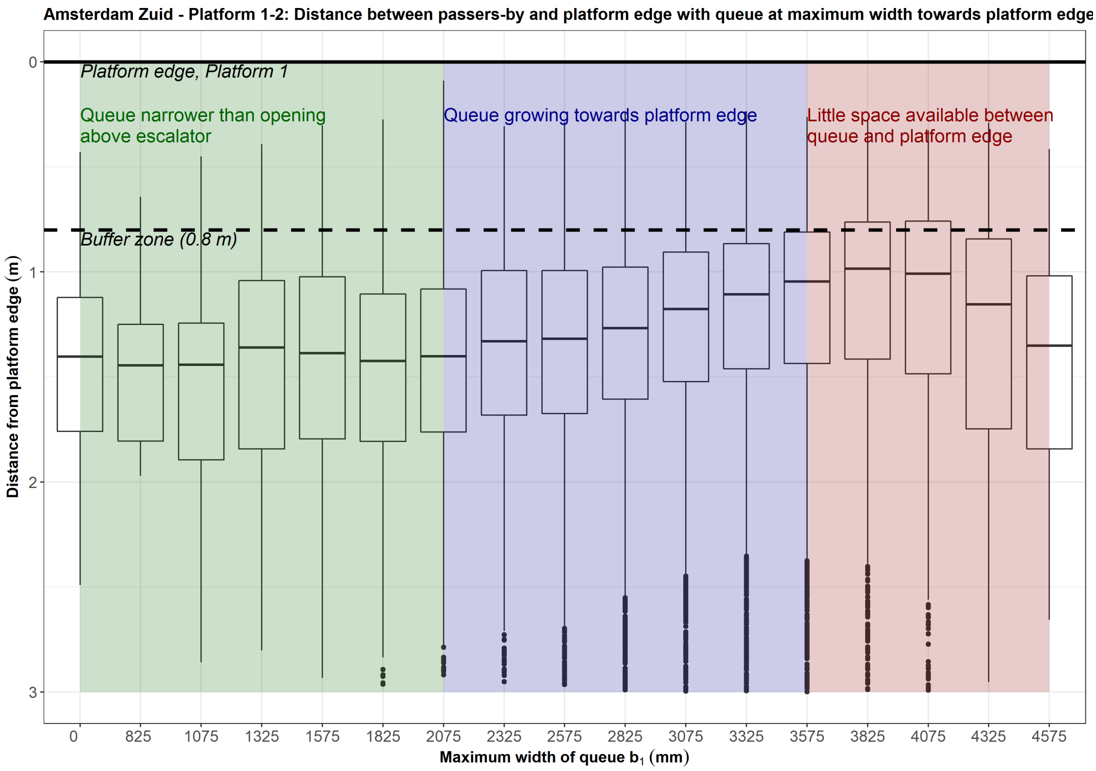


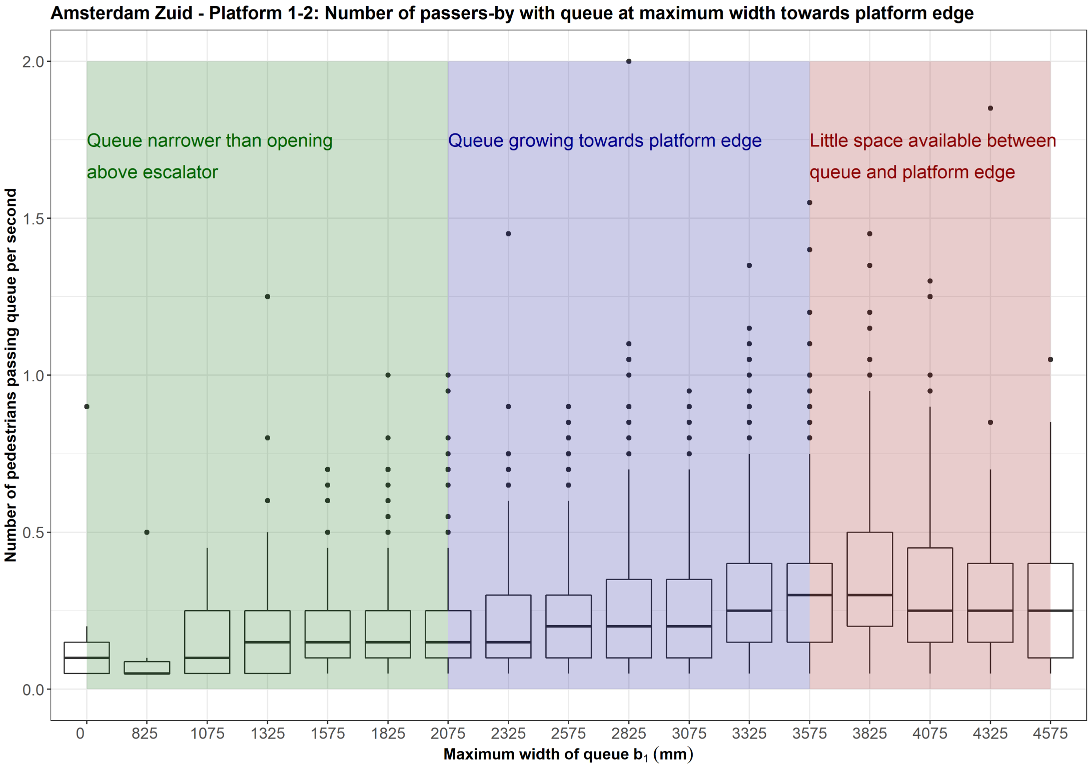
Figure 5.15: Obstacle effect for passers-by created by the queue at Amsterdam Zuid, Platform 1

the platform edge then increases again. This indicates that the queue has become so wide that it has almost reached the platform edge, and passers-by are waiting until it has narrowed before passing. Furthermore, the median distance indicates that half of the passengers are walking along the platform at a greater distance from the edge. The other half are closer to the edge. The absolute minimum is about 30 cm. Given the dimensions of a typical pedestrian (see Figure 4.14), a pedestrian with a measured distance to the platform edge of 30 cm is virtually walking along it.

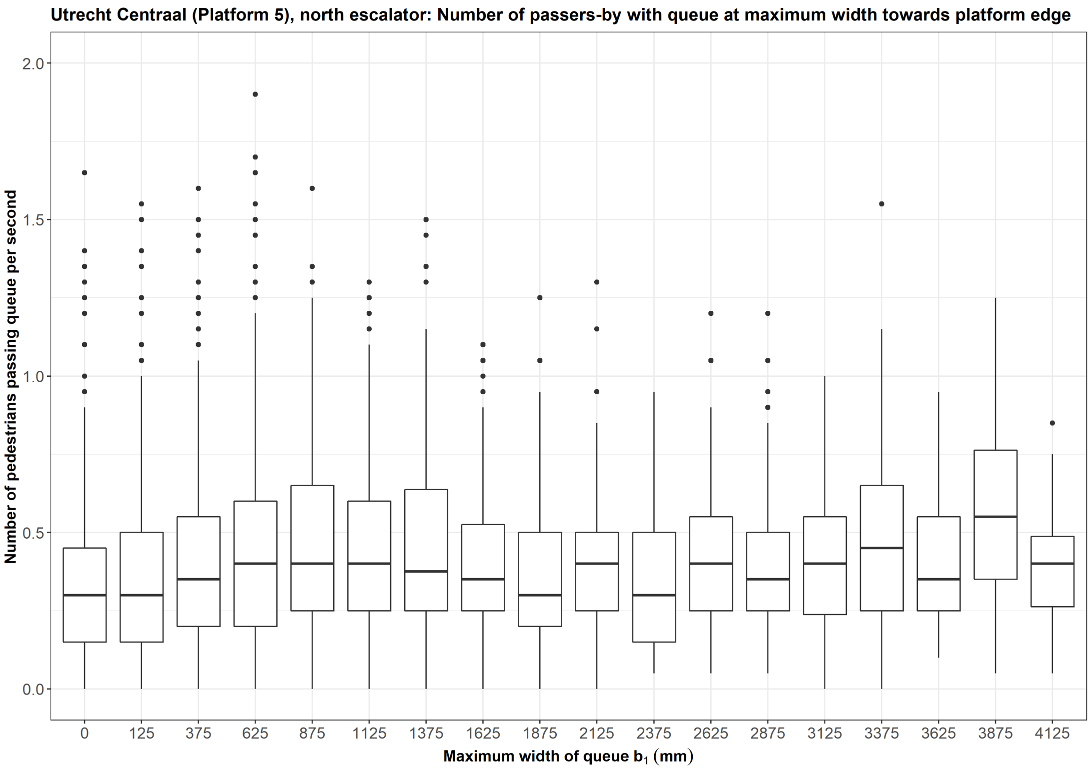
Figure 5.16a shows the numbers of passers-by who passed queues of various widths in the chosen time period centred on the critical moment, at Amsterdam Zuid, Platform 1-2. From that figure, it is apparent that the number of passers-by increases as the queue becomes wider, until a width of 3.5 m is reached. At that point there is a slight decrease. This confirms the observation made above, that once a queue reaches a certain width passers-by wait until it has narrowed before passing.

Figure 5.16b shows the flow of passengers arriving on Platform 5 at Utrecht Centraal via the north escalator while there is a queue at the exit escalator. Here again, a 20-second period has been used, centred on the time at which the queue for the exit escalator is at its maximum. This figure shows that the flow from the arriving escalator is not affected by the width of the queue for the exiting escalator. The figure clearly shows that in most cases that flow continued despite the queue for the exit escalator. It is not possible on the basis of this analysis to determine the extent to which the queue was obstructing flow, as was possible for the platform edge at Amsterdam Zuid.

On the basis of the above analysis, one can conclude that queueing at an exit esca-



(a) Platform edge, Amsterdam Zuid, Platform 1



(b) Arriving (north) escalator, Platform 5, Utrecht Centraal

Figure 5.16: Number of passers-by on the platform-edge side of the queue for the exit escalator

lator results in situations that practice-based standards define as dangerous. Because of the dynamic nature of queue formation and dispersion at escalators, it is not possible to use the aggregated analyses from this part of the study to identify the number of persons exposed to these risks.

5.5 Conclusions

This chapter has focused on the following hypothesis: *As a result of queues forming at an exit escalator immediately following the arrival of a train, passengers stand or walk too close to the platform edge, and/or passengers in the queue for the exit escalator wait in the run-off from the incoming escalator.* That hypothesis was tested against the answers to the following research questions:

1. To what extent does the size of a queue at an exit escalator increase with the number of people in the queue?

2. To what extent does the width of a queue at an exit escalator increase with the size of the queue?

3. Does the obstacle formed by the broader queue lead to any or all of the following?

   (a) People in the queue stand too close to the platform edge.

   (b) People in the queue stand in the run-off from the arriving escalator.

   (c) People wishing to get past the queue walk too close to the platform edge.

As regards the size of the queue (Research Question 1) and its width (Research Question 2), one can draw the following conclusions: The number of persons in a queue n is a good indicator of its area (a in m^2). Equation 5.4 accurately reproduces observations for queues of up to approximately 50 persons, for all the cases in this study.

$$a = n^{0.9} \tag{5.4}$$

The number of persons in the queue does not (or does not completely) predict its width, as expressed by the dimensions b_1 and b_2 (in m^1). This study has shown that this may be due to the dynamic character of queue formation and dispersion. In other words, the width of the queue resulting from each train arrival is different, even if the arrivals themselves are comparable. The spatial probabilistic approach has shown that the probability of increasingly wide queues increases with the number of persons in the queue.

For the platforms at Amsterdam Zuid, this study has established a clear link between the width of a queue and a tendency for people to get closer to the platform edge (Research Question 3). People in the queue do not themselves enter the buffer zone (Research Question 3a). However, the queue forms an obstacle for persons attempting to pass it, causing them to walk closer to the platform edge. As a result, these passers-by walk along the buffer zone (Research Question 3c). This effect was observed for some arrivals where queues contained approximately 20 persons, and for virtually all arrivals where queues contained 30 persons or more. The results of this thematic study also point to this effect being finite in nature. Once the queue reaches a certain width, an increasing number of passers-by wait (at least briefly) until it has become narrower, rather than walking along the edge (sometimes literally) to get past.

On Platform 5 at Utrecht Centraal, the queues are smaller. As a result, the queue does not spill into the buffer zone, and nor does it form an obstacle for passers-by who wish to pass it on the side nearer to the track (Research Questions 3a and 3c). However, the absence of a divider between the arriving and exit escalators does allow the queue for the exit escalator to obstruct the run-off from the arriving escalator (Research Question 3b). This is especially true in the case of the south escalator, once about 15 people have joined the queue. This effect occurs while the arriving escalator is bringing passengers to the platform (in the opposite direction). It was not possible to establish a direct link between avoiding action on the part of persons who had reached the platform via the arriving escalator on the one hand, and the queue for the exit escalator on the other, because of the analysis method used. However, it is reasonable to assume that such avoiding action occurs, given the probability of there being a queue and its position on the platform.

Generally speaking, this thematic study allows one to conclude that the hypothesis can be seen as valid for the platforms studied. In other words, when the queue for an exit escalator reaches a certain size, it can cause passengers to regularly get too close to the platform edge or enter the run-off zone of an arriving escalator.

5.6 Discussion

There are two important caveats regarding this study. 1. The degree to which one can apply the results more generally (see Sub-section 5.6.1). 2. The hazards to which people passing a queue on the side nearest the track are actually exposed when they walk along the buffer zone (see Sub-section 5.6.2).

5.6.1 General applicability

The platforms at Amsterdam Zuid are relatively narrow (total width: 9 m). Although slightly wider, the Platform 5 side of the Platform 5/7 island at Utrecht Centraal is also relatively narrow. Furthermore, the two escalators at Utrecht Centraal lie between stairs and other obstacles. Both platforms are subject to high peak loads, i.e. large numbers of alighters per arrival. This raises three questions regarding the general applicability of the results:

1. How the dimensions of the queue would develop if the same queue were to form on a wider platform at Amsterdam Zuid (all other things being equal). If the width of the queue in the direction of the nearest platform edge (b_1) were to develop in a manner similar to that observed, the queue would constitute less of an obstacle on a wider platform. If, however, the width of a queue increases with both the size of the queue and the width of the platform, a wider platform would result in a wider, shorter queue. It is not possible to draw any conclusions regarding this point on the basis of the

present study. At the same time, understanding the connection between these factors is of great importance when it comes to assessing the benefits of investing in wider platforms.

On the basis of his own observations, the author expects the two effects to occur concurrently. As an example, the photos in Figure 5.17 show the situation at ’s-Hertogenbosch. The island for Platforms 3 and 4 is much wider than in the case of Amsterdam Zuid. As at Amsterdam Zuid, large queues form at the exit escalator on this platform. The photos show that a relatively wide strip along the platform edge remains free of queueing passengers.

(a) 10 February 2017, 08.06 hrs (b) 16 February 2017, 08.27 hrs

Figure 5.17: Queues at the escalator serving Platform 3-4, ’s-Hertogenbosch (Photos: Stef de Vos)

2. The manner in which the queue for an exit escalator encroaches upon the run-off zone for a neighbouring arrival escalator. This occurred at Utrecht Centraal, Platform 5, but not at Amsterdam Zuid. The difference is very probably due to the divider between the escalators at Amsterdam Zuid. On the basis of his own observations, the author would expect there to be a high probability of the queue for an exit escalator encroaching upon the run-off zone of an arriving escalator in the absence of a divider whenever passengers alighting from a train have to make a sharp turn and then pass the run-off zone of an arriving escalator before joining the queue for the exit escalator.

3. The degree to which the peak loads observed on the platforms studied also occur on other platforms. Figure 5.18 shows the peak alighting loads from NS services, per platform, during the 2018 timetable period. These peak loads are not the highest peak loads for the year, but rather the 90th percentile of the number of alighters per train number (e.g. all runs of Train 3524 during 2018). For each platform, the train number with the highest 90th percentile value was selected.

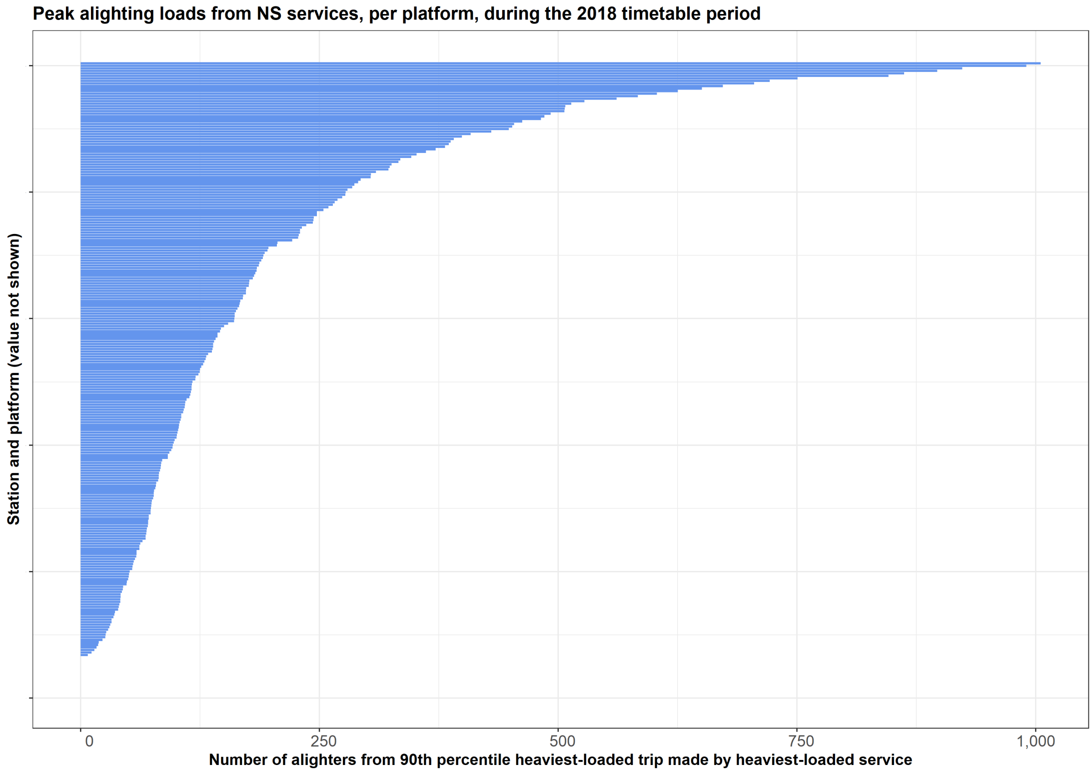


Figure 5.18: Peak alighting loads from NS services, per platform (all stations), during the 2018 timetable period (using ROCKT Station data)

Figure 5.18 shows that the highest peak loads involved approximately 1,000 alighters per train. However, the figures fall sharply in the case of the highest peak loads. Table 5.3 shows the top ten maximum peak loads for platforms that do not serve dead-end tracks. Dead-end tracks are ignored, as stops at such platforms are relatively long (at least 5 minutes, approximately) because the train has to change direction. On through tracks, stops generally last 2 minutes or less. The platforms included in this thematic study are shown in red in the table.

The table shows that the peak loads for the cases studied involved approximately 800 to 1,000 alighters. Peak loads at two other platforms at Utrecht Centraal also fall in this range. Further down the list, we see Eindhoven Centraal, three further platforms at Utrecht Centraal, plus Leiden Centraal. The table clearly shows that the cases studied were taken from the ten Dutch platforms with the highest peak loads, and that large queues very probably do not occur at all stations. At the same, one could argue that the cases studied are not necessarily unique.

5.6.2 Hazards

Whether or not a train is standing at the platform is of relevance when assessing the hazard to which passers-by are exposed if they walk along or near the platform edge. Given that the presence of a train is the cause of the queue at the escalator, one could argue that the risk is limited, as a train is standing at the platform during the time that the queue exists. However, this may not necessarily be the case. On the island plat-

Position	Station	Plat.	Alighters
1	Amsterdam Zuid	3	1,000
2	Utrecht Centraal	18	900
3	Utrecht Centraal	8	800
4	Utrecht Centraal	5	800
5	Amsterdam Zuid	1	800
6	Eindhoven Centraal	6	725
7	Utrecht Centraal	19	725
8	Utrecht Centraal	7	725
9	Utrecht Centraal	20	700
10	Leiden Centraal	5	700

Table 5.3: Top-ten peak loads for alighters on NS, per platform (excluding dead-end tracks) during the 2018 timetable period (using ROCKT Station data, rounded to the nearest 25)

forms at Amsterdam Zuid, it is possible for the queue and passers-by to be generated by trains on Platforms 2 and 4, whereas the queues cause people to take avoiding action by moving closer to Platforms 1 and 3. Trains may arrive at these platforms – or pass them – following the arrival of a train at Platform 2 or 4 respectively. Furthermore, a train may depart before its queue has dispersed. Many trains remain at the platform for one to two minutes, and in some cases more briefly (42 s). The photo in Figure 5.19 shows a train departing while a significant number of passengers are still queueing close to the platform edge. Further research is required to establish whether people walk close to the platform edge to get round escalator queues to the same extent (i.e. regularly) in such situations.

5.7 Recommendations

This chapter concludes with recommendations for further study (Sub-section 5.7.1) and practical application (Sub-section 5.7.2).

5.7.1 Further study

This thematic study has shown that the width of a queue, and hence the degree to which it constitutes an obstacle, cannot be predicted purely on the basis of the number persons in it. Queues have been observed that curl around an escalator, as a result of people approaching it from behind rather than in front. This causes a “banana” queue to form, rather than the cone-shaped queue that one would expect. But even in the case of the cone-shaped queues observed during this research, queue width is influenced by dynamics that have not been studied. The first recommendation for further study would therefore be to analyse the characteristics of a train arrival that determine the direction from which people join a queue. The position of the train doors relative to the escalator run-on zone and the distribution of alighters along the train could well be important in determining queue size and width.

Figure 5.19: Queue adjacent to a departing train (13 December 2016, 08.49 hrs). (Photo: Sebastiaan de Wilde)

The behaviour of passengers joining the queue and in the queue is another topic for further study. The literature study (Chapter 3) has shown that most microscopic pedestrian models are not capable of reproducing queue shape accurately. A number of researchers have stated that a lack of empirical data makes it impossible to develop, calibrate and validate such models. This study has shown that aggregated analyses of microscopic empirical data fail to capture certain unknown explanatory factors. However, the microscopic data used for the present thesis provide a basis for making progress in this area of research. Further research using those data could establish whether or not it is possible to predict the width of a queue at an exit escalator. It is recommended that further studies be conducted regarding the choices that passengers make when they join a queue and when they are in it, and what factors influence these choices. Such research could build on previous work (e.g. [138]), in which a distinction has been made between cooperative and competitive behaviour in queues.

A third recommendation for further study is the manner in which hazards related to the platform edge, and the perception of such hazards, affect passenger behaviour. This thematic study has shown that wider queues result in people using the buffer zone at the platform edge to pass the queue. It has also shown that they stop doing so when the queue reaches a certain width. However, this study has not established why people do or do not walk past a wide queue. Knowing this could be relevant both for developing models (see the second point above) and for practical risk assessments (see below).

5.7.2 Practical recommendations

Two practical recommendations are made on the basis of this thematic study.

1. Install dividers at more escalators. Dividers are currently not a standard item, and installing them is generally simple and inexpensive. Analysis at Amsterdam Zuid shows that a divider prevents passengers who are queueing for an exit escalator from obstructing an arriving escalator run-off.

2. Identify those platforms at which large queues occur. Using data from ROCKT Station, Figure 5.18 and Table 5.3 show that the number of platforms at which there is a high probability of large queues at exit escalators is limited. Because wide queues are particularly likely to lead to dangerous situations, it is advised that risk assessments be conducted on the basis of targeted qualitative observation, until such time as further study (see above) gives a clearer picture of the underlying patterns and the frequency with which such effects occur.

Chapter 6

Passengers too close to the platform edge because of crowding

Chapter 3 discussed the hazards that can arise when people get too close to the edge of the platform. The present chapter describes the results of research into passengers standing or walking too close to the edge of the platform owing to crowding. In Chapter 3, this was identified as the second limitation on the service capacity of a platform (see Figure 6.1). This chapter focuses on the following hypothesis: *As a result of crowding on the platform, passengers stand or walk too close to the edge.*

This chapter presents an aggregated study into whether passengers on the busiest platform at Utrecht Centraal regularly stand or walk closer to the platform edge when there are more people on the platform. The relationship between density and the presence of passengers close to the platform edge is quantified on the basis of the empirical data available for this research (see Chapter 4). The definition of "close to the platform edge" used in this study reflects the Dutch standard for the minimum distance between a person and the platform edge, which is 0.8 metres (see Chapter 3). To test the hypothesis, trajectory data from Utrecht Centraal were studied to find out where on the platform passengers stand and walk before their train arrives. The data from Amsterdam Zuid are less suitable for this sub-topic, as the measurement area at that location is relatively small, so those trajectory data have only been used to assess the degree to which the results can be generally applied.

In studying the position of passengers on the platform, both the distance between passengers and the platform edge and the distribution of passengers along the platform were investigated. As provided for in the standards, the criterion is whether a person stands or walks in the 0.8-metre zone along the platform edge, referred to as the "buffer zone". As other countries specify buffer zones of other widths, the width of the buffer zone was varied to examine the effect of different buffer-zone widths on the results. Research for this sub-topic shows that at both Utrecht Centraal and Amsterdam Zuid, walking and standing in the buffer zone increases as crowding increases. However, the relationship between crowding and proximity to the platform edge is not identical at the two stations. That relationship is also affected by the width of the buffer zone laid down in standards. This part of the study also shows that as crowding increases, passengers in the buffer zone stand still more and walk less. As a result, they spend longer in the buffer zone when the platform is crowded.

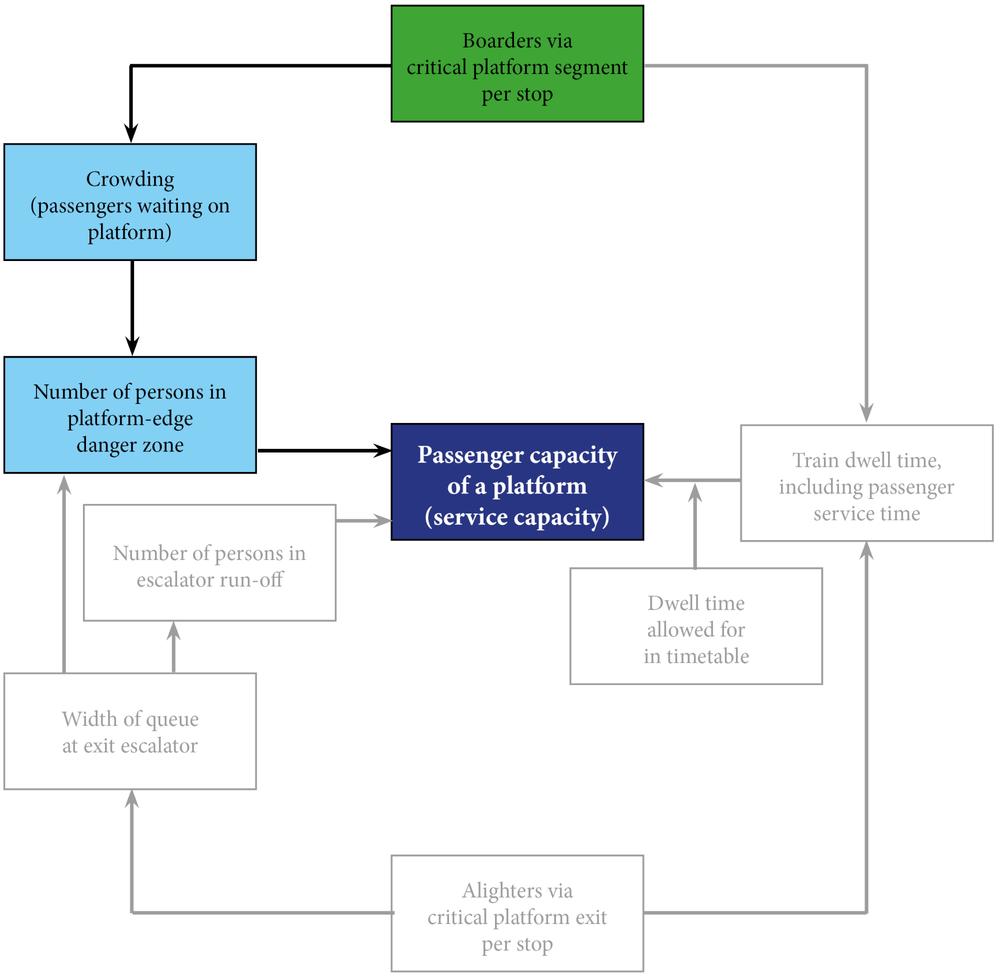


Figure 6.1: The topic in the context of platform capacity

The present chapter is structured as follows. Section 6.1 provides an overview of the limited literature on this subject. That overview forms the basis for the remainder of the thematic study. Section 6.3 describes how the research was carried out, and Section 6.4 presents the results. The chapter ends with conclusions (Section 6.5), points for discussion (Section 6.6) and recommendations (Section 6.7).

6.1 Literature study

The location on the platform at which a person waits for their train is the result of conscious or unconscious choices that they make in a specific situation. In view of the research question, this literature study will differentiate between the distribution of passengers along the platform and across it.

Heinz [72] divides passengers into two groups as regards their choice of where to stand *along* the platform. 1. Passengers who know their way. These passengers wait where they know from experience that they will be near a train door when the train stops. 2. Passengers who are unfamiliar with the situation, and do not know in advance where on the platform the train will stop. According to Heinz, members of this group mainly stand near other passengers. She notes that passengers in both groups who have a reason for using specific doors or sections of the train (e.g. they have made a seat reservation) behave differently from passengers who have to choose their own seats. Her study does not address the question of passenger distribution *across* the platform.

Bosina et al. [55] studied the manner in which waiting passengers distributed themselves over the available platform area at two stations in Switzerland. At low densities, and up to a certain time before the arrival of their train, passengers mainly wait near objects on the platform. They tend to choose benches, railings and the walls next to access points, as long as they are clean. Passengers also maintain a certain distance from one another. As passenger density increases, and the arrival of their train becomes imminent, passengers tend to stand increasingly close to the platform access points, causing passenger density on those parts of the platform to increase still further. Earlier research by Wirasinghe and Szplett [168], Szplett and Wirasinghe [169], Wu et al. [170] and Krstanoski [171] confirm that waiting passengers tend to congregate near platform entrances. None of those studies addresses the question of passenger distribution *across* the platform.

Like Bosina et al. and Heinz, Seitz et al. [172] report that passengers do not distribute themselves evenly along platforms, based on their observations of waiting behaviour on a metro platform in Vienna. They also noted that passengers stay at least 0.5 m from the platform edge. Their study provides no information regarding the number of passengers or the levels of density on the platform.

The Swiss *Bundesamt für Verkehr* (BAV) gives three reasons why passengers enter the marked zone along the platform edge [93]. 1. Waiting in this zone, to maintain sufficient distance from other people. 2. Walking in this zone, to pass people who are walking more slowly. 3. Avoiding people who are waiting. Their publication provides no figures regarding use of the marked zone along the edge of the platform.

In the United Kingdom, a "yellow line zone" was not always obligatory in the past, and there were various reasons for creating such zones where they did exist. On the basis of interviews with railway passengers in the United Kingdom, the *Rail Safety and Standards Board* [52] concluded that passengers do indeed perceive some form of hazard on a railway platform, but that they cannot describe it, and that they have little or no idea as to the purpose of the yellow line on a platform. A comparable survey of railway personnel – both platform staff and drivers – revealed that they see the risks as more severe than do passengers, but that they too are unable to describe them unambiguously. Using focus groups consisting of rail passengers in the UK, Cynk et al. [65] established that one reason for standing close to the platform edge was the wish to board the train as quickly as possible. Furthermore, a certain proportion of passengers said that they saw the yellow line as merely a recommendation. The RSSB has estimated the reduction in risk – expressed as the expected number of train/platform incidents – that is achieved by means of a yellow line [52]. They estimate that a yellow line on its own will reduce such incidents by 12%, while a yellow line plus public address announcements will yield a 68% reduction. At higher levels of crowding, risk reduction drops to 48%. By contrast, the same study reports a 98% fall in incidents on the London Underground. No explanation is given for this difference. The RSSB study mentions a risk associated with the positioning of the yellow line: on the London Underground, placing the line too far from the platform edge created a natural walking route along the edge, which would tend to increase the danger rather than reduce it. The publication does not state the exact distance between line and platform edge in either instance.

Thurau et al. [70] studied the link between crowding and waiting in the marked zone along the platform edge at three stations in Switzerland and the Netherlands. They found that use of this zone increased with crowding. Interviews with rail passengers in Switzerland for that research established that 80% of passengers at the three stations studied knew the meaning of the marked zone along the platform edge, the *Gefahrenbereich* (danger zone). However, the majority nonetheless took a conscious decision to use the danger zone when no train was standing at the platform. Finally, this study showed that how safe people feel is strongly influenced by the degree of crowding and by whether trains are passing the platform.

Cox et al. investigated the links between crowding, stress, health and subjective safety [173] in trains and on stations. They raise the possibility that there may be no linear relationship between the objective density of persons in a given situation and the degree of crowding that those persons perceive. Perceived crowding is influenced by the specific circumstances and by the state of mind of the person subjected to crowding. The predictability of the situation and the degree to which a person can control their proximity to others have a major influence on perceived crowding. Evans and Wener [174] come to a similar conclusion in their research on perception of crowding in trains.

It is not possible, on the basis of existing research, to obtain an unambiguous, quantified picture of the factors that influence the use of the buffer zone. The distribution of passengers over the length and width of the platform would appear to be important, and the highest levels of crowding are expected at the platform entrances. Existing research does not enable us to say how wide the buffer zone should be in order to achieve the desired results, or what role crowding plays in this. A certain percentage of passengers would appear to be aware of the hazards of the platform edge, but to nonetheless choose to wait or walk in the buffer zone. Crowding is named as one of the reasons for this behaviour. Only one publication has been identified that established a quantified relationship between crowding and distance from the platform edge [70]. The author of the present thesis was involved in that research. In this chapter, that relationship will be investigated further, using Platform 5 at Utrecht Centraal.

6.2 Conceptual model and research questions

Figure 6.2 sets out the conceptual model for this topic, based on the literature study. The model shows that as the number of persons on a platform increases, so do the number of persons at specific locations on the platform (such as platform entrances) – expressed as density – and the distribution of passengers along the platform. As a consequence of the increasing density at specific locations, people at those locations stand or walk closer to the platform edge. This leads to an increase in the use of the buffer zone for walking and/or waiting.

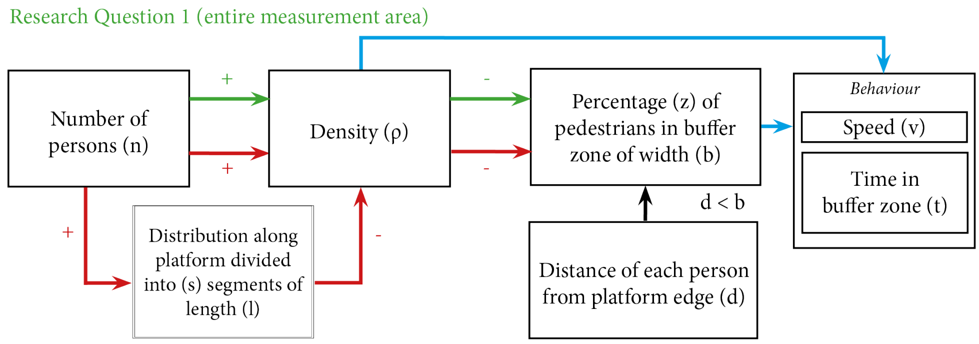


Figure 6.2: Conceptual model

Figure 6.2 encompasses the following three research questions:

1. To what degree does the number of persons in the buffer zone increase with the mean density of persons on the platform?
2. To what degree does the number of persons in the buffer zone increase with the density of persons on segments of the platform at different segment lengths?
3. Are the people in the buffer zone standing or walking?

For the first of these questions, the measurement area is examined as a single entity. Here, we are looking at the relationship between the number of persons in the measurement area – which can also be expressed as a mean density – and the distance between these persons and the platform edge, or the number of people in the buffer zone. This gives an initial overall impression of the situation, but does not make the distribution of passengers along the measurement area explicit. The second question does render this factor explicit. To achieve this, the measurement area is divided into segments along its length, and a similar analysis is carried out. The third question examines the behaviour of people in the buffer zone.

This study involves the following variables:

- The number of persons in the measurement area or a segment of it (n).
- The density of persons in the measurement area or a segment of it (ρ).
- The distance between persons and the edge of the platform (d).
- The number of persons in the buffer zone within the measurement area or a segment of it (z). Whether a person is in the buffer zone is deduced from the distance between the person and the platform edge (d).
- The behaviour of people while they are in the buffer zone, i.e. Whether they are walking or waiting. This is deduced from their walking speed (v).
- The length of time a person spends in the buffer zone, walking or waiting (t).
- The length of the measurement area or segment (l).

- The width of the buffer zone (b).
- The area of the measurement area or segment (a).
- The measurement area (m) or segment (s).

6.3 Research methodology

The conceptual model describes the relationship between platform density and use of the buffer zone. As for Chapter 5, this chapter will investigate the aggregated relationships between these factors. The following sub-sections will discuss the cases, the data and the analysis methodology.

6.3.1 Cases and data

For this topic, measurement data were available from one platform side at Utrecht Centraal and two platform sides on two islands at Amsterdam Zuid. There are differences between the two stations – as regards both situation and data availability – that are important for the present study.

1. The 30-metre measurement areas at Amsterdam Zuid cover only a limited portion of the total platform length (400 m) and of the length of the trains that stop there (60 m to 300 m). See Figure 4.8. The measurement area at Utrecht Centraal is approximately 130 m long and coincides with the section of the platform where all trains stop (see Figure 4.11).

2. The measurement areas on the platforms at Amsterdam Zuid do not necessarily cover those areas where the largest number of passengers board. This is because of the positions of the platform entrances relative to the train stopping positions (see Figure 6.3). By contrast, the measurement area at Utrecht Centraal does cover the part of the platform where crowding is most intense.

This study was therefore conducted using the data from Platform 5 at Utrecht Centraal. At the end of this chapter, the question is examined as to whether comparable analyses on the data for the four platforms at Amsterdam Zuid produce comparable results.

Section 4.4 describes the data available for this part of the study. The table below lists the subset of that data that was actually used. This subset was created by cleaning the dataset using the analysis method described below.

Station	Platform	n
Amsterdam Zuid	1-2	3,281
	3-4	2,927
Utrecht Centraal	5	6,826

Table 6.1: Number of stops (n) per case

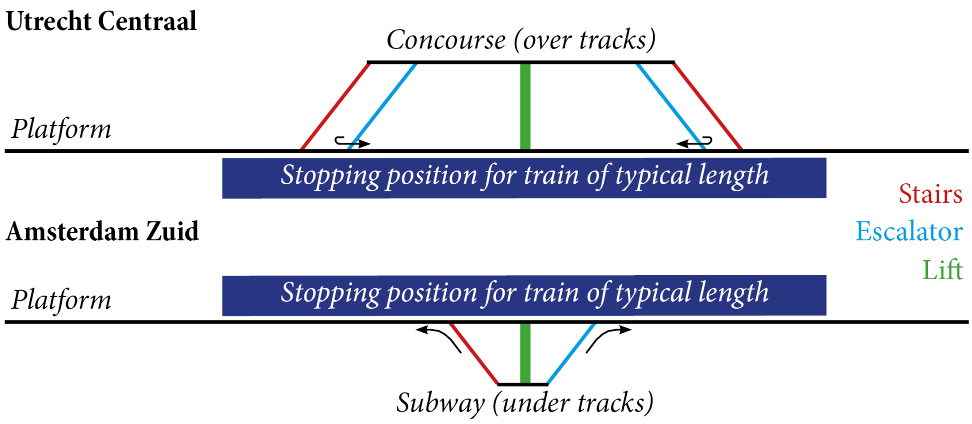


Figure 6.3: Schematic representation of the positions of the escalators on the platforms relative to the stopping position of the train, to the concourse (Utrecht Centraal) and to the subway (Amsterdam Zuid)

6.3.2 Analysis method

Analysis was conducted in five phases:

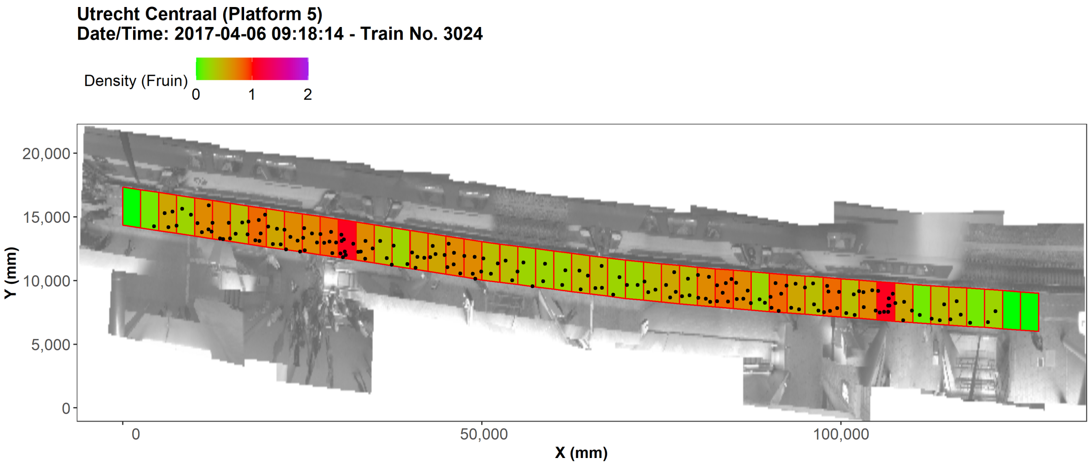
1. Define density and position (inside or outside buffer zone).
2. Select suitable segment length.
3. Select regression models.
4. Identify regular use of buffer zone owing to crowding.
5. Identify behaviour characteristics of persons in the buffer zone.

Define density and position (inside or outside buffer zone)

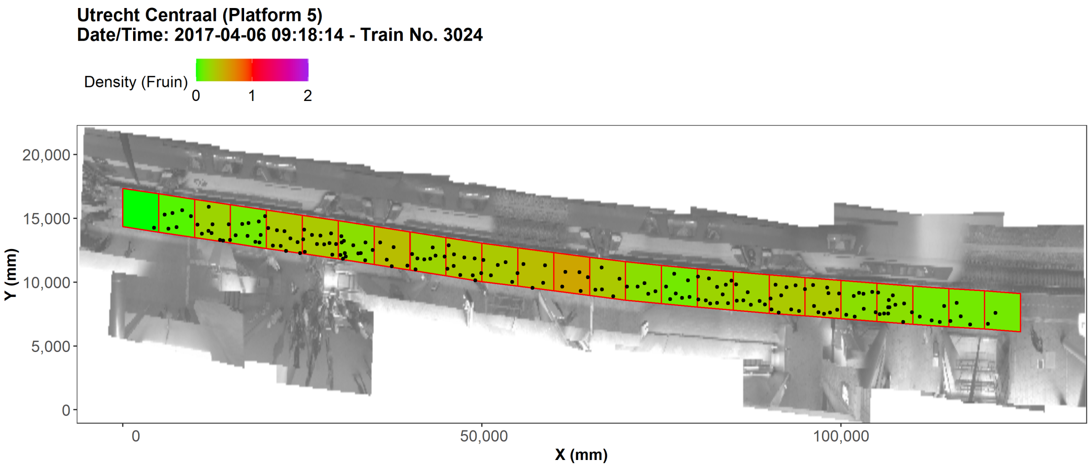
The Fruin density definition was used to analyse the relationship between crowding (density) and walking or waiting near the platform edge. See Section 4.3. The buffer zone was examined separately from the rest of the measurement area. Equation 6.1 was then used to determine whether each person (i) in the measurement area was inside the buffer zone, on the basis of the distance between the person and the platform edge. See Sub-section 4.3.5. The dimensions of a pedestrian were taken into account (see Figure 4.14).

$$d_{i;t} < b \tag{6.1}$$

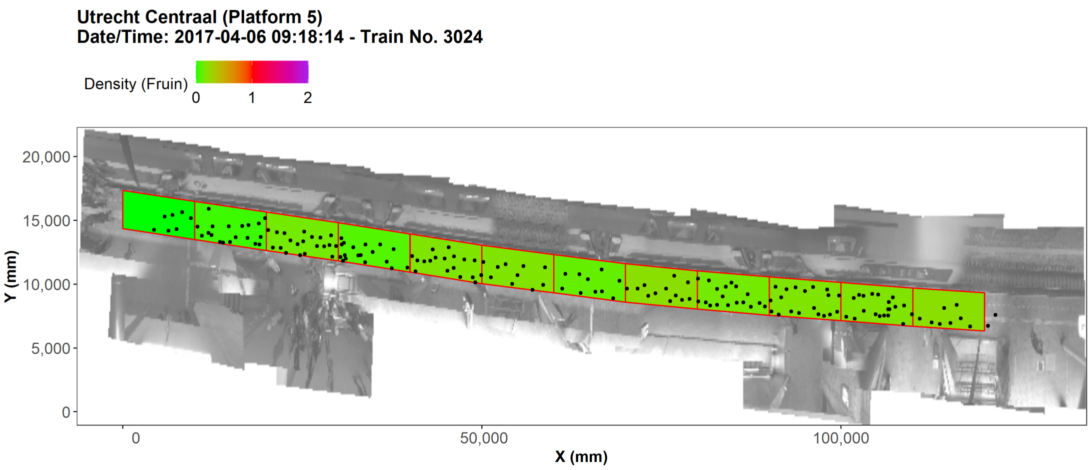
Using this definition of density, and the distinction between passengers being inside and outside the buffer zone, the relationship between crowding and use of the buffer zone was determined by comparing the number of passengers in the buffer zone with the number of passengers in the rest of the measurement area.



(a) Segment length (l): 2.5 m



(b) Segment length: (l) 5 m



(c) Segment length: (l) 10 m

Figure 6.4: Graphical representation of the dataset for Train 3024, 6 April 2017, Utrecht Centraal, various segment lengths

Selecting a suitable segment length

Measuring density in this fashion has the disadvantage that the choice of segment length can influence the results (see Figure 6.4). The measurement area was therefore divided into segments of various lengths. For Question 1, the measurement area was treated as one single segment, while for Question 2 it was divided into segments of 2.5, 5 and 10 metres.

The shortest segment length was so chosen that a relatively small number of persons would result in high density, without the segment length coinciding with the dimensions of an individual pedestrian. The longest segment length corresponds approximately to the distance between two doors on Intercity rolling stock commonly used in the Netherlands. This length was chosen on the assumption that at greater segment lengths, results would be very similar to those obtained when considering the measurement area as a single segment. The 5-metre length was chosen as being an intermediate value.

Selecting regression models

Next, as for Chapter 5, regression models were selected with which to quantify the relationship between crowding and use of the buffer zone on Platform 5 at Utrecht Centraal. Calculations were first performed with a buffer zone width (b) of 0.8 m, which is the Dutch standard, and then for other buffer-zone widths. The analysis with a 0.8-metre buffer zone was repeated using data from Amsterdam Zuid, to assess the degree to which it was possible to apply the results more generally.

As in Chapter 5, the following criteria were applied to the regression analyses [166] [167]:

1. There is a relationship between the independent variable – pedestrian density (ρ) for each stop (i) – and the dependent variable.

2. The dependent variable – the number of persons in the buffer zone (z) – is a continuous variable.

3. The observations in the dataset are independent of each other. In other words, there is no statistical relationship between queues A and B in the dataset to which the regression is being applied. If that were to be the case, autocorrelation would occur and the regression analysis could give a distorted picture.

4. The residuals (estimates of ε) are normally distributed and display the same variation for all independent values.

Two types of linear regression were used for this study (see Figure 6.5):

1. The first was a **standard linear model** as per Equation 6.2. This type of linear regression is based on the assumption that pedestrian densities on platforms will be in the lower part of the fundamental diagram (Figure 3.7), because of the safety standards that apply (see Section 3.2). At these lower density levels (up to approximately 1.5 pedestrians per square metre), the relationship between density and the number of persons in the buffer zone can be (almost) linear, as

can the relationship between density and flow in the fundamental diagram. In the linear model, β_0 is the minimum percentage of persons in the buffer zone. This value can be interpreted as minimal use of the buffer zone, i.e. few persons are present in the platform segment.

2. The second type of linear regression is an **exponential function**, as defined in Equation 6.3. This type is based on the idea that at higher densities, an asymptote must occur. It would not be logical for density in the buffer zone to become higher than that observed over the remainder of the width of the platform. The position of the asymptote can be derived from Equation 6.4, and Equation 6.5 gives the expected maximum value. For the exponential model, β_0 corresponds to maximum use of the buffer zone, i.e. a large number of persons in the platform segment.

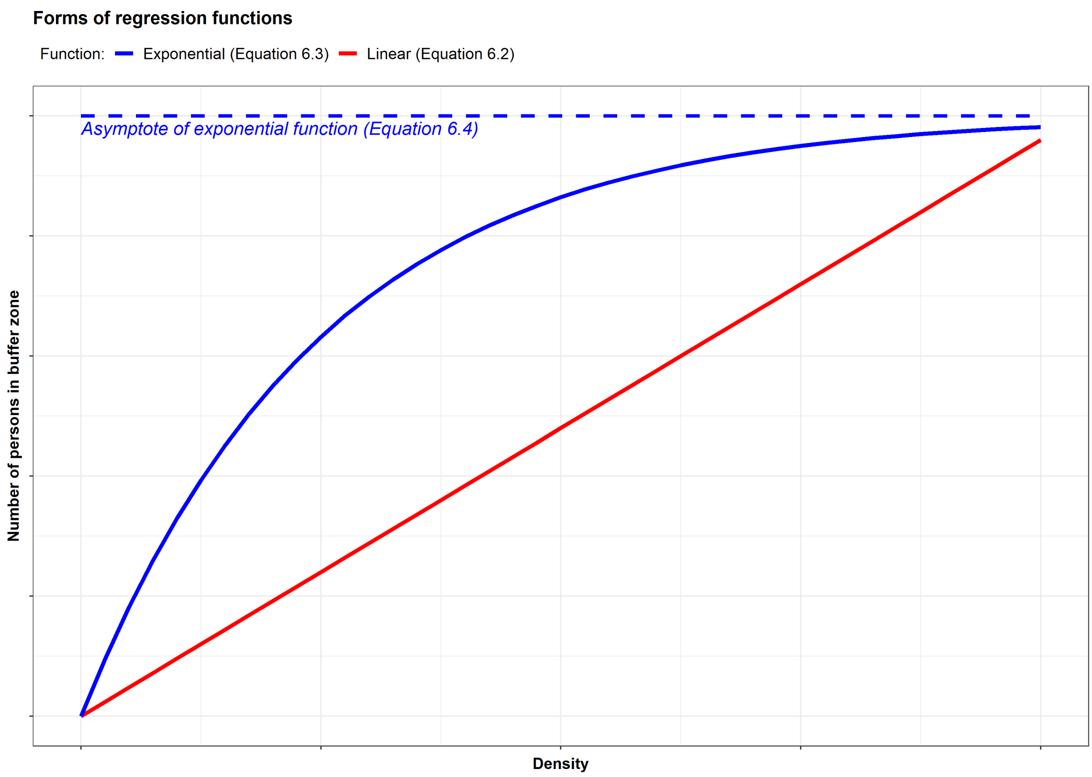


Figure 6.5: Forms of regression model

$$\frac{z_i}{n_i} = \beta_0 + \beta_1 \rho_i + \varepsilon_i \tag{6.2}$$

$$\frac{z_i}{n_i} = \beta_0 + \beta_1 e^{-\beta_2 \rho_i} + \varepsilon_i \tag{6.3}$$

$$\lim_{\rho \to \infty} f(\rho) = \beta_0 \tag{6.4}$$

$$\max(\beta_0) = \frac{b}{\text{Platform width}} \tag{6.5}$$

This study uses the value and significance of β_0, β_1 and β_2, together with the goodness of fit, to verify compliance with the first criterion.

- The **values** of the regression parameters are interpreted as indicating whether the independent variable influences the dependent variable and is hence relevant to the results.
- The **significance** of the regression parameters is used to distinguish between a relationship in the form of a pattern, and coincidence. If the estimated values of the regression parameters are not significant in terms of p, then the regression analysis is not capable of indicating the effect on the dependent variable. In such a case, it is also possible that there is an independent variable that was not included in the model. It is also possible that some of the preconditions for the regression model were not satisfied.
- **Goodness of fit** is assessed by visual inspection of the scatter plot on which the regression line is drawn. In addition, the mean absolute error (MAE) is taken into account. The lower the MAE, the better the estimated regression function fits the data.

As for queue formation at escalators (see Chapter 5), in the case of passenger flows on a platform before the arrival of a train there is also a time period with a possibility of autocorrelation, of which the duration is not known in advance. Earlier research has established that passengers are often distributed unevenly over the platform. Generally speaking, concentrations of waiting passengers form near platform entrances. When these concentrations result in high densities, it becomes difficult for passengers to reach less crowded areas of the platform, causing these concentrations to increase still further.

Autocorrelation can also occur between observations of two successive trains. This can occur, for instance, when two trains are going to leave in quick succession, and many passengers who intend to board the second train arrive on the platform while others are still waiting for the first. In such a case, the presence of a large number of passengers who are waiting for the first train influences the distribution over the platform of passengers who intend to travel by the second.

The reason for this is that departing passengers choose their time of arrival on the platform on the basis of the departure time of their train, and not its arrival time.

To avoid the first type of autocorrelation, one observation was selected for each stop, and all analyses were performed using that observation. The selection of observations was carried out in two stages:

1. A time was chosen between 90 and 30 seconds before the arrival of the train at which the largest number of unique pedestrians was recorded in the measurement area. That time was selected relative to the time of arrival of a train, as recorded by SMART Station sensors (see Section 4.1). A dataset was created for the chosen time, using enhanced trajectory data. Choosing the time when the number of passengers is at a maximum also maximizes variety in the number of observations with respect to the independent variable. Verification showed that

selecting a fixed time (e.g. 30 or 45 seconds before the arrival of a train) did not result in sampling bias.

2. Research by Van Hagen [32] has shown that most passengers in the Netherlands arrive on the platform no more than 5 minutes before their train is due to depart. To prevent any correlation between two stops, only those were used that occurred at least 5 minutes after the previous stop and 5 minutes before the following one. This ensured that the platform was clear of passengers from one train (or nearly so) before it began to fill up for the next.

Finally, to assess compliance with Criterion 4, each regression model was verified to check that the residuals were normally distributed. This verification was conducted by means of the widely-used Shapiro-Wilk test of normality [166]. Where relevant, and as in Chapter 5, the problem of the Shapiro-Wilk test being oversensitive when used on large samples was avoided by applying the test to a random sample of 500 observations from the dataset. In selecting observations for this sample, weighting was used to ensure that all values of the independent variable were equally represented. This procedure was repeated 500 times for each dataset, following which the mean significance parameter $\bar{p}$ was calculated. The residuals are deemed to be normally distributed if $\bar{p}$ is greater than 0.05 (= 95% significance).

Identifying regular use of the buffer zone owing to crowding

Earlier research [70] indicates that different passengers perceive the buffer zone differently and react to it differently. There are also differences in the way they interpret the buffer zone markings. ProRail's platform safety risk model (see Chapter 3) makes a distinction between "voluntary use" of the buffer zone and "use resulting from crowding". The individual trajectories in the dataset available for this sub-topic contain no information regarding the degree to which use of the buffer zone is voluntary or involuntary. For this study, use of the buffer zone when there are only a small number of passengers in the measurement area or segment is seen as a clear indicator of "voluntary" use. Utilization of the buffer zone is expressed in terms of the percentage of persons in the measurement area or segment who are in the buffer zone. By calculating these percentages for a large number of stops and segments, it is possible to distinguish between coincidental and regular use of the buffer zone. In calculating the percentages, at least 10 stops are combined for each density value. This is done by dividing the sum of all persons in the buffer zone for all stops within a group by the sum of all persons (in the buffer zone and elsewhere on the platform). A test calculation demonstrated that doubling the minimum number of observations to 20 did not produce any difference in results. Groups of comparable observations were drawn up in two ways:

1. Observations with the same density per segment ($\rho;s$).
2. Observations with the same density, but without distinguishing by segment (ρ).

Examining the behaviour of persons in the buffer zone

Finally, Question 3 was answered by looking at the behaviour of passengers in the buffer zone. Walking speeds (see Sub-section 4.3.4) and time spent in the buffer zone at various densities were investigated using the data available.

6.4 Results

This section describes the results of this thematic study. First, as part of the process of interpreting the results, the influence on the results of the segment length of each platform field was assessed. The next step was to examine use of the 0.8-metre buffer zone on Platform 5 at Utrecht Centraal, 0.8 m being the standard width in the Netherlands. The Utrecht Centraal analyses were then repeated using other buffer zone widths, and for the Amsterdam Zuid data, with a 0.8-metre buffer zone. The two analyses indicate the degree to which the results can be more generally applied. The section concludes with an analysis of the behaviour of people in the buffer zone. The questions are whether they mainly walk or stand, and how long they spend in the buffer zone.

6.4.1 Influence of segment length

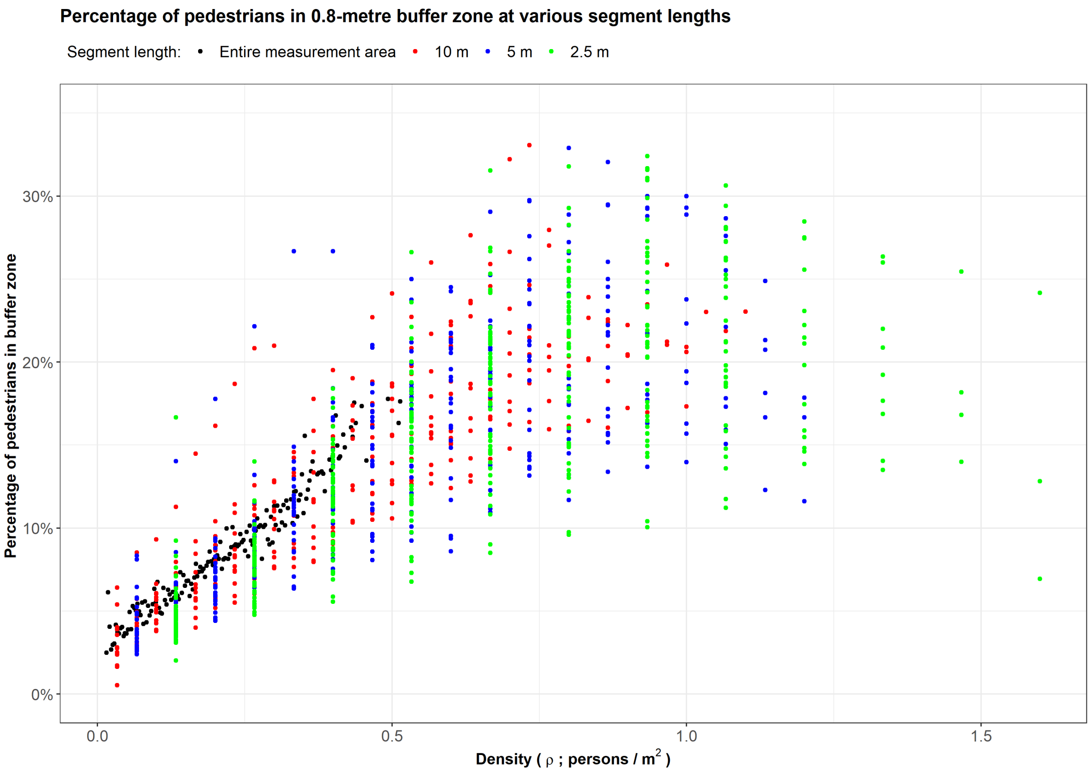
Figure 6.6 plots the percentage of pedestrians in the 0.8-metre buffer zone against pedestrian density, for various segment lengths. The figure shows that where the first definition is applied, the variation in the percentages is high. A regression analysis would therefore result in a poor fit. Using the second definition produces much less variation. Figure 6.6a shows the scatter plots for both group definitions at the four segment lengths.

To discover whether different segment lengths produce different results, the cumulative distributions of all observations were compared using a Kolmogorov–Smirnov test, for the four segment lengths and the two group definitions. Table 6.2 gives the p values for these tests. If p is greater than 0.05, the two distributions can be considered comparable. See Figure H.2 in Appendix H for the cumulative distributions.

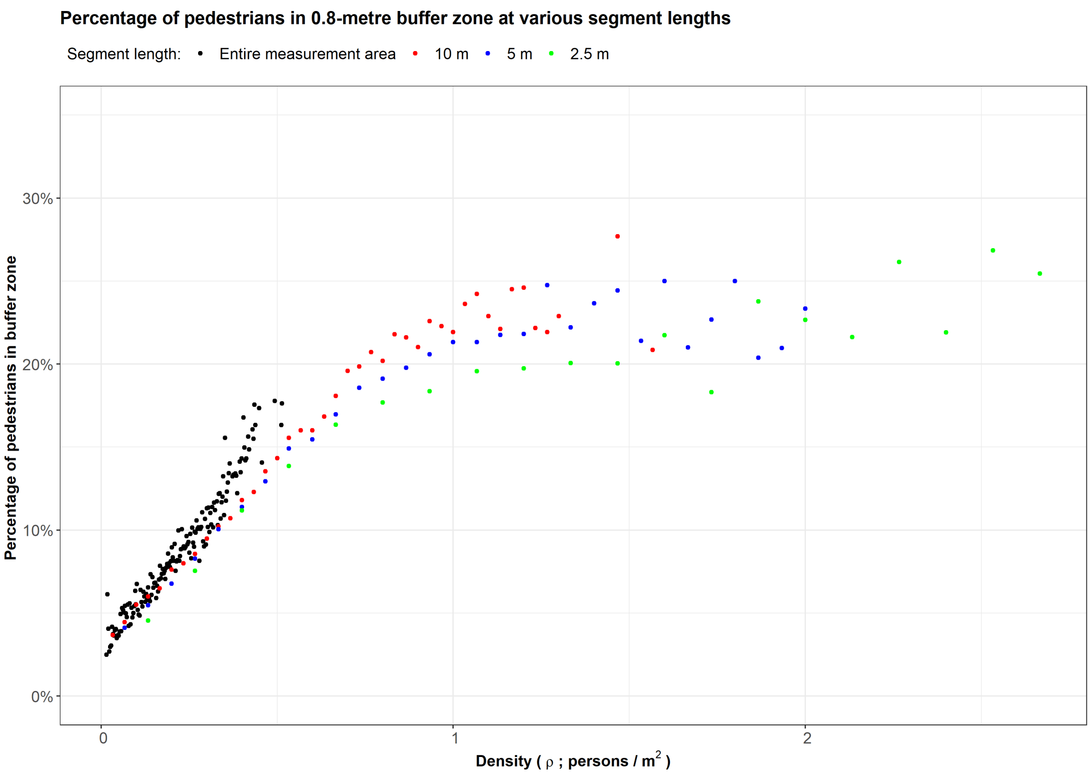
Group	**Segment length**	**2.5 m**	**5 m**	**10 m**
$\rho;s$	Entire measurement area	0	0	0
	2.5 m	1	.25	.01
	5 m	.25	1	.24
	10 m	.01	.24	1
ρ	Entire measurement area	0	0	0
	2.5 m	1	.89	.35
	5 m	.89	1	.75
	10 m	.35	.75	1

Table 6.2: Values of P from Kolmogorov-Smirnov tests on distribution of datasets for each segment length

Comparison of the cumulative distributions reveals that the results obtained when treating the measurement area as a single unit differ from those obtained when the measurement area is divided into segments of various lengths. Figure 6.6a shows that the percentage of persons in the buffer zone rises considerably, whereas the (mean) density remains relatively low. The distribution for a 10-metre segment length differs from that observed with 2.5-metre segments. The distribution for a 5-metre segment length is comparable to that for both 10-metre and 2.5-metre segments. Figure 6.6a



(a) Percentages as a function of density ρ and segment length *s*



(b) Percentages as a function of density ρ (all segment lengths)

Figure 6.6: Percentage of pedestrians in 0.8-metre buffer zone at various segment lengths

shows that a 2.5-metre segment length results in a higher maximum density (ρ), but also that the variation in the percentage of persons in the buffer zone increases at higher densities. These differences between the distributions are important when interpreting the results presented in the next section.

If the second group definition is applied, it is possible for a few segments to determine the results of analyses at higher density values. In practice, the same segments often experience high levels of crowding when the number of passengers increases. To prevent misinterpretation of the analysis results, Figure H.1 and Tables H.1 and H.2 in Appendix H were examined to verify that for a 5-metre segment length, groups for higher densities also included a sufficient number of different segments.

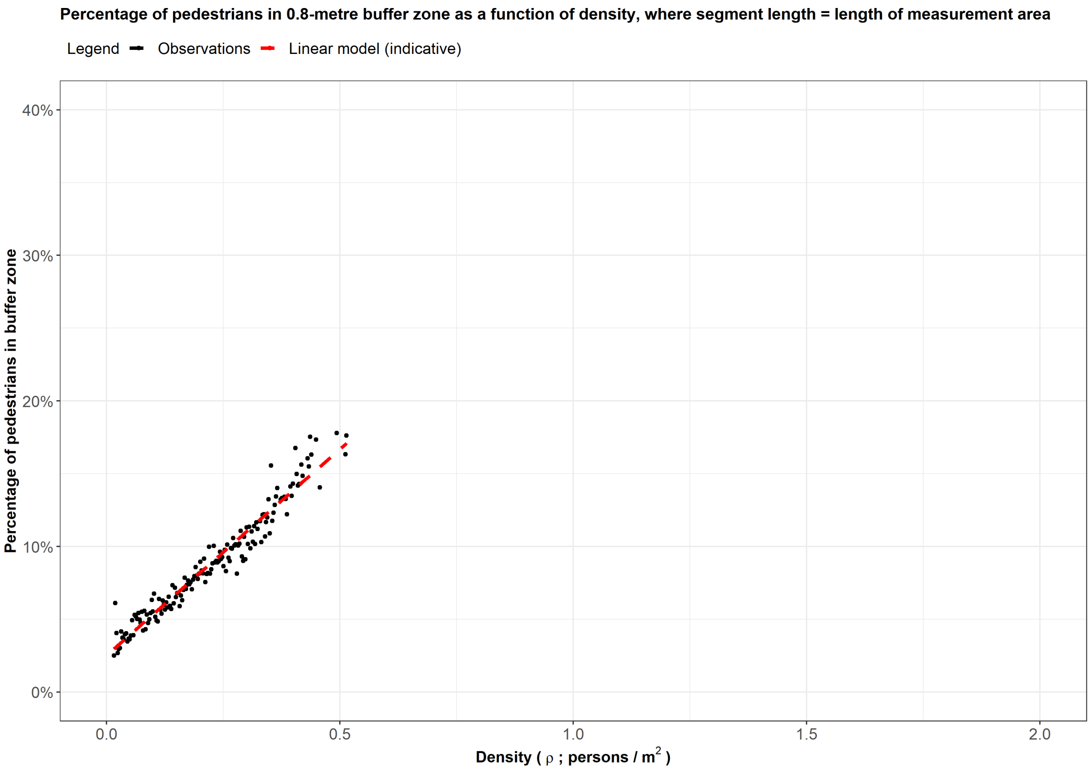
6.4.2 Regression analysis for a 0.8-metre buffer zone

The scatter plot in Figure 6.7 plots the percentage of pedestrians in the buffer zone against pedestrian density. Figure 6.7a shows the results for the measurement area viewed as a single segment. In Figure 6.7b, the measurement area is divided into 5-metre segments. The percentages were calculated for each segment number and density. Figure 6.7c also shows results with segmentation. However, that figure does not distinguish between segment numbers; observations are only grouped by density. Figure 6.7d shows the results for various segment lengths, with observations grouped by density (only) and the percentages of persons in the buffer zone calculated for each group. Table 6.3 shows the parameters used for the linear and exponential regression models, for which the curves are shown in Figure 6.7.

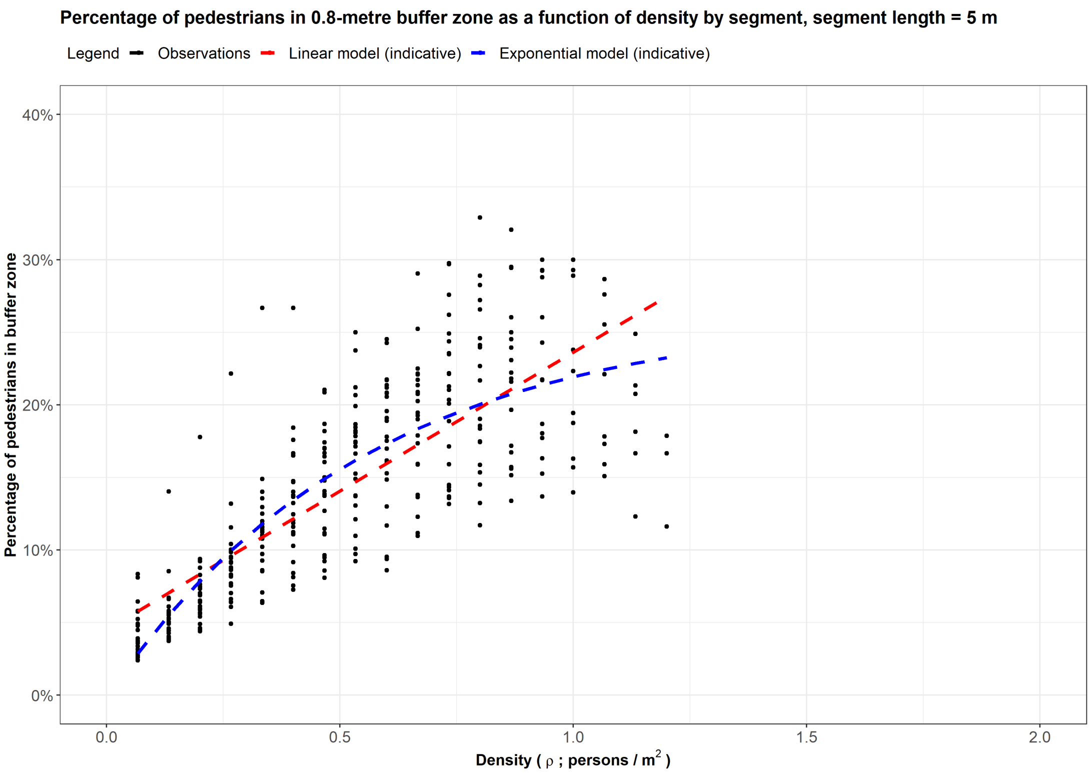
Grp	**Mod**	l	ρ_{max}	β_0 **(p)**	β_1 **(p)**	β_2 **(p)**	**MAE (e-2)**	P_{ks}
ρ	lin	m	.5	.025 (0)	.284 (0)	–	.6	0
ρ	exp	m	.5	-.13 (.01)	.16 (0)	-1.3 (0)	.6	0
ρ;s	lin	5	1.2	.045 (0)	.19 (0)	–	3.6	0
ρ;s	exp	5	1.2	.26 (0)	-.26 (0)	1.8 (0)	3.3	0
ρ	lin	5	2.0	.088 (0)	.091 (0)	–	2.7	.01
ρ	exp	5	2.0	.24 (0)	-.25 (0)	1.9 (0)	1.1	.95
ρ	lin	2.5	2.7	.095 (0)	.067 (0)	–	2.1	.045
ρ	exp	2.5	2.7	.25 (0)	-.24 (0)	1.3 (0)	1.2	.70
ρ	lin	10	1.6	.059 (0)	.15 (0)	–	1.8	0
ρ	exp	10	1.6	.28 (0)	-.28 (0)	1.4 (0)	1.1	.03

Table 6.3: Regression model parameters (lin = Model 6.2; exp = Model 6.3)

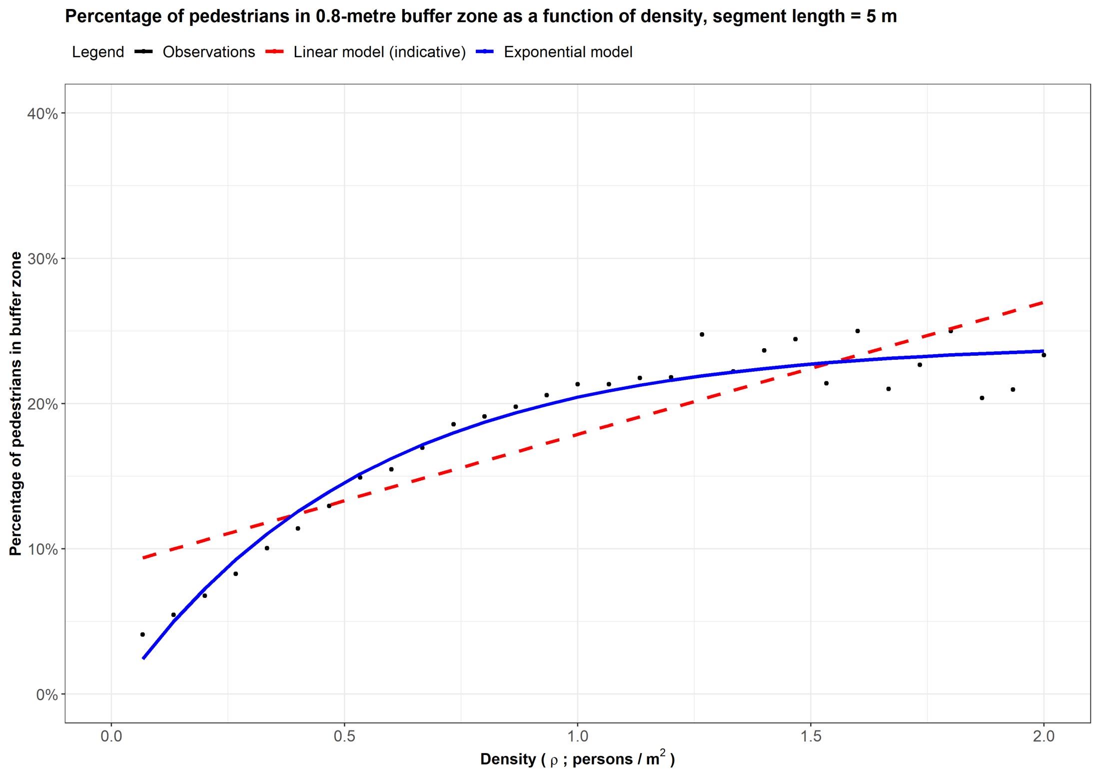
The P_{ks} values from this analysis show that if one uses a segment length of 10 m or treats the measurement area as a single segment, none of the regression models meet the criterion of the residuals being normally distributed. It is hence possible that these models do not provide valid results for this study; they are therefore marked as indicative in Figure 6.7. The analysis also shows that linear models based on Equation 6.2 are not suitable if the measurement area is divided into segments. The best results are obtained using the exponential model (Equation 6.3), with a 5-metre segment length. That model gives the lowest MAE and also satisfies the criterion of normally-



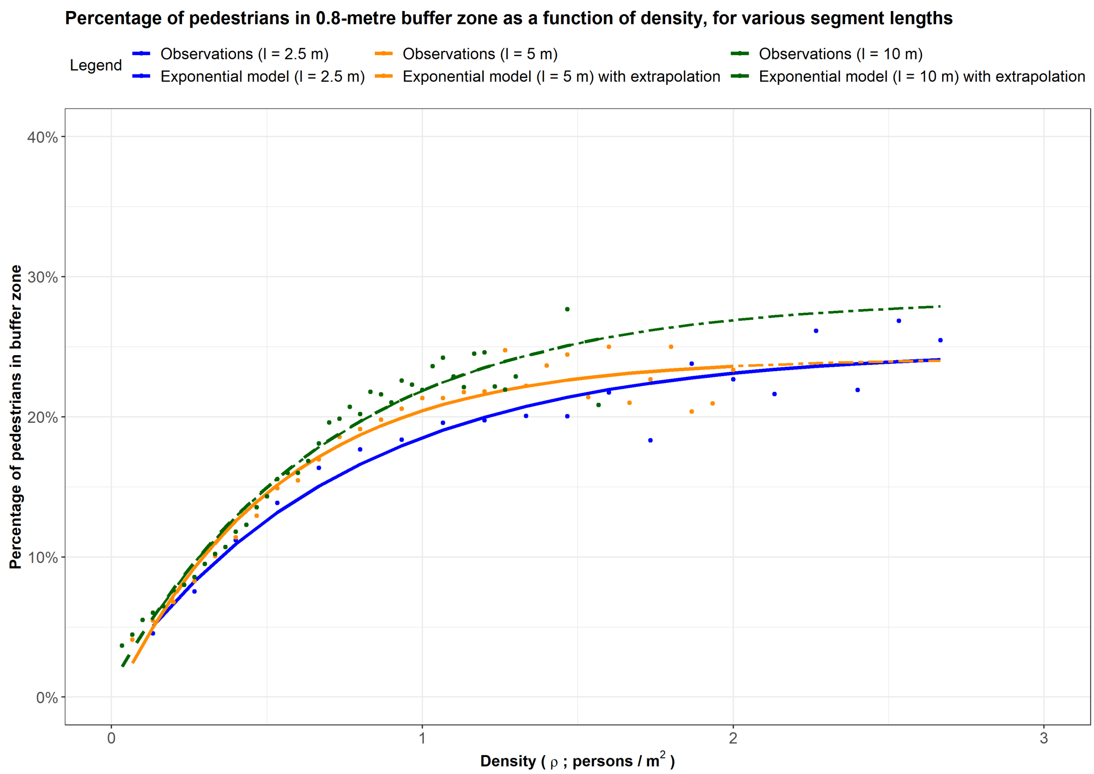
(a) Based on density, entire measurement area



(b) Based on density, by segment



(c) Based on density, all segments



(d) Based on density (all segments), at various segment lengths

Figure 6.7: Percentage of pedestrians in 0.8-metre buffer zone, for measurement area as a whole and various segment lengths

distributed residuals. The exponential model also produces valid results with 2.5-metre segments. The disadvantage of using 5-metre segments is the slightly smaller range of density values ($\rho_{max} = 2$ pedestrians). With a segment length of 2.5 m, the maximum density is 2.7 pedestrians per square metre. The increased variation in estimated percentage at higher densities shows that model uncertainty is increasing. If we extrapolate the exponential model with a 5-metre segment length from 2 to 2.7 passengers per square metre, the results are the same as for a 2.5-metre segment length. The effect of the different segment lengths manifests itself at densities of 0.25 to 2 passengers per square metre. The greatest difference (approximately 3 percentage points) occurs at a density of 1 passenger per square metre.

From the analyses in this section and the previous one, it was concluded that for Platform 5 at Utrecht Centraal the exponential regression model (6.3), in combination with a segment length of 5 m, produces the best results in terms of validity and accuracy. The exponential regression model corresponds both quantitatively and qualitatively to the pattern observed in practice, which is that density in the buffer zone approaches that of the rest of the platform as crowding increases. Using a 5-metre segment length gives the best fit in that range of density values where fit is most relevant.

6.4.3 Regression analysis for buffer zones of other widths

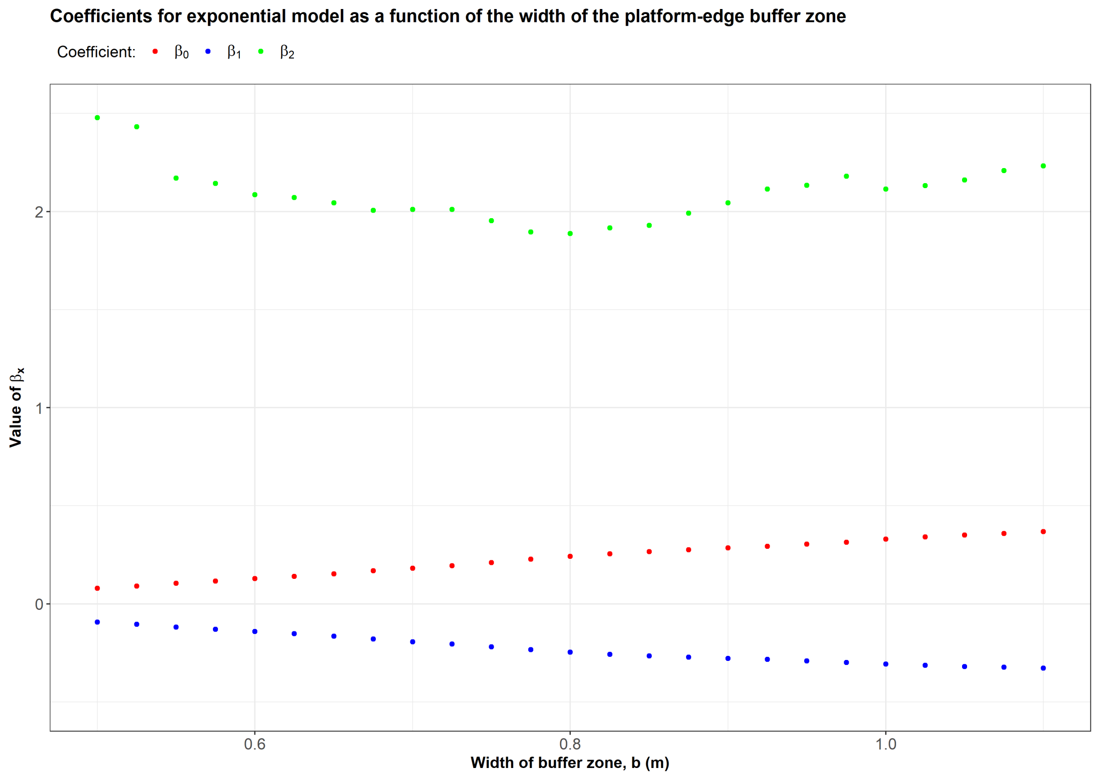
Figure 6.8 shows the results obtained when repeating the same analysis with the exponential regression model, a segment length of 5 m and buffer zone widths other than 0.8 m. For these purposes, it is assumed that the markings on the platform have no effect on passenger behaviour.

Table 6.4 shows the corresponding regression coefficients. The table also shows the maximum expected value of β_0 for the exponential model as a function of the area of the platform segment that is occupied by the buffer zone. The value of P_{ks} indicates whether the residuals are normally distributed. This was the case for all models, with the exception of the model for a 0.4-metre buffer zone. That model was therefore excluded from further study.

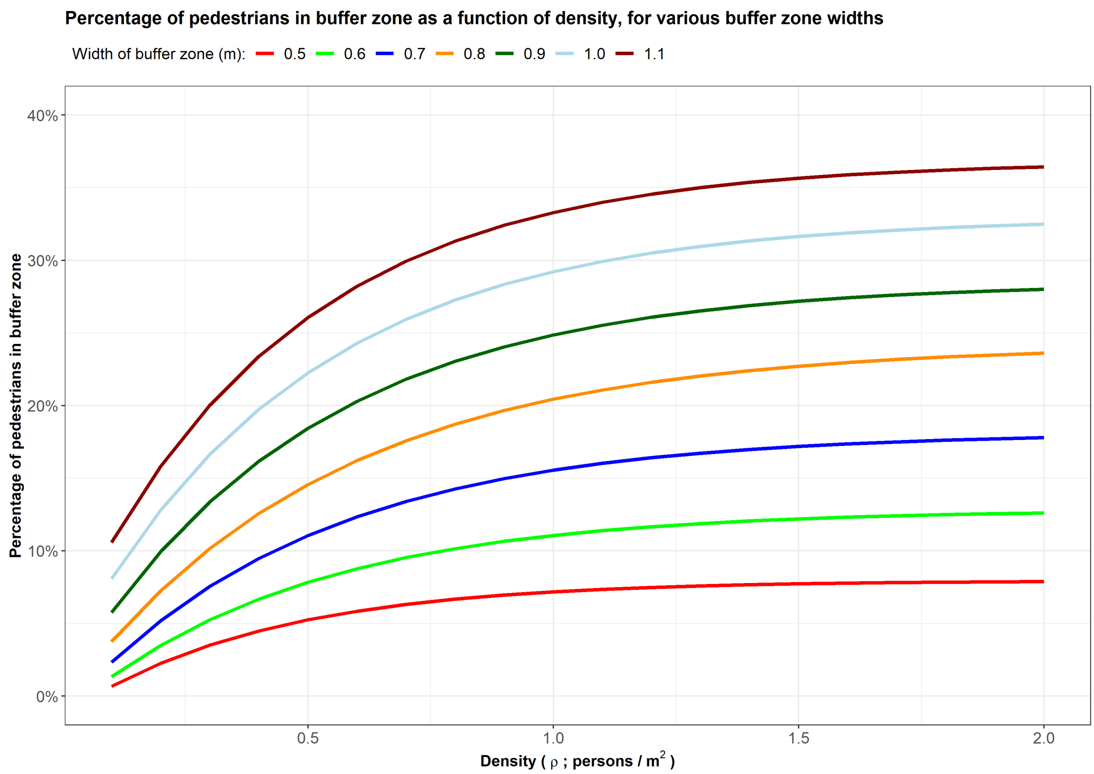
b	max(β_0)	β_0 (p)	β_1 (p)	β_2 (p)	MAE (e-2)	P_{ks}	β_0 / max(β_0)
.4	.13	.05 (0)	-.06 (0)	2.7 (0)	.6	.01	–
.5	.17	.08 (0)	-.09 (0)	2.5 (0)	.9	.19	.48
.6	.2	.13 (0)	-.14 (0)	2.1 (0)	1.0	.22	.65
.7	.23	.18 (0)	-.19 (0)	2.0 (0)	1.1	.10	.77
.8	.27	.25 (0)	-.25 (0)	1.9 (0)	1.1	.95	.93
.9	.3	.28 (0)	-.28 (0)	2.0 (0)	1.0	.15	.93
1.0	.33	.33 (0)	-.31 (0)	2.1 (0)	1.1	.80	1
1.1	.37	.37 (0)	-.33 (0)	2.3 (0)	1.2	.72	1

Table 6.4: Regression model parameters

Figure 6.8 and Table 6.4 show that the width of the buffer zone has a major influence on the percentage of passengers in it. This applies at all densities. At very low densities, the percentage of passengers in the buffer zone is estimated at 3% with

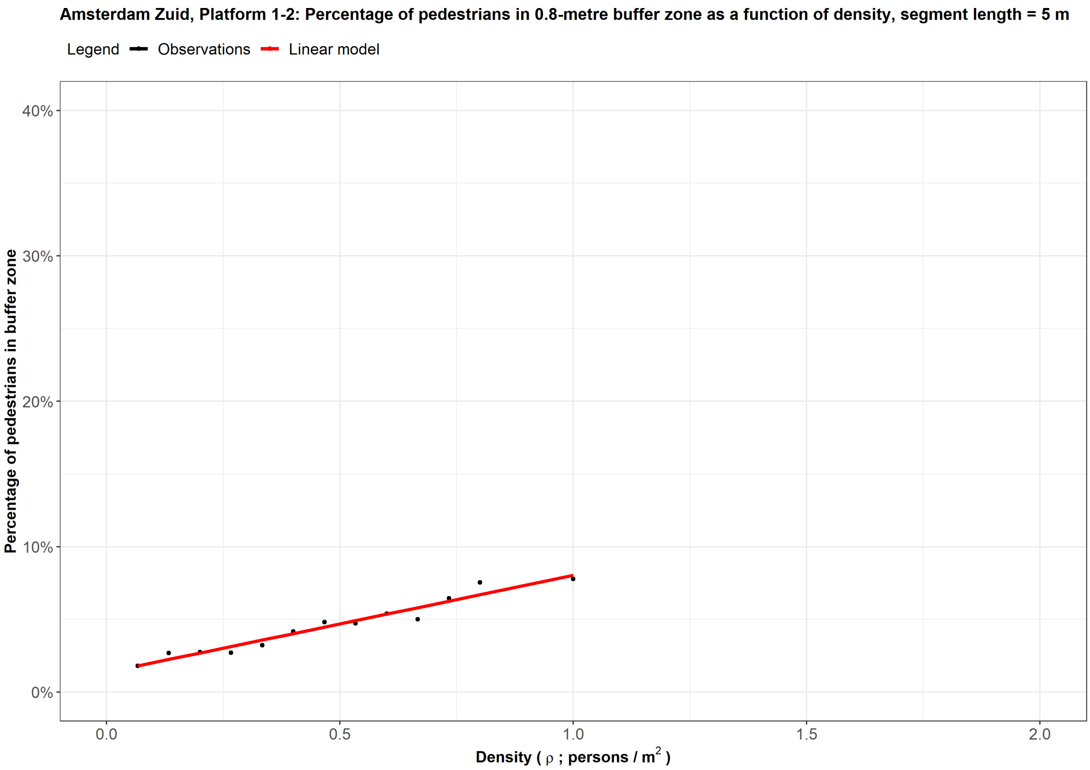


(a) Coefficients

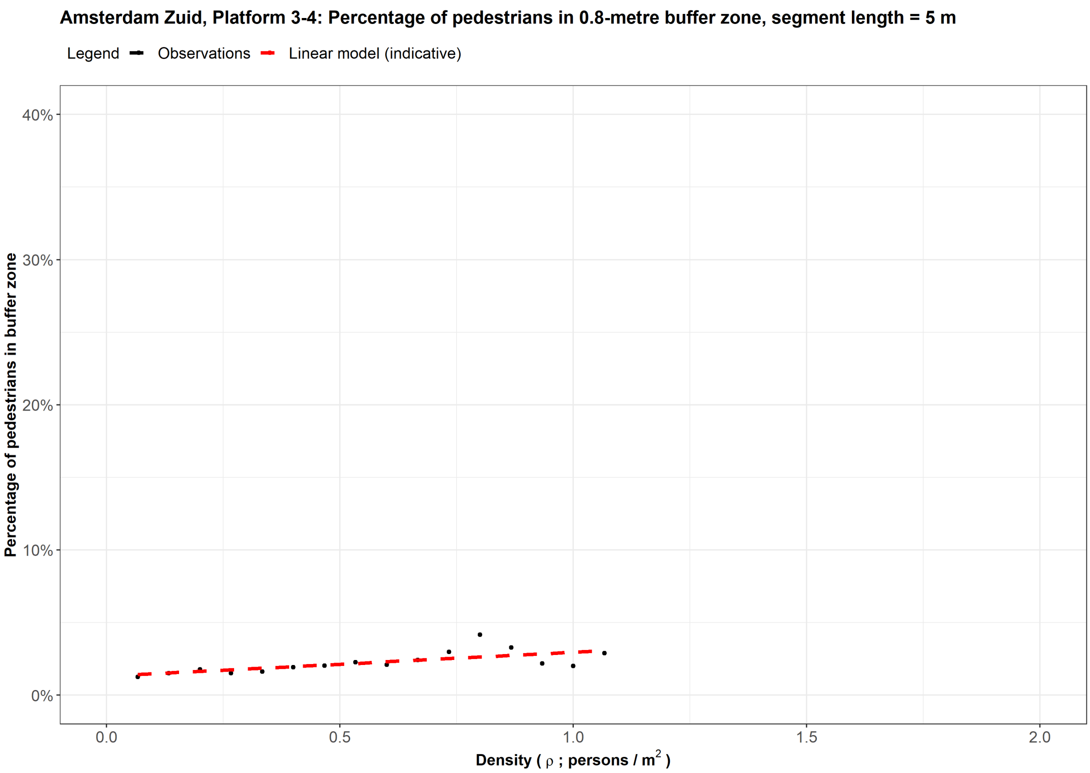


(b) Values

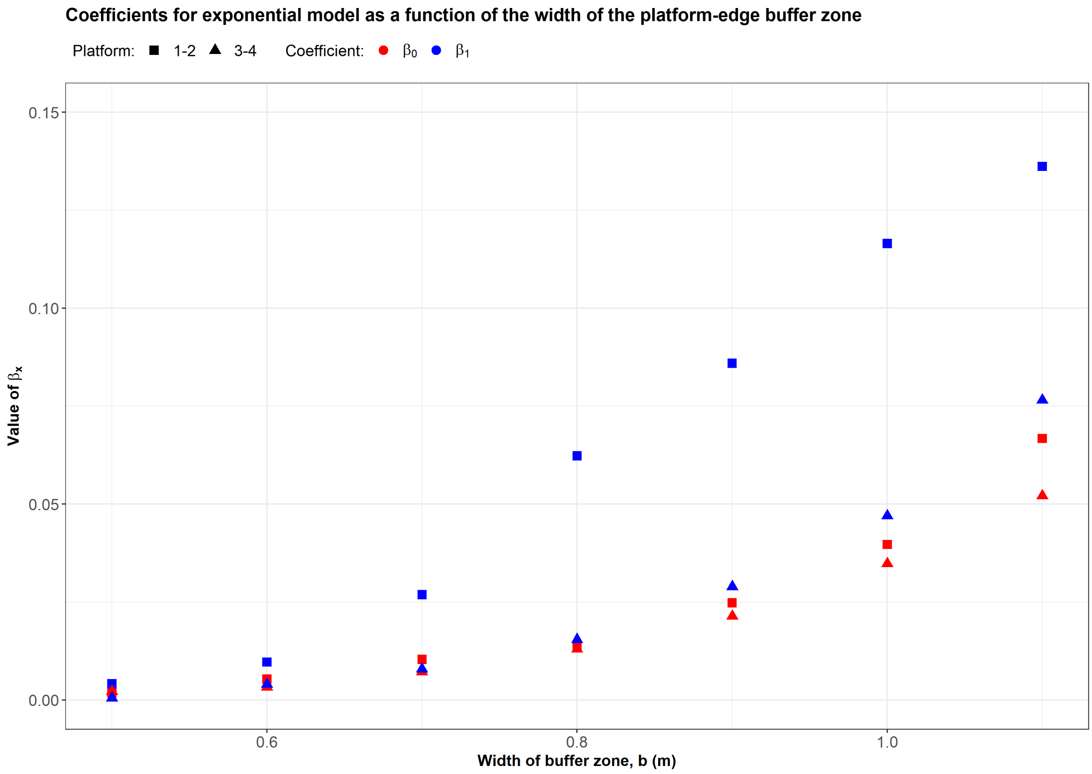
Figure 6.8: Exponential model, various buffer zone widths, segment length = 5 m



(a) Platform 1-2 (with 0.8-metre buffer zone)



(b) Platform 3-4 (with 0.8-m buffer zone)



(c) Coefficients for various buffer zone widths

Figure 6.9: Percentage of pedestrians in the buffer zone, 5-metre segments, Amsterdam Zuid

a 0.8-metre buffer zone and at 1% and 11% with buffer zones of 0.5 m and 1.1 m respectively.

The maxima also vary widely. The maximum is 23% with a 0.8-metre buffer zone and 8% and 37% respectively with the narrowest and broadest zones. Comparison between β_0 and $\max(\beta_0)$ in Table 6.4 shows that at high levels of crowding, the density in wider buffer zones approaches that of the rest of the platform. This effect occurs with buffer zone widths of 0.8 m and above. From this it may be concluded that passengers have a natural tendency to maintain a certain distance between themselves and the platform edge, but only when they are within a limited distance from the edge. Once they get further away from the edge, maintaining a distance from other passengers becomes more important.

6.4.4 Comparison with Amsterdam Zuid

Figure 6.9 and Table 6.5 present the results of repeating the regression analysis with a 0.8-metre buffer zone, a segment length of 5 m and groups consisting of all observations for a given density (all segments together). Three aspects of the results are noteworthy:

1. The range of densities ($\rho_{max} \approx 1$) is much smaller on the two platforms at Amsterdam Zuid than at Utrecht Centraal.

2. The relationship between density and the percentage of persons in the buffer zone is linear and not exponentially decreasing, as was the case for Utrecht Centraal. However, it is possible that an exponentially decreasing function would be observed at higher densities. It is not possible to confirm this on the basis of the present study, owing to the absence of observations at higher densities ($\rho > 1$).

3. Although the platforms at Amsterdam Zuid are physically very similar, it is not possible to produce a valid regression model for Platform 3-4 (P_{ks} = .04), as the residuals are not normally distributed. However, that is the case for Platform 1-2 (P_{ks} = 1).

Aggr.	**Model**	**Platform**	l	ρ_{max}	β_0 (p)	β_1 (p)	**MAE**	P_{ks}
ρ	lin	1-2	5	1	.014 (0)	.067 (0)	.3e-2	1
ρ	lin	3-4	5	1.1	.013 (0)	.017 (0)	.3e-2	.04

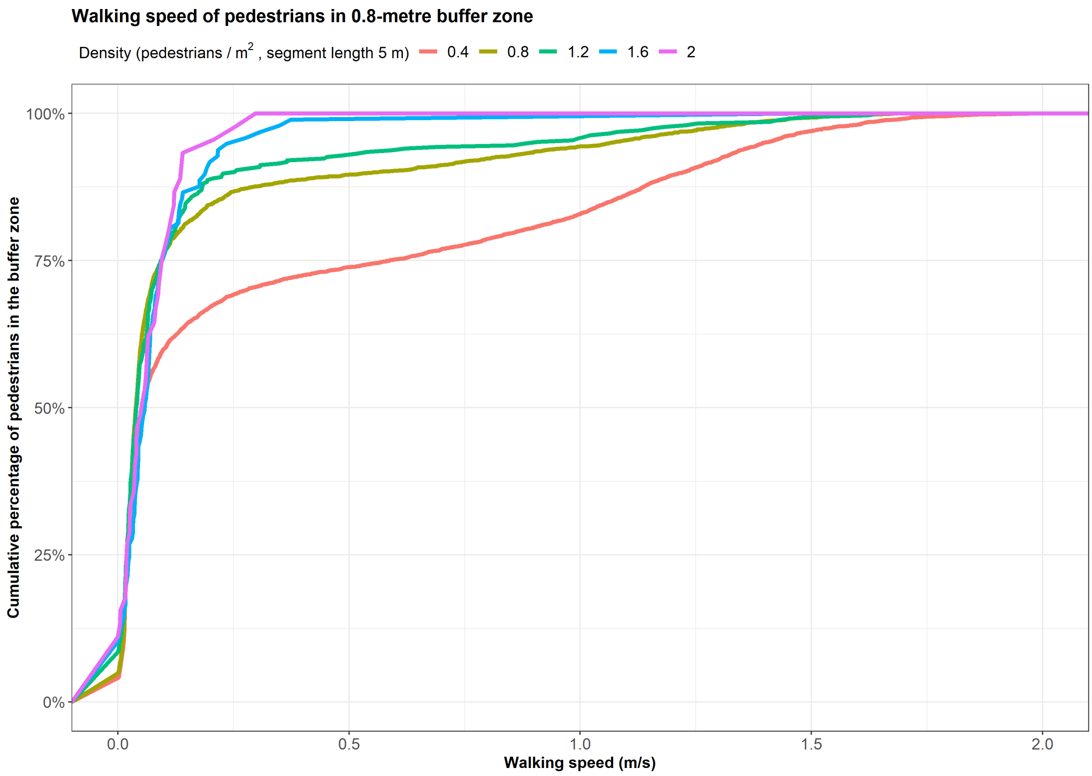
Table 6.5: Linear regression model parameters, Amsterdam Zuid

Comparing the Amsterdam Zuid and Utrecht Centraal results shows that the exponential regression model and parameters selected for Utrecht Centraal are not applicable to other situations on a one-for-one basis. The differences point to the existence of factors that were not taken into account in the present study. These could include the width, layout and utilization of those parts of the platforms that were included in the measurement areas.

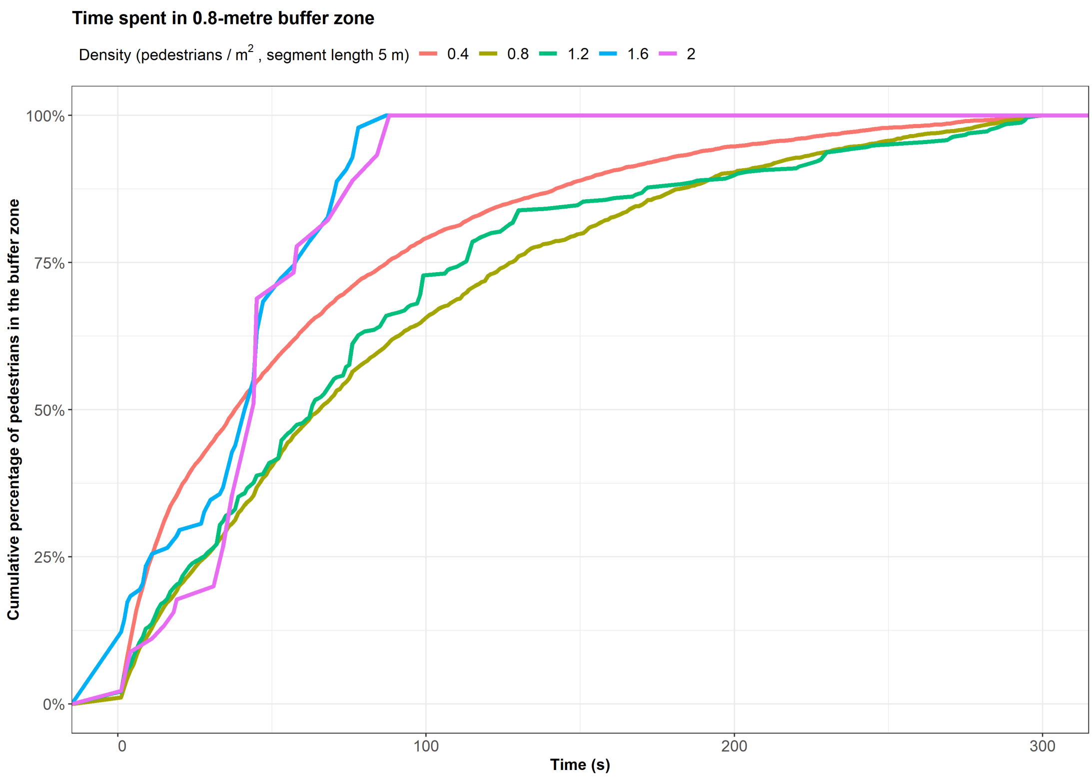
6.4.5 Behaviour in the platform-edge buffer zone

The final part of this analysis involved examining the behaviour of passengers in the buffer zone. This analysis was carried out for a 0.8-metre buffer zone, which corresponds to the situation at Platform 5 of Utrecht Centraal. The first behavioural characteristic is walking speed, from which it is possible to deduce the extent to which passengers are standing in the buffer zone or walking. Figure 6.10a shows that this depends on the pedestrian density in the segment of which the buffer zone forms a part. At a low density (0.4 pedestrians per square metre), over half the passengers in the buffer zone are standing still. Somewhat fewer than half are walking, at speeds of up to about 1.5 m/s. As density increases, the percentage of persons who are walking and their speed both decrease. At high density (2 pedestrians per square metre), approximately three quarters of passengers are standing still, and the maximum speed of those who are walking has fallen to well under 0.5 m/s.

Figure 6.10b shows time spent in the buffer zone. The figure shows that as density increases from 0.4 to 0.8 passengers per square metre, time spent in the buffer zone also increases. As density increases further, time spent in the buffer zone decreases. This is probably because the higher densities mainly occur just before a train arrives. The arrival of a train is the point at which being in the buffer zone ceases to be perceived as dangerous, and is considered an essential part of the boarding process. From this analysis it is therefore concluded that an increase in pedestrian density on the platform will, all other things being equal, lead to a larger number of passengers standing in the buffer zone, who will remain within it for a longer period.



(a) Walking speed



(b) Time spent in buffer zone

Figure 6.10: Behaviour of persons in the buffer zone, Utrecht Centraal, Platform 5

6.5 Conclusions

This thematic study has focused on the following hypothesis: *As a result of crowding on the platform, passengers stand or walk too close to the edge.* That hypothesis was tested against the answers to the following research questions:

1. To what degree does the number of persons in the buffer zone increase with the mean density of persons on the platform?

2. To what degree does the number of persons in the buffer zone increase with the density of persons on segments of the platform at different segment lengths?

3. Are the people in the buffer zone standing or walking?

For **Question 1**, the measurement area was studied as a single unit. However, this part of the study revealed that treating the entire measurement area as one entity does not produce valid results. If the measurement area is large, crowding at specific locations is averaged away with lower levels of crowding on less busy parts of the platform. Treating the measurement area or the platform as one item erroneously ignores the uneven distribution of passengers along the platform that typically occurs. As a result, the relationship between density and the number of persons in the buffer zone is obscured.

For **Question 2**, the measurement area was divided into segments, which does take the uneven distribution of passengers into account. This part of the study revealed that using a segment length of 10 m had similar disadvantages to treating the entire measurement area as one segment. At segment lengths of 2.5 to 5 m, the relationship between density and number of persons in the buffer zone was apparent. A 5-metre segment length gave the best results in terms of validity and accuracy. Equation 6.6 describes, for Platform 5 at Utrecht Centraal, the quantitative relationship between the percentage of persons on the platform who are in the buffer zone and the density of persons in a given platform segment, for a segment length of 5 metres and a buffer zone 0.8 m wide (the standard width in the Netherlands).

$$\frac{z_i}{n_i} = 0.25(1 - e^{-1.9\rho_i)} \tag{6.6}$$

No valid quantitative relationship was found when the method used for Utrecht Centraal was applied to Platform 3-4 at Amsterdam Zuid. However, such a relationship was found for Platform 1-2 at Amsterdam Zuid. The author has no explanation for the difference between the two platforms at Amsterdam Zuid.

The analysis for Platform 1-2 showed that use of the buffer zone increases as the platform becomes more crowded. However, the influence of crowding on use of the buffer zone is less pronounced than at Utrecht Centraal. The fact that applying the function created for Utrecht Centraal produced different results with the Amsterdam Zuid data indicates that the Utrecht Centraal results are not applicable to other stations on a one-for-one basis. However, it should be pointed out that the results for Amsterdam Zuid could be skewed by the small size and specific nature of the measurement area. The measurement area at that station covers the run-on/run-off area of the escalator, and not the buffer zone along the platform edge (see Sub-sections 4.2.1 and 4.2.2 and Section 6.3).

Answering Question 2 also revealed that the width of the buffer zone has a major influence on the percentage of passengers in the buffer zone at a given density. With buffer zones of 0.8 m or wider, at higher densities the density in the buffer zone approaches that observed across the remainder of the platform. In practice, this means that a buffer zone 0.8 m wide (including marking) is of no value at higher densities.

Equation 6.6 shows that a certain percentage of passengers use the buffer zone even at low densities. The present research revealed no reason for this. However, previous research has shown that passengers may have a number of reasons for such behaviour. Other researchers have pointed to passengers perceiving the risks associated with the platform edge as low. Research conducted in Switzerland has found that passing slower-moving passengers and avoiding standing passengers may also prompt people to use the buffer zone. In the United Kingdom, a desire to board the train as quickly as possible after it arrives was cited as a reason for being in the buffer zone.

Answering **Question 3** involved examining the behaviour of passengers who use the buffer zone. That analysis revealed that as density increases, more passengers stand in the buffer zone and fewer walk through it. At lower densities, more than half of those in the buffer zone are walking. At higher densities, this drops to about a quarter. The speed of those passengers who are walking along the buffer zone also falls as density increases. Furthermore, time spent in the buffer zone increases at higher densities. This confirms the expectation that more passengers stand in the buffer zone for longer periods when the platform becomes more crowded.

Generally speaking, this thematic study indicates that one cannot reject the hypothesis for the platforms studied. As crowding on the platform increases, so does use of the buffer zone. As crowding increases on the platform, density in a buffer zone of 0.8 m or wider approaches that observed across the remainder of the platform.

6.6 Discussion

There are two important caveats regarding this study. 1. The degree to which one can apply the results more generally (see Sub-section 6.6.1). 2. How one can assess the hazards to which people using the buffer zone are exposed (see Sub-section 6.6.2).

6.6.1 General applicability

In considering the degree to which the results can be generally applied, the question arises as to the causes of the differences between Utrecht Centraal and Amsterdam Zuid. Both platforms are subject to high peak loads, i.e. large numbers of alighters per arrival. This prompts the question as to whether the peak loads on these platforms are exceptionally high, or whether similar loads occur on other platforms in the Netherlands.

In the author's view, the major differences between the relationships observed at Utrecht Centraal and those at Amsterdam Zuid cannot be ascribed to differences in the passengers themselves or in their behaviour. The two stations are closely linked, in the sense that many of the passengers leaving Utrecht Centraal via Platform 5 in the morning will be boarding a train at Amsterdam Zuid in the evening.

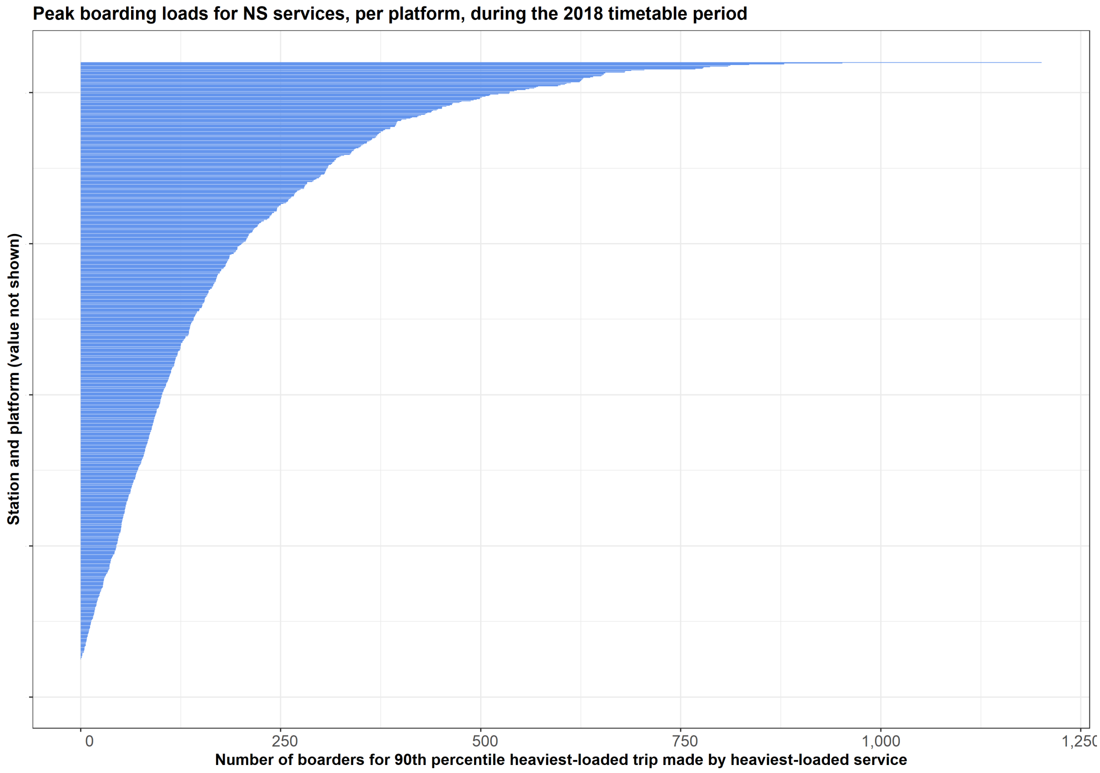


Figure 6.11: Peak boarding loads for NS services, per platform (all stations), during the 2018 timetable period (using ROCKT Station data)

The author suspects that differences in the distribution of passengers and passenger flows along the platforms could explain the differences between the relationships. The two stations differ fundamentally as far as these two factors are concerned. Figure 6.3 shows the differences clearly. To reach the central section of Platform 5 at Utrecht Centraal – the section where most trains stop – passengers arriving on the platform via the stairs or escalator must turn through 180 degrees and walk along the platform to the area situated under the concourse (which covers a large portion of the platform length). The platform at Amsterdam Zuid is served by a relatively narrow subway, and most passengers distribute themselves along the platform by continuing to walk along it in the direction in which they have arrived.

In a manner analogous to Chapter 5, Figure 6.11 shows the top ten peak loads in terms of number of boarders. That figure shows that the highest peak loads consisted of approximately 1,200 boarders per train. Here again, however, the figures fall off sharply. Table 6.6 shows the top ten peak loads for platforms that do not serve dead-end tracks. See Section 5.5 for an explanation. The platforms included in this thematic study are shown in red in the table.

Position	Station	Platform	Boarders
1	Utrecht Centraal	7	1,200
2	Utrecht Centraal	5	950
3	Utrecht Centraal	19	775
4	Zwolle	7	775
5	Leiden Centraal	8	700
7	Dordrecht	3	700
8	's Hertogenbosch	3	675
9	Amsterdam Centraal	14	650
10	Rotterdam Blaak	1	650

Table 6.6: Top-ten platforms in terms of peak boarding loads on NS (excluding dead-end tracks) during the 2018 timetable period (using ROCKT Station data, rounded to the nearest 25)

It is concluded that the regression functions for Platform 5 at Utrecht Centraal and Platform 1-2 at Amsterdam Zuid are not directly applicable to other platforms. Further research is required in this area (see Sub-section 6.7.1).

6.6.2 Hazards

The ProRail/NS platform safety risk model [73] makes a distinction between "voluntary" and "involuntary" use of the buffer zone. In this context, "voluntary" means that passengers choose (consciously or unconsciously) to expose themselves to a hazard rather than stand close to other passengers or be unable to pass other passengers. For the purposes of this thematic study, "involuntary" means "regular use of the buffer zone because of crowding".

From the definitions of Fruin's levels of service (see Figure C.2 in Appendix C) one can argue that the tipping point is reached at LOS C, i.e. 0.5 persons per square metre. Fruin states that at this LOS it is no longer possible for pedestrians to choose their walking speed and that their freedom to pass other pedestrians is restricted. Figure 6.12 shows the estimated regression models for use of the buffer zone on Platform 5 at Utrecht Centraal, superimposed on Fruin's levels of service. Adopting a limit of 0.5 persons per square metre implies that presence in the buffer zone is voluntary for 13% to 15% of passengers. It also implies that a higher density could no more than double this percentage (approximately).

The Dutch standard gives a different perspective. According to that standard (see Chapter 3), the maximum density on a platform (or a section of a platform) is over 1 person per square metre. That limit is also shown in Figure 6.12. If we take this as the boundary between "voluntary" and "as a result of crowding", then 20% of those in the buffer zone are there voluntarily, and increasing crowding will only increase that percentage to a limited degree (to a maximum of 25%).

Figure 6.13 shows both limits superimposed on Figure 6.8. That figure shows that a different buffer zone width results in a different assessment of what is and is not acceptable. That diagram raises the question as to what the optimum width is for the

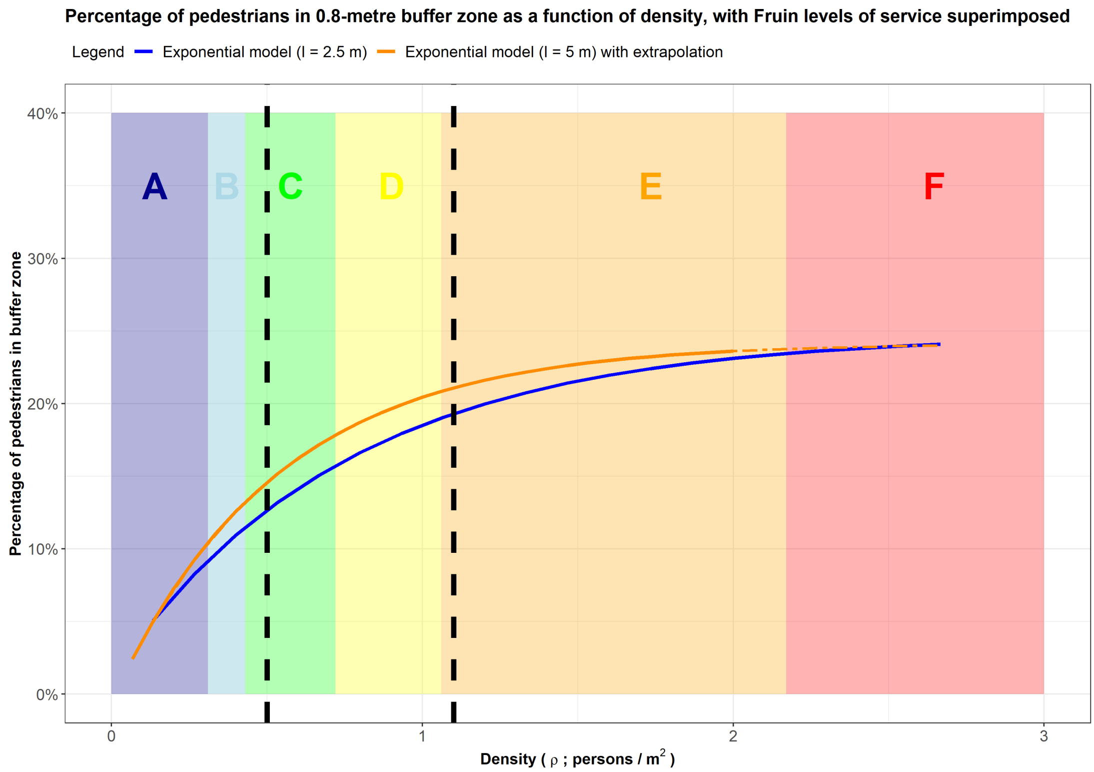


Figure 6.12: Results for use of the buffer zone in the context of Fruin levels of service [36]

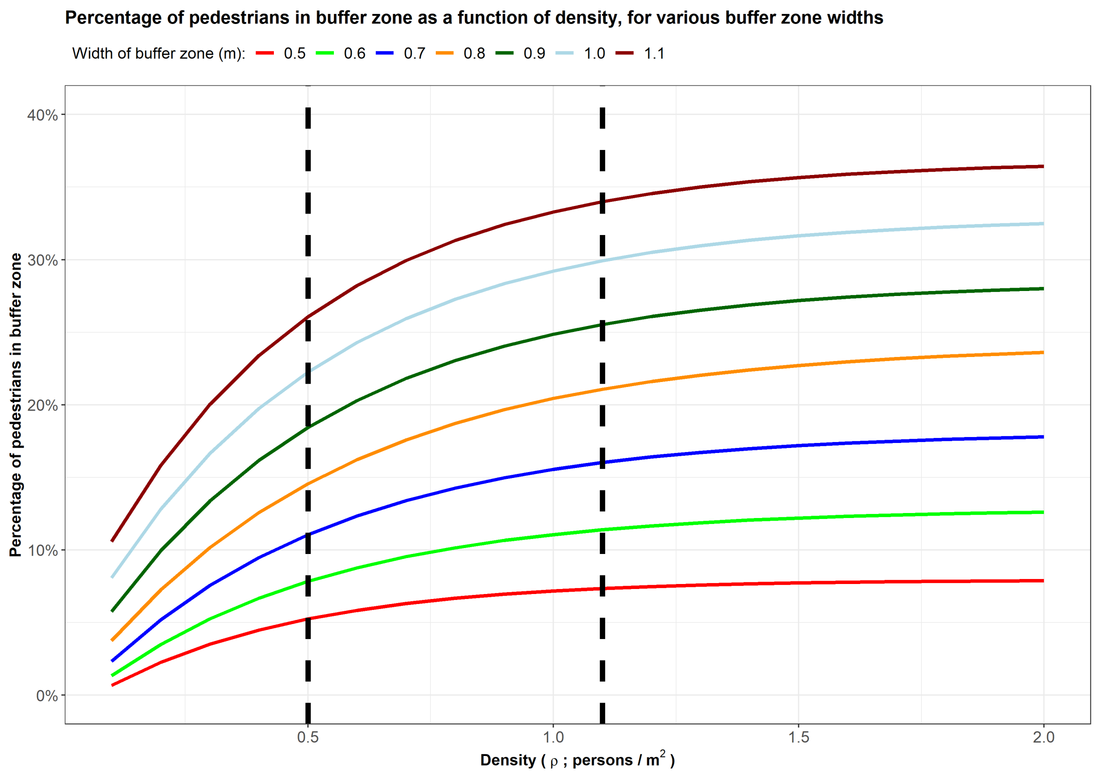


Figure 6.13: Exponential model, various buffer zone widths, segment length = 5 m, density standard applicable in the Netherlands

buffer zone, both as regards the standards and in terms of passenger perception. This is in line with experience on the London Underground, where it has been noted that creating too wide a buffer zone leads to more passengers walking along the edge of the platform (see Chapter 3).

There is also the question of what is more dangerous. If a person is walking, they will generally spend less time in the buffer zone but are less stable and hence more likely to fall. If they are standing still, they are more stable but spend longer in the buffer zone. In comparing these two situations, one must especially bear in mind the problem of passing freight trains, which can create powerful gusts.

There is also the question as to what role platform marking plays in use of the buffer zone. In the Netherlands, the buffer zone is indicated by a broken white line. In the United Kingdom, a continuous yellow line is used. In Switzerland, the line marking the edge of the buffer zone is also the tactile strip for people with a visual impairment. It is not possible to draw any firm conclusions regarding this point for the Dutch situation on the basis of the present study. What the results do indicate is that the effect of safety markings is limited, especially when the platform becomes more crowded. The author suspects that this is partly because the markings are less visible when the platform is crowded.

6.7 Recommendations

This chapter concludes with recommendations for further study (Sub-section 6.7.1) and practical application (Sub-section 6.7.2).

6.7.1 Further study

The regression functions for Platform 5 at Utrecht Centraal and Platform 1-2 at Amsterdam Zuid are not directly applicable to other platforms. It will only be possible to use generic functions for the relationship between crowding and use of the buffer zone once an explanation has been found as to why the regression functions for Utrecht Centraal and Amsterdam Zuid differ. It will also be necessary to establish why no significant regression parameters were found for Platform 3-4 at Amsterdam Zuid, whereas such parameters were found for Platform 1-2 at the same station, which is very similar. It is therefore recommended that this research be repeated on other platforms with high peak boarding loads (see Table 6.6 for instance). As the distribution of passengers along the platform has a decisive effect on the pattern of crowding, the author advises that when repeating this research for other platforms, careful attention be paid to the positions of the platform entrances relative to the location at which trains stop (see Figure 6.3).

This thesis shows that passengers frequently use the buffer zone. Buffer zone usage increases as the platform becomes more crowded. However, passengers still use the buffer zone even when there are few others on the platform. This research does not explain why. We do not know whether passengers use the buffer zone consciously or unconsciously, nor how passengers perceive hazards that station operators aim to manage via their standards. Furthermore, where passengers are aware of a hazard, what choices do they make as to whereabouts on the platform they stand or walk? So one question for further research would be how passengers balance (perceived) distance from other passengers against (perceived) hazards. The author suspects that *being able to* step back or to the side plays a role here, for instance when a train arrives or passes the platform at speed. Learning more about what motivates passengers is an important building block for the further development of models capable of analysing the use of platforms (see previous recommendation). Furthermore, it will be possible to deploy risk-mitigation measures in a more targeted fashion if passengers' motives are known.

6.7.2 Practical recommendations

This thematic study has clearly demonstrated that the buffer zone on Platform 5 at Utrecht Centraal is regularly being used because of crowding. This conclusion is in line with risk analyses that NS and ProRail have conducted in the past, which in part formed the basis for the introduction of crowd control on that platform during morning and evening peak times on working days. It is recommended that the existing risk analyses be reviewed in the light of the results reported here. That review should in particular focus on whether everything possible is being done to distribute passengers along the platform when crowding is at its most severe. The advantage of distributing passengers along the platform is that this reduces crowding in the most heavily-used sections of the platform, thereby reducing use of the buffer zone.

The second recommendation is to identify those platforms on which large numbers of passengers are present before their train arrives. Figure 6.11 and Table 6.6 show that there is only a limited number of stations at which there is a high probability of severe crowding on a platform prior to the arrival of a train. Because concentrations of passengers within specific platform sections are a source of risk, it is recommended that a risk assessment be conducted on the basis of targeted qualitative observation. This would constitute a temporary measure, until further study (see above) has provided more quantitative information regarding platforms with high peak loads that were not investigated as part of this thematic study.

Chapter 7

Passenger-related dwell time

The present chapter describes the results of research into the influence of the number of alighters and boarders on train dwell times. In Chapter 3, this was identified as the third limitation on the service capacity of a platform (see Figure 7.1). This chapter focuses on the following hypothesis: *As a result of the number of alighting and boarding passengers, trains regularly depart with a delay, or with more delay.*

To test this hypothesis, ROCKT and TRENTO data for all stops made by NS trains during the 2018 timetable year were used to establish at which stations and platforms dwell times were longer than planned for in the timetable. A large number of stops were systematically compared with other, and steps were taken to exclude the influence of factors other than the number of alighters and boarders as far as possible. The aim of the analyses was to isolate the passenger service time (the time required for all passengers to alight from and board the train) from the total dwell time, using the number of alighters and boarders. The passenger service time is not contained in the dataset, whereas the total dwell time and the number of alighters and boarders are. As a number of regression models from previous research were suitable, existing models were used for this topic. The following step was to identify those stations and platforms at which passenger service time had caused dwell times to be longer than provided for in the timetable.

The present chapter is structured as follows. Section 7.1 provides an overview of the literature on this subject. Drawing on earlier research, that section provides a definition of dwell time (including passenger service time), lists the factors that influence dwell time and describes the models available for estimating both dwell time and passenger service time. Section 7.2 contains a conceptual model, which is used in Section 7.3 to select the method of investigation. Section 7.4 presents the results for this topic. Section 7.5 contains a number of conclusions, points for discussion and recommendations.

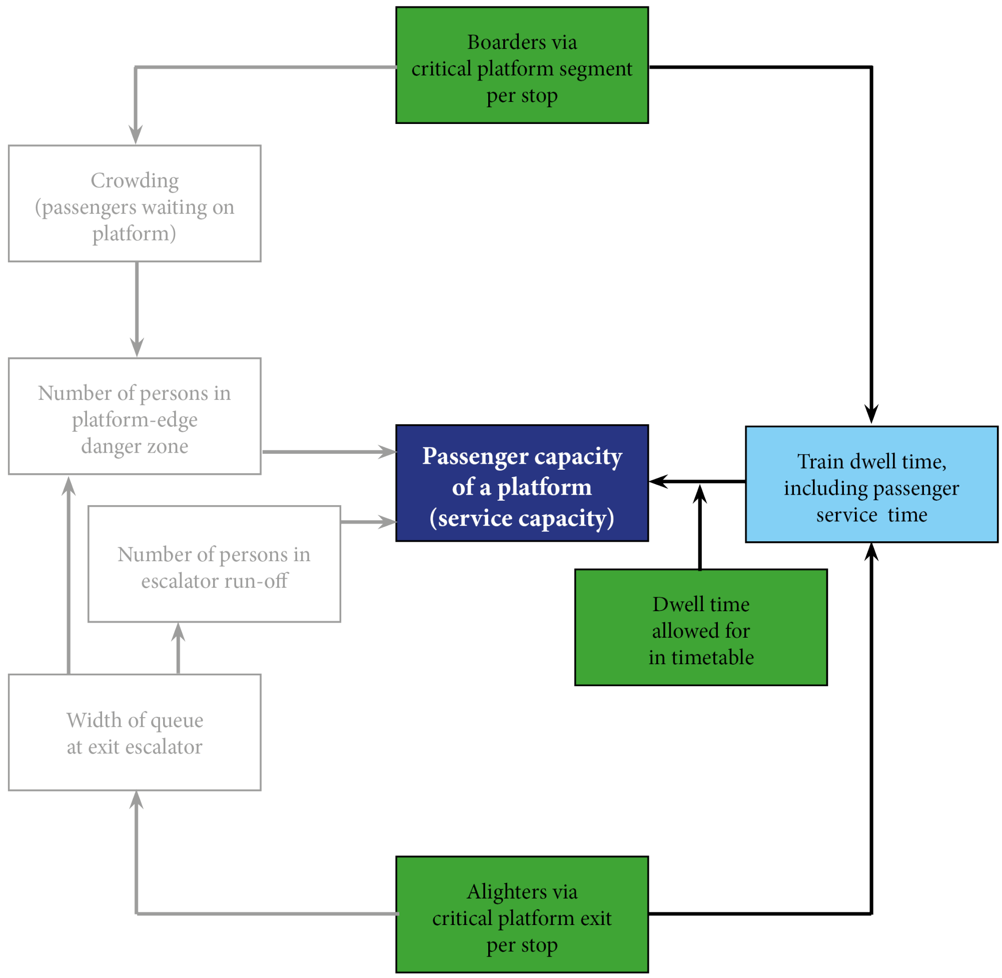


Figure 7.1: The topic in the context of platform capacity

7.1 Earlier research

This section will start by defining *dwell time* and the *passenger service process*, which forms part of a stop. Those factors will then be listed that affect passenger service time. This will be followed by an overview of existing work on modelling dwell time and passenger service time. The section concludes with a partial conclusion, which forms the basis for the next stage of this research.

7.1.1 Definitions of dwell time and passenger service time

According to Dirmeier [175], Weidmann [113], Heinz [72] and Lee et al. [176], *dwell time* (*stationnementstijd* or *halteertijd* in the Netherlands and *Aufenthaltsdauer* in German-speaking Switzerland) is the time between the moment at which the train comes to a halt at the platform and the moment at which it moves off again. The following three sub-processes take place during that period:

1. **Arrival process**: The opening of the doors, defined as the time between the

moment at which the train comes to a halt and the moment at which the first passenger alights or boards.

2. **Passenger service process** (*Fahrgastwechselzeit* in German): alighting and boarding.

3. **Departure process**: Departure, defined as the time between the moment at which the last passenger boards and the moment at which the train starts to move. This includes waiting for the moment of departure (i.e. waiting for the planned departure time and for the departure signal to display a permissive aspect), the departure announcement and the closing of the doors.

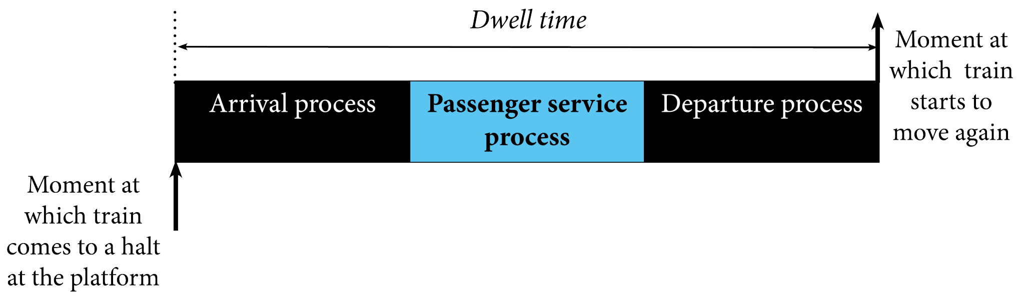


Figure 7.2: Definition of dwell time

Parkinson and Fisher [104] and Vuchic [114] examine dwell time from the perspective of the (minimum) headway between two successive trains. They distinguish between the time a train requires to stop, the duration of the stop, the time the train requires to reach full speed after starting off again and the safety margins that must be incorporated into the time between successive trains to ensure that they do not collide. The authors use the sub-processes described above in calculating dwell time. Figure 7.3 illustrates the headway approach to dwell time using a time-distance diagram. The figure shows Trains A, B, C and D on a line, with a station (S) halfway along. Of the four trains, only B stops at Station S. The headway between trains is indicated in the form H_{xy}. In this example, the headway for all four trains is equal to the minimum headway. In other words, the line is being used to full capacity, which means that a delay to any given train will cause a delay to the following train. The planned dwell time for Train B at Station S is $d_{B;s}$. At the start of the section, the headway between Trains A and B is the same as that between C and D. Because Train B is scheduled to stop at the station (h_b), the headway between Trains B is C greater, and is equal to the minimum headway plus the dwell time plus the time that the train loses as a resulting of slowing down before arrival and accelerating after departure. Following Train B's stop, the headway between trains B and C (H_{BC}) is reduced to the minimum headway, while the headway between trains A and B (H_{AB}) increases, and is now equal to the headway that existed between Trains B and C before Train B made its stop. Increasing Train B's dwell time by v_B will automatically result in a delay of v_B to Trains C and D.

It is possible to avoid delays by scheduling a longer dwell time for Train B at Station S (h_B+v_B). This will cause Trains C and D to depart later. An alternative would

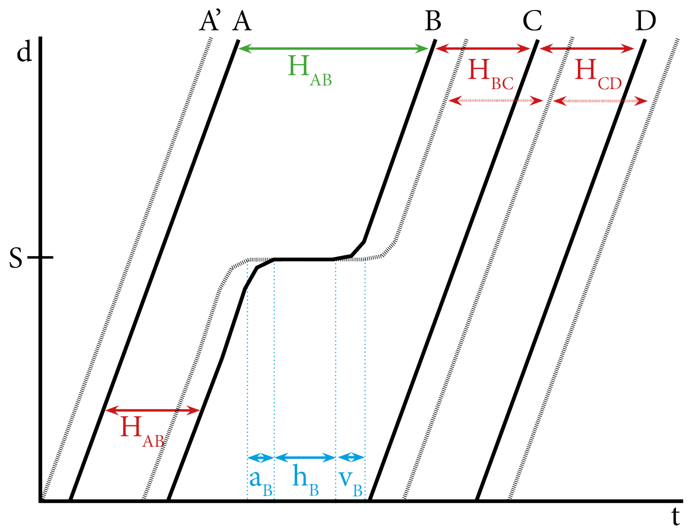


Figure 7.3: Headways and the effect of a stop

be to increase the headway between Trains A and B. In Figure 7.3, this is illustrated by Train A', which is scheduled to depart earlier than Train A. This also makes it possible for Train B to depart for Station *S* earlier, increasing dwell time by a_B. Both solutions reduce the capacity of the line, which means that fewer trains can use it over a given period.

7.1.2 Factors affecting the passenger service process

The literature mentions the following factors as affecting passenger service time:

1. Number of alighters and boarders [175] [177] [169] [178] [179] [180] [181] [113] [182] [183] [72] [184] [185] [176] [186] [187] [188] [25]. For both variables, passenger service time increases with the number of alighting and boarding passengers.

2. Friction between alighters and boarders on account of opposing flows. [175] [168] [179] [180] [181] [113] [185] [189] [176] [188]. Contraflows lead to longer passenger service times for a given number of passengers. Dirmeier [175] incorporates the friction between alighters and boarders into his model as a random factor, while Weidmann [113] applies a factor to door capacity. Harris et al. [188] show that having passengers alight and board on opposite sides of the vehicle results in a shorter passenger service time. Seriani and Fernandez [190] come to a comparable conclusion as regards the effect of "differentiated doors" (designating doors on the same side of a vehicle as either alight-only or board-only).

3. Passenger characteristics [72], such as reason for journey (commuting, etc.) [179] [113] [176], luggage [181] [113] [176] [191], the presence of groups and/or people with a handicap, plus age and gender [113] [176]. Commuters

with no luggage alight and board relatively quickly, whereas tourists with luggage require more time (all other things being equal).

4. Vehicle characteristics, such as door configuration (number, width [178] [192], spacing and opening speed) and difference in height between platform and vehicle [175] [179] [181] [113] [193] [184] [72] [185] [187] [191] [188], gap between vehicle and platform and the ergonomic characteristics of the vehicle [178] [113] [72] [185] [176] [186]. The following factors all result in a shorter passenger service time: a larger number of doors, wider doors and minimum vertical and horizontal spacing between platform and vehicle. The layout of the vestibule can increase passenger service time, if a narrow passageway causes a queue to form that extends back to the doors or even out onto the platform.

5. Operational factors such as seat reservations [179], first and second class seating [181] [113] [186] and inspecting tickets as passengers board the train [184] [187]. Passengers with seat reservations have to board the correct coach. This often causes passengers to walk along the platform in search of their coach while the train is standing at the platform. A similar effect can occur if the train has first and second class accommodation, especially if first class is located at one end of the train. (Most railway operators outside the UK still use the term "second class" rather than "standard class".) In some cases, tickets are inspected at the coach doors as passengers board the train. This results in a longer passenger service time than if passengers can board without ticket inspection.

6. Operational factors, such as the actions of the train crew [179] and train crew reaction time in connection with such actions as unlocking the doors or initiating the departure process [113]. This category includes keeping the doors open after the scheduled departure time to allow late-arriving passengers to board [181] [176]. Wiggenraad [193] also mentions extending a stop to allow passengers from another train to make their connection.

7. Platform characteristics, e.g. the locations of platform entrances and sightlines and width restrictions that can interfere with the passenger flow [181] [193] [184] [176] [186] [188], how much space is available for boarders to wait until alighters have cleared the train [113] [192] and the presence of platform edge/screen doors [194]. Using a sample calculation, Wirasinghe & Szplett [168] show that platform design has an influence on dwell time. The more narrow passageways and/or restricted sightlines there are, the longer the passenger service time.

8. Crowding on the platform and the distribution of passengers along the platform and over the train doors [175] [177] [169] [113] [183] [72] [176] [190]. Fritz maintains that increased platform crowding near the doors has a positive effect, as this motivates passengers to board faster [177]. Uneven distribution of passengers along the platform results in uneven usage of train doors. As a result, the duration of the alighting and boarding process at one door determines the total

passenger service time. Szplett & Wirasinghe [169] point out that the distribution of platform entrances and the use of trains of different lengths lead to uneven distribution of passengers along the platform [177] [169]. Like Parkinson and Fisher [104], Heinz [72] points out the significance of the distribution of passengers along the platform and train. She maintains that uneven distribution results in a “dimensioning door”. This is the door through which the largest number of passengers wishes to alight and/or board, and hence the door that determines overall dwell time.

9. Crowding on board the train [175] [177] [181] [113] [183] [185] [176] [188] [190], especially in the vestibules serving the doors through which the passengers alight and board (see vehicle characteristics).

10. Weather [175] [179] [180] [113] [176]. Dirmeier reports that the use of umbrellas can lengthen the alighting and boarding process [175]. Weidmann [113] states that weather can influence the distribution of passengers along the platform, and hence influence crowding and the distribution of crowding along the platform, over the train doors and within the train.

While several studies mention one or more of the above factors, few studies examine the interaction between them. The first such study identified for the present research was that by Weidmann [113]. See Figure I.1a in Appendix I for the conceptual model of that study. As that figure shows, and as Weidmann explains in his comments on it, many factors play a role and those factors influence each other. Recent work by Li et al. [195] paints a similar picture. See Figure I.1b (Appendix I). That study does not specifically examine the passenger service process, owing to a lack of data regarding passenger numbers.

A number of external factors also increase dwell time [25]. These include train or infrastructure defects, waiting for the scheduled departure time or a signal at danger because the next track section is still occupied. Occurrences during the alighting and boarding process such as accidents can extend the dwell time, as can the manner in which the train crew carry out the departure process.

From the above overview, one can conclude that a large number of factors can affect passenger service time, in addition to the number of alighters and boarders. This means that one cannot compare the number of alighters and boarders between stops without first determining whether other factors have influenced the passenger service process.

7.1.3 Measuring passenger service time

Several researchers have investigated the duration of the alighting and boarding process. Some studies have looked at the effects of direction (alighting vs boarding), step height (level vs one or more steps) and door width. Their results are summarized in Table 7.1 below. On the basis of his research in the Netherlands, Wiggenraad [193] also shows that the sum of [duration of departure process] and [time between last passenger alighting or boarding and departure of train] is constant at about 25 s, and is not influenced by the station, train/rolling stock type or service type (intercity, etc.).

Source	Value	Unit and context
Weidmann [113]	.93	pass/s/m door width, no step
	.69	pass/s/m door width, with step
Wiggenraad [193]	.9	s/pass, wide doors (1.3-1.9 m)
	1.1	s/pass, narrow doors (0.8-1.3 m)
Harris [185]	.65	s/alighter/m door width
	.87	s/boarder/m door width
Fernandez [187]	.7	s/alighter
	1.1	s/boarder
Harris [188]	1	alighters/s
	.8	boarders/s

Table 7.1: Alighting and boarding rates from earlier research

The values in Table 7.1 would lead one to expect alighting and boarding rates of 0.7 to 1.25 seconds per passenger for typical Dutch rolling stock, with door widths of 1.2 m to 1.3 m [196], with and without steps.

7.1.4 Models for deriving dwell time from the number of alighters and boarders

Some of the existing research focuses on models for predicting the dwell times of trams and of metro and main-line trains. These models distinguish between the duration of the arrival and departure processes on the one hand and the passenger service time on the other. See Figure 7.2 for the definitions of these terms and Figure 7.4 for the relationship between these definitions and the corresponding regression models. These regression models therefore differ from both pedestrian simulations and line models. Pedestrian simulations can only model the passenger service process, allowing us to derive the passenger service time. They do not allow us to calculate total dwell time. While railway line models do allow us to determine dwell time, they do not allow us to determine the percentage of dwell time accounted for by passenger service time.

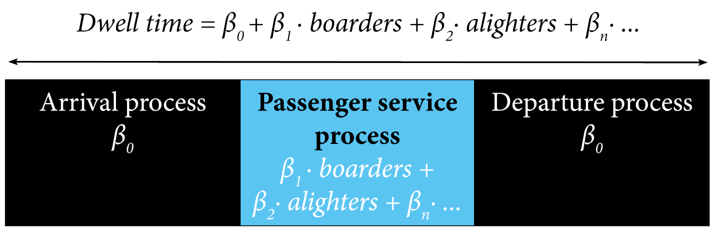


Figure 7.4: Regression models in the context of the definition of dwell time

Table 7.2 gives an overview of regression models in earlier research. That table shows that all models estimate regression coefficients for the number of boarders (*in*) and alighters (*out*), either separately or together (*in and out*). Two models also estimate a regression coefficient for the number of passengers standing in the vestibule (*standing*). The reason for adding this parameter is that crowding in vestibules increases passenger service time. Similarly, two other models estimate a coefficient for the *friction* resulting from the conflicting alighting and boarding flows.

The table also shows the units used. As far as this aspect is concerned, the regression models in earlier research can be divided into three categories. 1. Those that estimate the coefficients for passenger flows via the busiest door. For these models, one must know which door was busiest during the stop under investigation. 2. Those that estimate coefficients for passenger flows for an entire vehicle. 3. One model that focuses on passenger flows via the average door. This model requires one to know how many doors were available to passengers. For further discussion of these models, please see Appendix I.

Source	Coefficient	Unit	Function
Dirmeier [175]	β_0, in, out	Busiest door	I.1
Wirasinghe et al. [168]	β_0, in, out	Busiest door	I.2 I.3 I.4 I.5
Lin & Wilson [180]	β_0, in, out, standing	Whole vehicle	I.6 I.7 I.8
Hennige & Weiger [181]	β_0, in and out	Whole vehicle	I.9
Parkinson & Fisher [104]	β_0, in, out	Busiest door	I.11 I.12 I.13
Lam et al. [182] [183]	β_0, in, out	Whole vehicle	I.14
Puong [197]	β_0, in, out, standing	Average door	I.15
Harris [185]	β_0, in, out, friction	Busiest door	I.16
Douglas [198]	β_0, in, out, friction	Busiest door	I.17

Table 7.2: Regression models in earlier research

7.1.5 Conclusions

Earlier research divides stops into three sub-processes: the arrival process, the alighting and boarding process (or passenger service process) and the departure process. A wide range of regression models are available for estimating dwell time. One feature common to all these models is that they use regression analysis on datasets consisting of a relatively large number of stops at one station – or at a small number of stations – on metro networks or urban rail networks such as *S-Bahn* systems.

A survey of existing research reveals that all researchers see the number of alighters and boarders as the most important factor determining the passenger service time component of total dwell time. Some studies have also looked at crowding in the vehicle, crowding on the platform, the distribution of passengers along the platform and inside the train and friction between alighting and boarding passengers. Only two studies – Weidmann [113] and Heinz [72] – have examined the influence of the vehicle and the platform. All other studies have taken only one type of vehicle and one station (or a small number of stations) into consideration. It is therefore not possible to determine any influence that the vehicle or platform might have on the basis of those studies. Most studies only mention the other factors in conceptual terms, without incorporating them into their research. Existing research also addresses the role played by headway. If scheduled headways are short, longer dwell times resulting from large numbers of alighters and boarders cause delays to train departures. Longer headways allow trains to make up delays by arriving early. Another alternative is to schedule longer dwell times, but this reduces line capacity.

The survey of existing research indicates that various types of regression model exist that are of relevance to the topic addressed in this chapter. The most suitable regression models will be identified on the basis of the possibilities offered by the data available for the present study. Existing research also shows that many factors can influence the passenger service process and dwell times. A method has therefore been developed for the next stage of this study that makes it possible to control for the influence of factors other than the number of alighters and boarders when analysing passenger service time and dwell time.

7.2 Conceptual model

Weidmann [113] and Li et al. [195] have proposed conceptual models that include the passenger service process. Those models describe the entire stop, identifying the passenger service process separately. Figure 7.5 shows the conceptual model adopted for the present study. That model is based on the sub-processes that make up a stop and on the conceptual models developed by Weidmann and by Li et al.

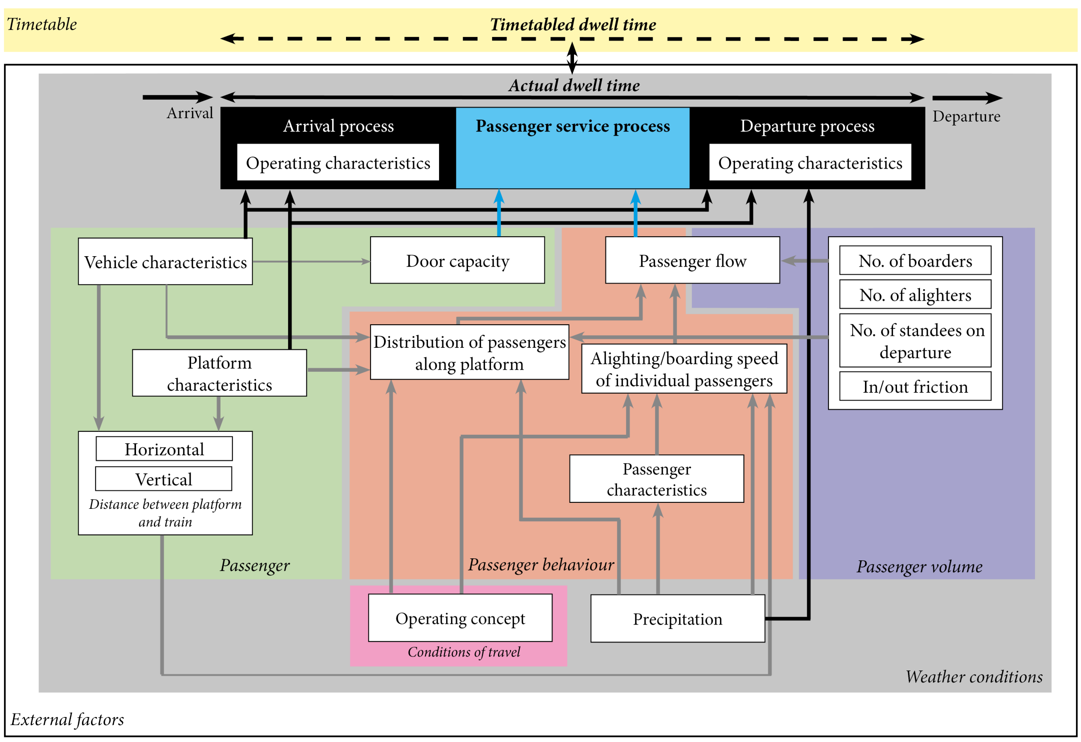


Figure 7.5: Conceptual model (based on [113] and [195])

This model includes the stop as defined in Figure 7.2, including the passenger service time. The following six factors/groups of factors influence dwell time:

1. **Passenger volume**, i.e. the number of alighters and boarders, friction between conflicting flows and the negative effect on the boarding rate of standing passengers in the train.

2. **Passenger infrastructure**, i.e. platform and train (vehicle) characteristics and door capacity.

3. **Passenger behaviour**, i.e. the distribution of passengers along the platform and the rate at which they alight and board. This also includes a "travel conditions" sub-factor: whether the train consists of first and second class accommodation and whether seat reservation is possible or obligatory.

4. **Operational characteristics**, i.e. all aspects related to the arrival and departure processes, but excluding those related to the passenger service process.

5. **Weather**, especially rain.

6. **External factors** that extend dwell time but are not related to the normal arrival, passenger service and departure processes.

To calculate any delay caused by the passenger service process, actual dwell time is compared with timetabled dwell time. Figure 7.2 shows this as "Timetable".

The next stage of this study will look at whether each group of factors influences dwell time. We shall then examine the manner in which stops are incorporated into the planning and implementation of the timetable. The following research questions have been formulated for this sub-topic on the basis of the conceptual model:

1. Do the factors from Groups 2 to 5 have a significant effect on dwell time?

2. What is the effect of passenger volume (i.e. the number of alighters and boarders) on dwell time?

3. At what stations was the passenger service process the reason (or one of the reasons) for trains departing late during the 2018 timetable period?

7.3 Research methodology

To test the hypothesis of this sub-topic, it is necessary to separate passenger service time from the time required for the other two sub-processes that make up a stop. This can be achieved using the regression models from earlier research described in the previous section (see Figure 7.4). This being so, no new models have been designed for the present study. Instead, regression coefficients have been estimated for suitable existing models. This study uses ROCKT and TRENTO datasets containing data for almost all stops made by NS trains during the 2018 timetable year (see Chapter 4). The advantage of using these secondary data sources is that data are available for a large number of stops. As mentioned in connection with the survey of earlier research, this approach does mean that considerable attention was devoted to isolating the many factors that could influence dwell time as a whole and passenger service time in particular. The analysis method will be examined in more detail following discussion of the data available and selection of regression models.

7.3.1 Dwell time and passenger number data

The ROCKT and TRENTO datasets contain data for almost all stops made by NS trains during the 2018 timetable year (10 December 2017 to 8 December 2018 inclusive). The ROCKT dataset contains the number of boarders, alighters and transferring passengers per stop, plus the number of through passengers. For the purposes of the present study, the ROCKT data for each stop were supplemented with the following data, which were used during analysis to filter or group data, or as part of the process of estimating the regression coefficients:

- Timetabled arrival and departure time, actual arrival and departure time, rolling stock, train length, signal aspect, stop type and re-numbering of trips. The signal aspect indicates the time at which the signal showed a permissive aspect and hence the time at which the train could depart. The type of stop (arrival/departure or short stop) provides information regarding dwell time. Re-numbering of a trip is often an indication of a service perturbation, especially if the re-numbering was unplanned. These data are based on the TRENTO data available for this study.

- NS records train defects (e.g. technical faults) per trip and per route, in a manner analogous to the TRENTO database. These data were used to identify those stops in the combined ROCKT-TRENTO dataset for which a defect was recorded.

- The number of doors per unit and the number of seats, taken from the NS *Materieelgids* [196].

- The time of day (peak or off-peak), as an indicator for the type of passenger. The NS definition of peak and off-peak was used. Peak = 0700-0900 and 1600-1800, Monday to Friday. Off-peak = all other times Monday to Friday, plus all day on Saturday and Sunday.

As the author was aware of certain inaccuracies in the data, the following initial filtering was applied:

1. It is known that the ROCKT data for trains between Amsterdam Centraal, Schiphol Airport and Rotterdam Centraal, and between Amsterdam Centraal, Haarlem and Zandvoort aan Zee can be less accurate than those for other routes. For the first of these routes, the inaccuracies stem from unresolved problems with the manner in which the ROCKT data are generated. For the route to the seaside resort of Zandvoort aan Zee, problems arise as a result of the large number of passengers making this journey on what are known as “beach days”, i.e.

days with good weather. Because of these inconsistencies, all trains on those routes were removed from the dataset.

2. Passenger numbers for international trains are incomplete, as the OV-chipkaart (on which the passenger count is based) is only used by passengers whose trips start and end in the Netherlands. All international trains were therefore removed from the dataset.

The combined ROCKT-TRENTO dataset available for this study contained 14,442,801 stops and 297 stations.

7.3.2 Selecting regression models

The dataset available for this research does not contain data from which it would be possible to identify the busiest (i.e. critical or "dimensioning") door. Nor is any data available regarding the distribution of passengers along the platform. This means that those regression models that rely on the busiest door cannot be used for this sub-topic (see Table 7.2). That leaves the following models: Lin & Wilson [180] (Function I.8), Hennige & Weiger [181] (Function I.9), Lam et al. [182] [183] (Function I.14) en Puong [197] (Function I.15).

Table 7.3 shows the values for the coefficients that the authors of the various models have published. That table also shows (adjusted) R^2, which indicates the goodness of fit for the model concerned. For some models, two values are shown for each coefficient. In those instances, the researchers investigated a number of situations. The right-hand column indicates the factor on which the values of the coefficients depended.

Model	β_0	β_1 / $\beta_{1;2}$	β_2	β_3 (E-3)	R^2	Factor
Lin (I.8)	12.5	.55	.23	7.8	.62	Train length
	13.9	.27	.36	8	.70	Train length
Hennige (I.9)	13	.81	–	–	–	–
Lam (I.14)	10.5	.016	.021	–	.75	–
Lam (I.14)	6.6	.68	.68	–	.80	Station
	.71	.71	.79	–	.80	Station
Puong (I.15)	12.22	2.27	1.84	.62	.89	–

Table 7.3: Coefficient values for each regression model

7.3.3 The analysis phases

Table 7.4 applies the regression models to the dataset, with the external factors kept as constant as possible (Group 6 – see next section). The table shows that all coefficients are significant, but that the fraction of variance explained (adjusted R^2) for the dwell time is very small, for all models. This confirms that factors other than the number of alighters and boarders may be influencing dwell time.

The results in Table 7.4 show that stops involving different stations, platforms, train types and conditions cannot simply be merged into one regression analysis. This is to

Model	Adj. R^2	Coefficient	Estimated value	SD	p
Lin (I.8)	0.161	β_0	40.55	0.02	0
		β_1	0.15	0	0
		β_2	0.14	0	0
		β_3	-0	0	0
Hennige (I.9)	0.161	β_0	40.57	0.02	0
		$\beta_{1;2}$	0.14	0	0
Lam (I.14)	0.161	β_0	40.57	0.02	0
		β_1	0.15	0	0
		β_2	0.14	0	0
Puong (I.15)	0.164	β_0	39.69	0.02	0
		β_1	1.91	0	0
		β_2	1.82	0	0
		β_3	0	0	0

Table 7.4: Parameters for regression analysis on dataset containing all stops (n = approx. 2.5 million)

be expected, given the diversity in the observations that the dataset contains. Previous empirical research has involved little variation in station, platform and/or train type. To carry out this part of the study as correctly as possible, four measures were taken, as explained below. The "groups" referred to below are the groups of factors mentioned in the previous section. The measures taken were as follows:

1. All **external factors (Group 6)** that could have influenced passenger service time and/or dwell time were kept as constant as possible. This was achieved by coarse filtering of the dataset by type of stop, extended stop, signal aspect and disruption to train services.

2. The available data were then used to establish whether passenger infrastructure, passenger behaviour, conditions of travel and weather (**Groups 2-5**) had a significant influence on dwell time. This was achieved by systematically comparing groups of stops, keeping all other factors as constant as possible.

3. Those data subsets were then identified that allowed the best estimates of the parameters for the selected regression models to be made, in order to determine the influence of the number of alighters and boarders on dwell time.

4. Finally, those stops were identified for which the number of alighters and boarders had caused the dwell time to be longer than provided for in the timetable.

Step 1 - Excluding external factors (Group 6)

An initial coarse filter was applied to the dataset, to reduce the effect of the external factors identified in the previous section.

- The only **stop types** selected were short stops and those that consisted of an arrival and a departure. For these purposes, "short stops" are stops at stations along the open track and "stops involving arrival and departure" are those at rail interchanges. Stops that involved a train arriving at its final destination or departing from its start point were excluded. Those types of stop often last several minutes, which means that the passenger service process is not the factor governing dwell time.

- If all passengers have alighted and boarded, but the train still has to **wait for the scheduled departure time**, it will spend longer at the platform than necessary for the passenger service process. To eliminate the influence of this factor, stops were only included if their actual arrival time was later than the scheduled departure time. In such cases, one may safely assume that the train crew would have been aiming to ensure that the train spent no longer in the station than was necessary for the passenger service process.

- For the same reason, a stop was only used if the **signal aspect** was such that the train could have departed immediately after its actual arrival time. This excludes those stops where a train had to wait for longer than required by the passenger service process, on account of a signal at danger.

- **Disruptions** to the service downstream or problems with the train itself can prevent a train departing even if the scheduled departure time has passed and the signal is displaying a permissive aspect. In the first instance, the driver will receive an order from traffic control (possibly orally) not to depart. In the second, it will not be possible to depart. If a train does not continue to its final destination it is re-numbered, and that re-numbering is recorded. All re-numbered trains were deleted from the dataset. Stops for which the arrival and/or departure time were not recorded in TRENTO – often on account of a defect or disruption – were not used.

- If a **defect** was recorded for a train number on a particular day, then all references to that train number on that day were deleted, regardless of the station or track section on which the defect occurred. The reason for this is that the type of defect is unknown, which means that it is not possible to establish the influence of the defect on stops.

The post-filtering dataset contained over 2.5 million stops (approximately one-fifth of the number in the original dataset) at 1,069 platforms, at 219 different stations. This corresponds to approximately three-quarters of the stations in the original dataset.

Step 2 – Establish the influence of other factors (Groups 2–5)

The next step involved establishing whether the factors from Groups 2–5 had affected dwell times. This operation consisted of a three-stage analysis process, using a simplified version of the conceptual model (see Figure 7.6) and expectations regarding the influence of each factor:

- The **passenger infrastructure (Group 2)** is the pedestrian infrastructure formed by the platform and the train during the passenger service process (the "platform-train combination"). The dimensions of the platform determine the space available to the passengers, while the layout of the platform influences the manner in which they are distributed. Passengers may be distributed differently along a platform with access from one end only than on a platform with an entrance in the centre. A train is described by its rolling stock type and its length. The rolling stock determines the doors, the distance between them and the available space inside, e.g. the size of vestibules. Train length influences the distribution of passengers along the platform and within the train. The situation on the platform may also affect the departure process (see operational characteristics). A conductor may well be able to carry out the departure process quicker on a straight platform with good lines of sight than on a curved platform with multiple obstacles.

- **Passenger behaviour (Group 3)** may vary over the course of a day. During peak hours (0700-0900 and 1600-1800, Monday to Friday, in the case of the Netherlands), commuters will predominate. It is reasonable to assume that this group is used to train travel – and crowding. We can therefore assume that these passengers will alight and board more quickly, which means that (all other things being equal, including circumstances and number of passengers) dwell times will be shorter during peak hours. Passengers travelling during off-peak periods will include a certain number who use the train less frequently, which could extend the duration of the alighting and boarding process. This would lengthen dwell times (again, all other things being equal).

- The **conditions of travel (Group 3)** – whether a train includes both first and second class accommodation and whether seat reservations are possible or necessary – are the same for all domestic trains in the Netherlands. On Dutch trains, first class accommodation is usually located at a number of points along the train, the exact positions varying somewhat between trains. As a result, there is no difference in the distribution of passengers according to whether they are travelling first or second class. We can therefore treat this factor as being constant for stations in the Netherlands and need take no further account of it.

- The **operational characteristics (Group 4)** may depend on the rolling stock and the platform. The duration of the departure process may depend on the length of the train, for instance. For each train, the conductor must decide whether it is safe to close the doors and then verify that all doors are indeed closed. This process may require more time for a long train than for a shorter one. If the doors are designed to close automatically if no passenger alights or boards for a certain number of seconds, the conductor will have fewer doors to check and the departure process may take less time than for trains where all doors remain open until the conductor initiates the departure process.

- **Weather (Group 5)** may affect the stop, exerting an influence via two other external factors: 1. It may affect **operating characteristics**, such as the departure process. In the Netherlands, the conductor has to stand on the platform during this process, to see whether all doors are closed. How this is done may differ between dry and wet weather. 2. It may affect **passenger behaviour**. On platforms in the open, passengers will be concentrated in and around covered waiting areas such as shelters during rain or snow, whereas they may well be more evenly distributed along the platform in good weather.

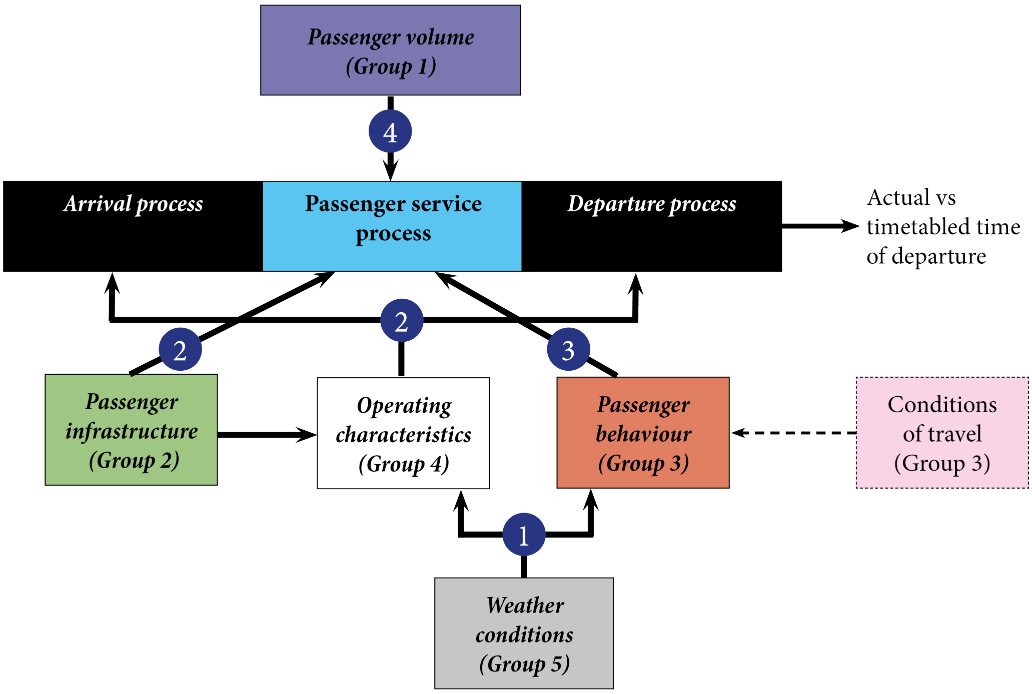


Figure 7.6: Analysis stages based on the conceptual model in Figure 7.5

Whether the above-mentioned groups of factors have a significant influence on dwell time was determined from the differences between the cumulative distribution curves of dwell time (see [186], for instance) in combination with two commonly-used nonparametric statistic tests on two samples. The tests were the Wilcoxon-Mann-Whitney (WMW) and Kolmogorov-Smirnov (KS) tests. Unlike commonly used t-tests [199] or multivariate regression models that require large samples ($n \geq 25$ [200]), the tests selected here have the advantage that they can be applied to small samples ($n < 10$). This makes it possible to filter the data in accordance with more demanding criteria, thereby eliminating factors that are external as far as the tests are concerned. Two different types of nonparametric test were used, to identify any doubtful cases (such as might result from using small samples). For both tests, the null hypothesis

(H_0) was that the two subsets have the same distribution. This is true if the p value from the test is greater than the minimum value chosen. The commonly-used reliability level of 95% was applied, which meant that the limiting value was 0.05 for both p_{WMW} and p_{KS}. For this study, it was assumed that a group of factors has an influence if at least one of the two nonparametric tests leads to rejection of the null hypothesis.

Hypothesis $\mathbf{H_0}$: $\mathbb{P}_{Subset_A} = \mathbb{P}_{Subset_B}$

Hypothesis $\mathbf{H_1}$: $\mathbb{P}_{Subset_A} \neq \mathbb{P}_{Subset_B}$

The influence of factors in Groups 2–5 was determined as explained below. In order to maximize the power of the tests, the extreme values of the factor under consideration were used wherever possible. As certain factors affect each other, or act only indirectly, the following sequence was followed:

1. **Weather (Group 5):** The presence or absence of rain was used as the indicator for precipitation. It is therefore safe to assume that this type of weather did actually occur during stops contained in the dataset. Weather conditions may affect situations both with and without alighters and boarders. The possible influence of weather was therefore tested for in the cases of Groups 2 and 3 (see below).

2. **Operating characteristics (Group 4):** Differences in dwell times between stops during which no passengers alighted or boarded (or the number of alighters/boarders was insignificant) give an indication of the effects that rolling stock type and/or train length are exerting on dwell time. As weather conditions could have an effect, these were kept as constant as possible for this analysis. The results of analyses carried out under the previous point were used in order to achieve this.

3. **Passenger behaviour (Group 3):** Whether the stop occurred during peak or off-peak times was used as an indicator of passenger behaviour. This analysis was repeated for each type of passenger infrastructure (platform/train combination), keeping weather as constant as possible.

4. **Passenger infrastructure (Group 2):** The final analysis covered the effect of platform-train combinations on stops during which significant numbers of passengers did alight and board. The number of passengers was kept constant for this analysis.

Step 3 – Determine the influence of number of alighters and boarders on dwell time

The factor groups identified as significant during Step 2 were used to create a number of scenarios. Those scenarios formed the basis for filtering the cleaned-up dataset (containing over 2.5 million stops) by weather conditions and stratifying it by the factors from the other groups. The possible influence of weather was controlled for by selecting only dry-weather stops and rejecting those during which rain was present. Then, for each sub-group, all factors were assumed to be constant, with the exception of the number of alighters and boarders and the dwell time. The regression coefficients for the models developed by Lin (I.8), Hennige (I.9), Lam (I.14) and Puong (I.15) were estimated for each subset of data. As an example, Equation 7.1 shows Puong's model, which is the model with the largest number of regression coefficients. For descriptions of the other models, please see Appendix I.

$$t_T = \beta_0 + \beta_1 \frac{I_t}{d} + \beta_2 \frac{U_t}{d} + \beta_3 (\frac{V_t}{d})^3 \frac{I_t}{d} \tag{7.1}$$

To obtain valid results, only those scenarios were selected that included a certain minimum number of stops. As a result, the results are valid for the most commonly-occurring situations. Jenkins [200] recommends a minimum of 20 to 25 observations for univariate regression models. The minimum was set at 50 for this study, as multivariate regression models with two independent variables were used.

Following filtering and stratification, the dataset consisted of 1.1 million stops at 177 stations. This corresponds to 80% of the original 2.5 million stops at 219 stations.

Step 4 – Identify those stops of which the duration was excessively long owing to the number of alighters and boarders

Using the available data and the selected regression models, passenger service time (PST_T) was determined from total dwell time (t_T) for each train T per subset of the data, in accordance with Equation 7.2.

$$\%PST_T = \frac{t_T - \beta_0}{t_T} \tag{7.2}$$

Those stations and platforms were then identified at which trains stopped for longer than timetabled, with the passenger service process being at least partly responsible for this longer dwell time. This was achieved using the following four criteria:

1. That **part of the variance** that was **explained** by the regression model ((adjusted) R^2). For this study, that parameter served as an indicator of statistical significance. If the value is high, the passenger service process explains a large percentage of the variation in dwell time. Low values indicate that other factors influence the variation in dwell time more than does the passenger service process. As this part of the study focuses on those stops for which the passenger service process is a determining factor, a minimum of 0.4 was chosen for (adjusted) R^2. The thinking behind this choice is that if the passenger service process accounts for substantially less than half the variation in dwell time (less than 40%), other factors must be more significant.

2. The **percentage of total calculated dwell time that is accounted for by passenger service time** (*%PST*). This figure serves as an indicator of relevance. If the value is high, the passenger service time is relevant to dwell time. As earlier research (Wiggenraad [193] and Lehnhoff & Janssen[184]) have shown this percentage to be subject to substantial variation, no limiting value was set before the analysis was conducted. Interpretation of the results therefore depends on knowledge acquired from the analysis.

3. The **percentage of trains that remained at the platform for longer than timetabled** (*%lang* – *lang* means "long" in Dutch). This figure serves as an indicator of relevance. If it is high, then an extended dwell time caused by the passenger service process will delay the departure of the train, or increase any existing delay.

4. The **percentage of trains that departed later than the scheduled time** (*%laat* – *laat* means "late" in Dutch). This figure also serves as an indicator of relevance. If this figure and the two previous figures (*%PST* and *%lang*) are high, then increased passenger service time has contributed to the train departing late, or later than it already was.

In addition to the influence of the passenger service process on dwell time, the influence of train type and platform on the passenger service process were also studied.

7.4 Results

This section describes the results of this thematic study. Initial inspection of the dataset was conducted after the observations had been filtered for external factors (Group 6). Whether the other factors (Groups 2 to 5) have a significant effect on dwell time was then determined. On the basis of the first two steps, the scenarios were described for which subsets of stops were compiled, and the coefficients were estimated using the regression models suitable for those subsets. Those estimated regression regression coefficients were then used to determine the percentage of total dwell time accounted for by passenger service time. Finally, the 2018 timetable as implemented was used to identify those stations at which passenger service time had resulted in dwell times that exceeded those timetabled and in delayed departures.

7.4.1 Initial inspection of the dataset

Initial inspection of the dataset confirmed the assumption that dwell time increases with the number of alighters and boarders. Figure 7.7 shows all stops with dwell times of between 0 and 600 s (i.e. 10 minutes). Rejecting stops with recorded dwell times in excess of 600 s meant that 112 stops were not included. These were probably the result of unrecorded defects or disruptions, or incorrect or inconsistent data registration. The figure clearly shows that the scatter in dwell times decreases as the number of alighters and boarders increases. The sharp boundary along the underside of the point cloud indicates that minimum dwell time increases with the number of alighters and boarders.

The large amount of scatter at low passenger numbers indicates that factors other than the number of alighters and boarders are playing a role.

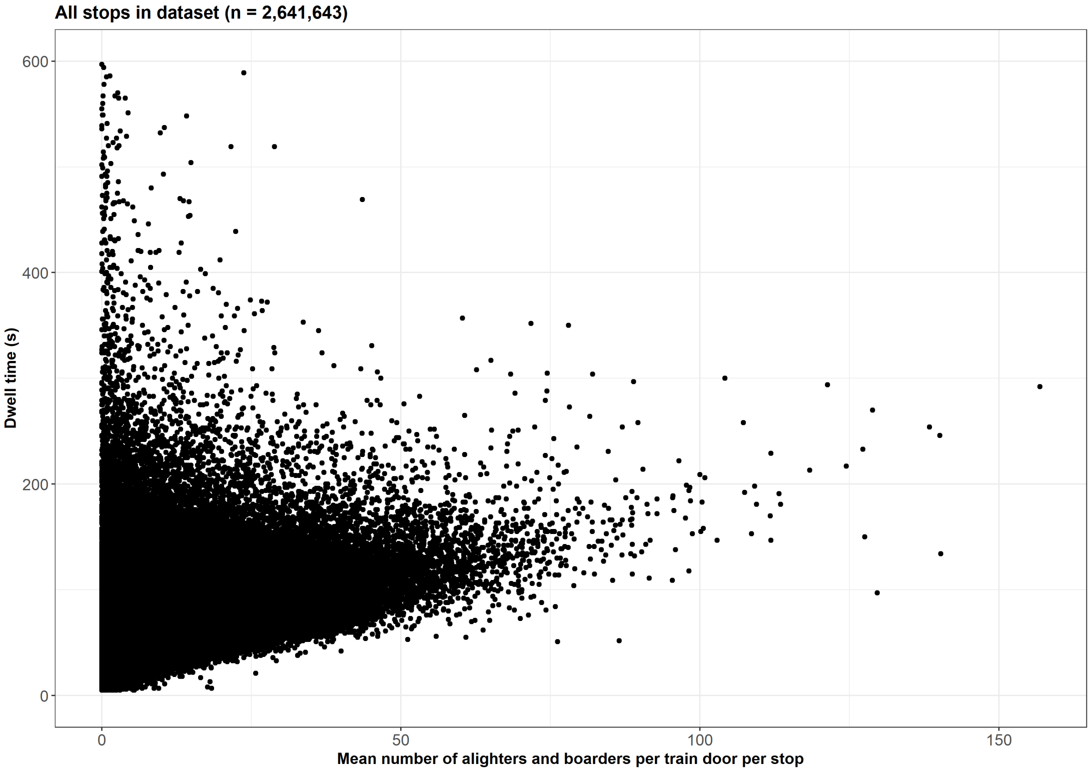
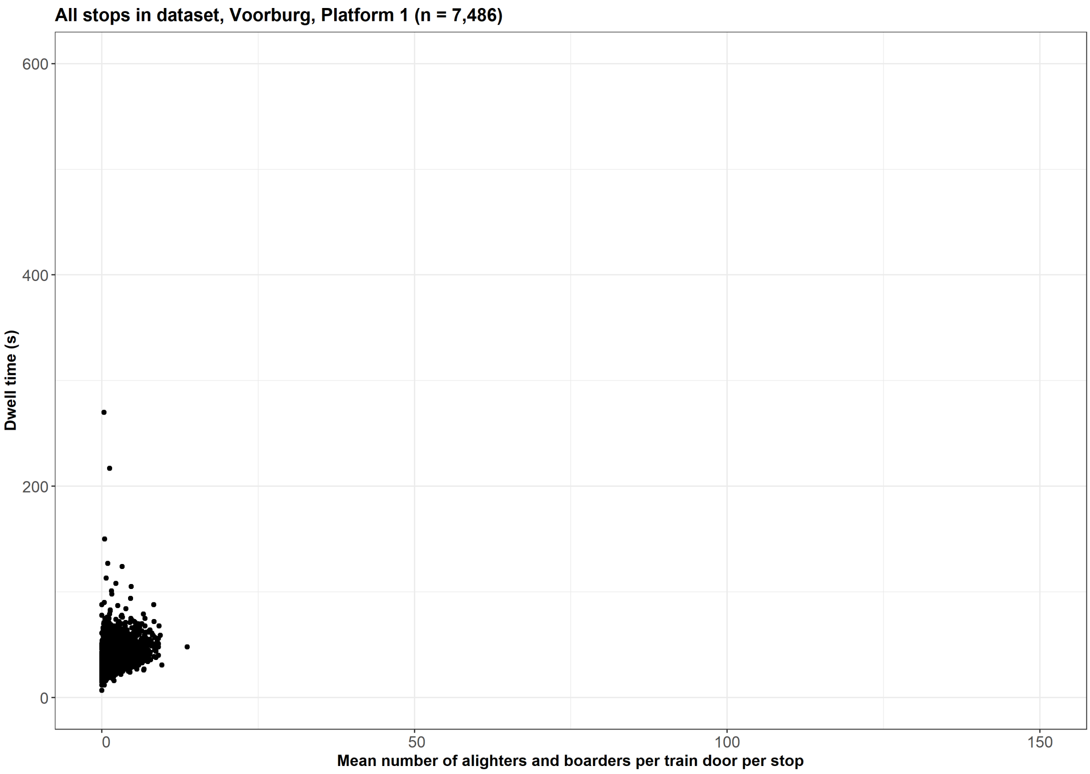


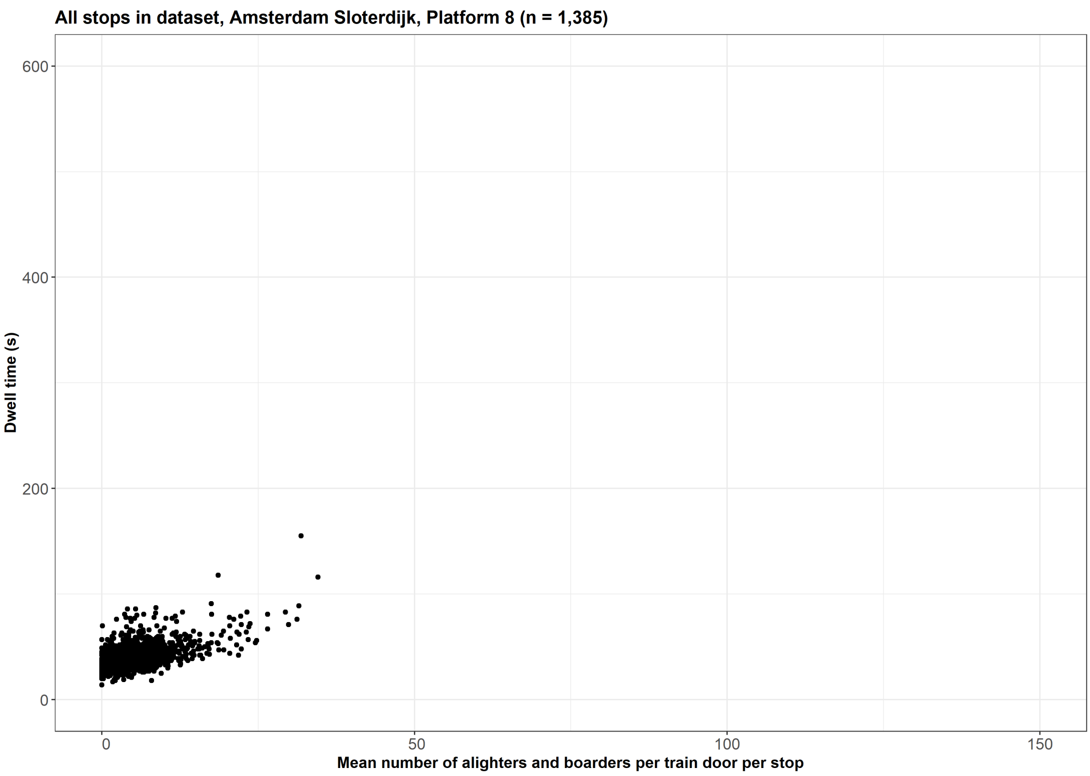
Figure 7.7: Dwell times for all stops, for each train in the dataset

To further illustrate the variation between observations, Figure 7.8 presents a similar scatter plot for observations from individual platforms at three stations: Voorburg (Platform 1), Amsterdam Sloterdijk (Platforms 6 and 8) and Utrecht Centraal (Platform 5). These have been so selected as to show different ranges of values for the independent variable – the mean number of alighters and boarders per door. The figure shows that the variation in number of alighters and boarders is small for Voorburg Platform 1 and Amsterdam Sloterdijk Platform 8, and large for Amsterdam Sloterdijk Platform 6 and Utrecht Centraal Platform 5. The variation in dwell time appears to be very similar in all of these examples.

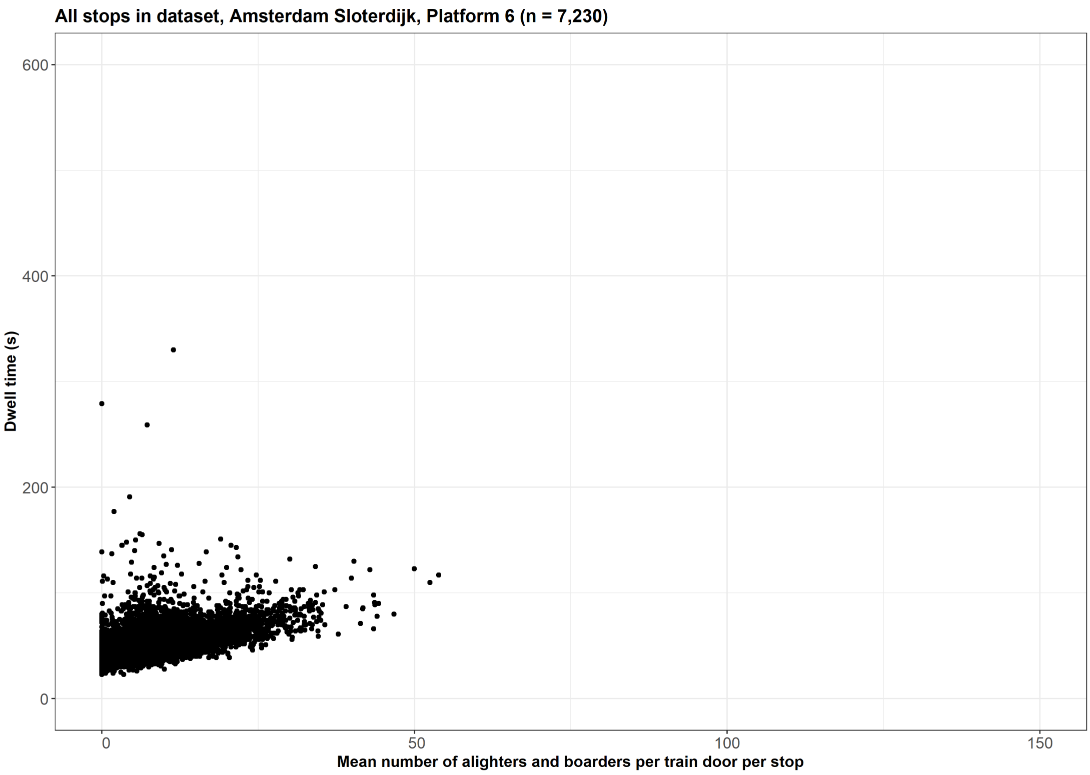
Table 7.5 shows the results of regression analyses conducted using Puong's model (Equation 7.1) for each subset of station/platform combinations shown in Figure 7.8. This model uses a larger number of regression coefficients than the others. An initial analysis with this model therefore gives a first impression of the relevance of factors other than the number of alighters and boarders. The table indicates that the explained variance (R^2) in dwell time is still small and that the variance in the independent variable H is large. H is the percentage of observations for which there were more than 25 alighters and boarders per door. Generally speaking, station/platform combinations with a high value of H also have a higher value of R^2. There is also considerable variance in the values of regression coefficients β_0, β_1 and β_2. Taken together with the value of explained variance (R^2) this clearly indicates that one or more factors other than the number of alighters and boarders are playing a role. For some of the stops,



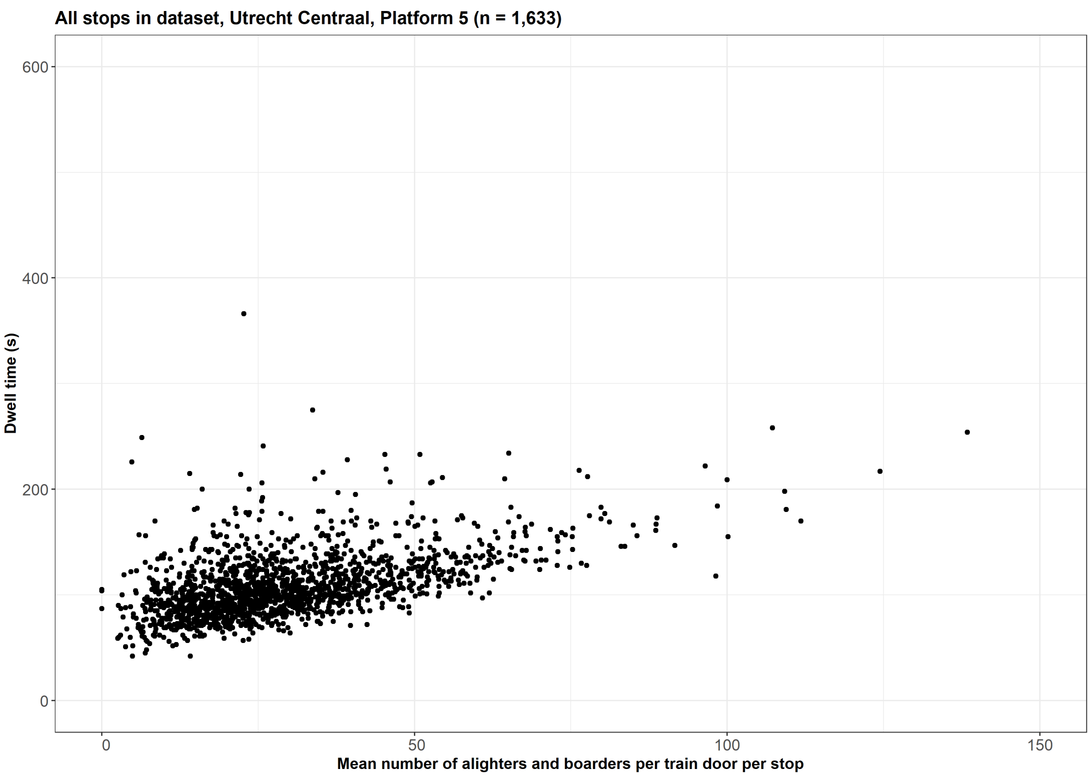
(a) Voorburg – Platform 1 *(Subset Vb_1)*



(b) Amsterdam Sloterdijk – Platform 8 *(Subset Ass_8B)*



(c) Amsterdam Sloterdijk – Platform 6 *(Subset Ass_6BA)*



(d) Utrecht Centraal – Platform 5 *(Subset Ut_5)*

Figure 7.8: Dwell times for a selection of station/platform combinations contained in the dataset

the number of alighters and boarders is a secondary factor. The coefficient for the crowding factor (β_3) is zero. Puong's model (Equation 7.1) has therefore not been used further. Table J.1 in Appendix J lists all subsets with more than 500 observations per sample.

Subset	n	Adj. R^2	Coefficient	Est.	Std. err.	Stat.	p
Amsterdam Sloterdijk	7230	.23	β_0	44.22	0.29	150.27	0
Platform 6			β_1	0.99	0.06	16.87	0
(Subset Ass_6BA)			β_2	1.10	0.03	36.93	0
H = 3%			β_3	0	0	2.90	0
Amsterdam Sloterdijk	1385	.33	β_0	31.95	0.29	73.39	0
Platform 8			β_1	2.24	0.16	13.97	0
(Subset Ass_8B)			β_2	1.12	0.08	14.66	0
H = 0.5%			β_3	0	0	5.04	0
Utrecht Centraal	1633	.27	β_0	82.23	1.36	60.42	0
Platform 5			β_1	0.89	0.09	10.26	0
(Subset Ut_5)			β_2	0.93	0.09	10.16	0
H = 53%			β_3	0	0	3.05	0
Voorburg	7486	.09	β_0	34.69	0.17	203.03	0
Platform 1			β_1	1.95	0.23	8.48	0
(Subset Vb_1)			β_2	1.65	0.12	13.83	0
H = 0%			β_3	0	0	7.58	0

Table 7.5: Results of regression analyses on subsets of stops, using Puong's model (Equation I.15)

7.4.2 Influence of other factors

In determining the influence of the other factors, the sequence was as indicated in Figure 7.6. The factors examined were weather, operating characteristics and passenger behaviour, in that order. For each analysis, the other factors and the number of alighters and boarders were kept as constant as possible.

Weather (Group 5)

The first step in establishing whether weather affects dwell time was to examine stops at which no passengers alighted or boarded. Weather data from the KNMI were used, assigning a weather station to each railway station (see Chapter 4). Minimum and maximum weather types were selected, while avoiding extreme situations such as storms. Extreme weather rarely occurs, but when it does it often causes major disruption to train services. Earlier research had indicated that rain might well be an influencing factor. For this part of the study, therefore, dry days were compared with days on which rain occurred for long periods. The aim of selecting days with those types of weather pattern was to minimize the risk of inaccurate assumptions regarding weather conditions, e.g. assuming that stops in the evening peak period had been affected by rain, whereas in fact it had only rained during the morning peak period. Weather conditions are defined below. In the KNMI data, DR stands for duration of rainfall (in tenths of an hour) and SQ for sunshine duration (in tenths of an hour) calculated from global radiation.

1. **No rain:** no precipitation (DR = 0)

2. **Rain:** at least 10 hours of precipitation (DR $\geq$ 100) and less than 2 hours of sun (SQ $<$ 20)

The enriched ROCKT dataset available for this research contained virtually no stops with zero alighters and boarders. In order to isolate weather as a factor, without re-introducing the influence of alighters and boarders, stops were selected for this analysis during which fewer than 5 passengers alighted or boarded. The assumption is that such a small number of alighters and boarders will have no influence on dwell time, as it will take longer to open the doors on arrival and to initiate the departure process than it will for these few passengers to alight and board.

To compare the variation in dwell time, scenarios were created for different combinations of station, platform, time of day (peak/off-peak), rolling stock and train length. This made it possible to keep all other factors constant. For each scenario, those samples were selected that contained at least 10 observations per weather type. This resulted in a dataset containing 34 stations, 76 time/platform/rolling stock/train length combinations and 2 weather types, in 152 data subsets. Most time-related scenarios covered the off-peak period. This was to be expected, as there will be very few stops with fewer than 5 alighters/boarders during peak times.

The variation in dwell time was then compared for the two weather types, for each scenario. This comparison involved the use of the statistical tests described in Section 7.3 – Kolmogorov-Smirnov (KS) and Wilcoxon-Mann-Whitney (WMW). The following hypotheses were adopted for both tests:

Hypothesis $\mathbf{H_0}$: $\mathbb{P}_{rain} = \mathbb{P}_{norain}$

Hypothesis $\mathbf{H_1}$: $\mathbb{P}_{rain} \neq \mathbb{P}_{norain}$

Table J.2 in Appendix J) presents the results of the tests for a 5% confidence interval. Multiple train types (combinations of rolling stock and length) were available for certain station/platform combinations. For Almere Poort (Almp), for instance, stops at Platform 2 were divided into three train types. The rolling stock was the same in all cases – a SprinterLightTrain (SLT) – but train length varied: 4, 6 or 10 coaches. The values n and m in the table indicate the number of stops per scenario with and without rain respectively. The results of the tests are followed by an overview of observations with rain (sample m). The column “Mths” indicates the number of months in the sample, “Days” the number of different days of the week (i.e. Monday to Sunday) and “Tnos” the number of different train numbers. As train numbers in a timetable are linked to trains that are always timetabled to run at the same time of day, the train number is a good indicator of the time at which the stop occurred. The values in the three columns mentioned show that observations for the rain scenarios are distributed over several months, days of the week and times of day. This guarantees that the observations for a given scenario are not clustered around a particular time, which could have caused the statistical tests to produce erroneous results.

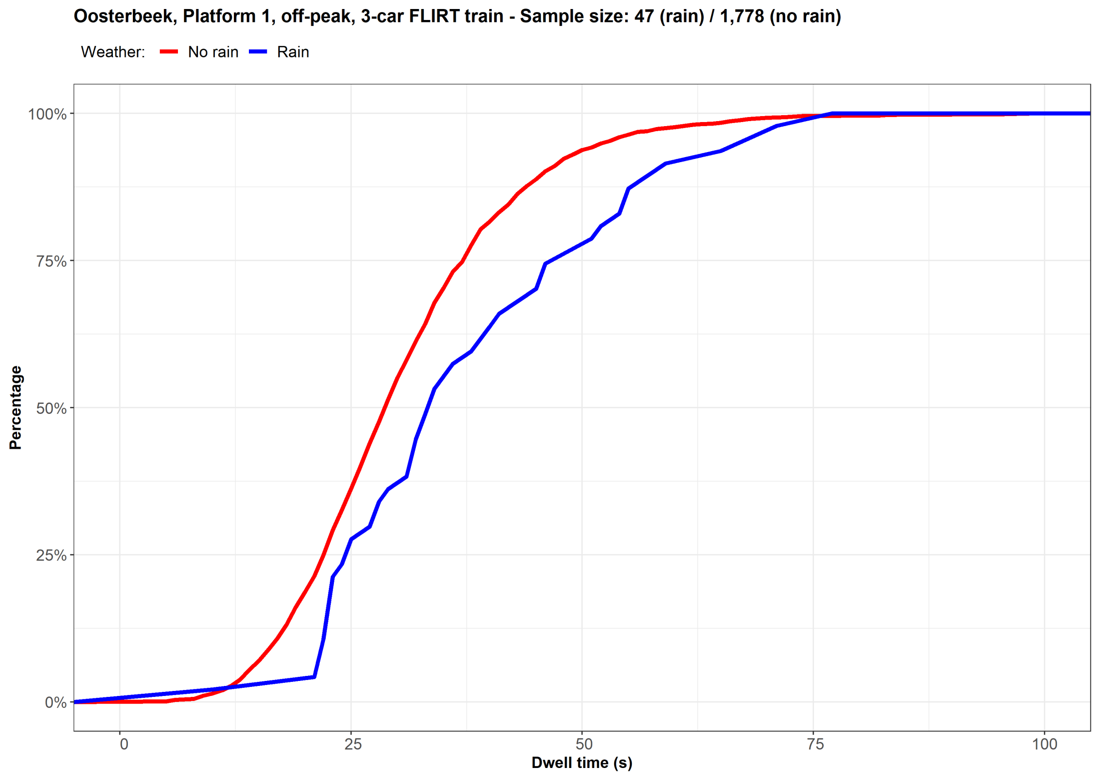
The results shown as (H_1) in Table J.2 indicate that in a number of scenarios the weather altered the distribution of dwell time. The dataset indicates that the stations concerned are Amsterdam Sciencepark (Assp; Platform 2), Dordrecht Zuid (Ddzd; Platform 2), Eindhoven Strijp-S (Ehs; Platform 1) Groningen Europapark (Gerp; Platform 3), Oosterbeek (Otb; Platforms 1 and 2) and Wolfheze (Wf; Platform 1). As an illustration, Figure 7.9a shows the cumulative distribution of dwell time for one scenario on Platform 1 at Oosterbeek station (Otb). That figure clearly shows that dwell time is distributed differently during rain than under dry conditions. Figure 7.9b shows a scenario at Waddinxveen Noord (Wadn), in which the presence of rain makes no statistically significant difference to the cumulative distribution.

On the basis of the above analysis, one can conclude that weather conditions can be a determining factor for dwell time. The analysis also shows that this can be the case even if no passengers alight or board. At the same time, weather conditions do not automatically have an influence, as a significant difference was noted in only 9% of the 76 scenarios in this sub-topic.

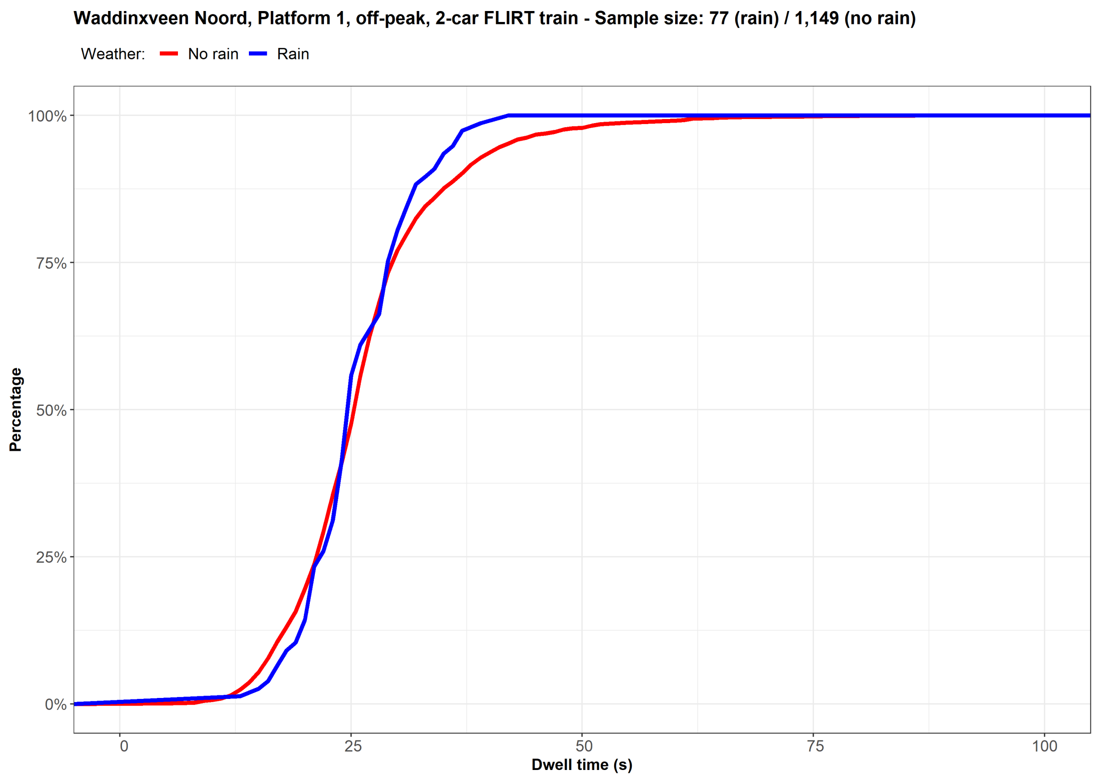
To determine whether these results are also valid for situations with alighting and boarding passengers, the procedure was repeated for stops with the same number of passengers in both samples. The test results are shown in Table J.3. From that table, we can see that the distribution of dwell time only differed in the case of Oosterbeek station (Otb; Platform 1). This is the same result as that obtained when testing stops during which no passengers alighted or boarded (see above). The test results were also comparable for stops with and without alighters/boarders in the other scenarios. It should be pointed out that in this dataset the number of passengers alighting or boarding was relatively small, even in the case of stops with passengers. The largest number was observed at Almere Parkwijk (Almp; Platform 2, SLT6), with a maximum of 19 alighters/boarders. Generally speaking, one can conclude from this analysis that weather conditions can have a significant influence on dwell time, both during stops with alighters/boarders and during stops with none (or with a very small number). However, one can also conclude that this influence is limited if one compares the number of scenarios with weather influence to the total number of scenarios. The author has found no explanation for the fact that weather has an influence in some of the scenarios studied and not in others.

Operating characteristics (Group 4)

Figure 7.10 shows the cumulative distribution curves for all scenarios in which weather had no significant influence on dwell time (see previous section). In all those scenarios, there were fewer than 5 alighters and boarders, which means we can assume that passengers had no influence on dwell time. The figure shows that large differences can occur in the distribution of dwell time. This means that dwell time can depend on station, platform, train and train length, even in the absence of alighting and boarding passengers.



(a) Station Oosterbeek, Platform 1



(b) Waddinxveen Noord, Platform 1

Figure 7.9: Frequency distributions for dwell times, rain and no rain

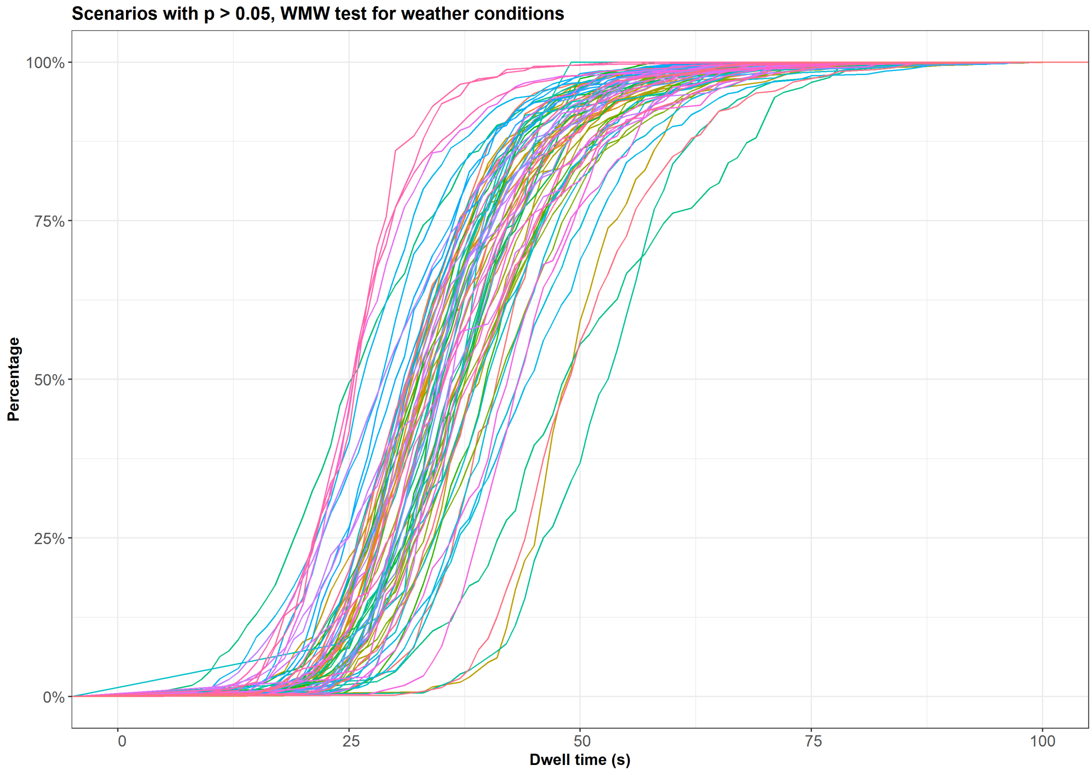


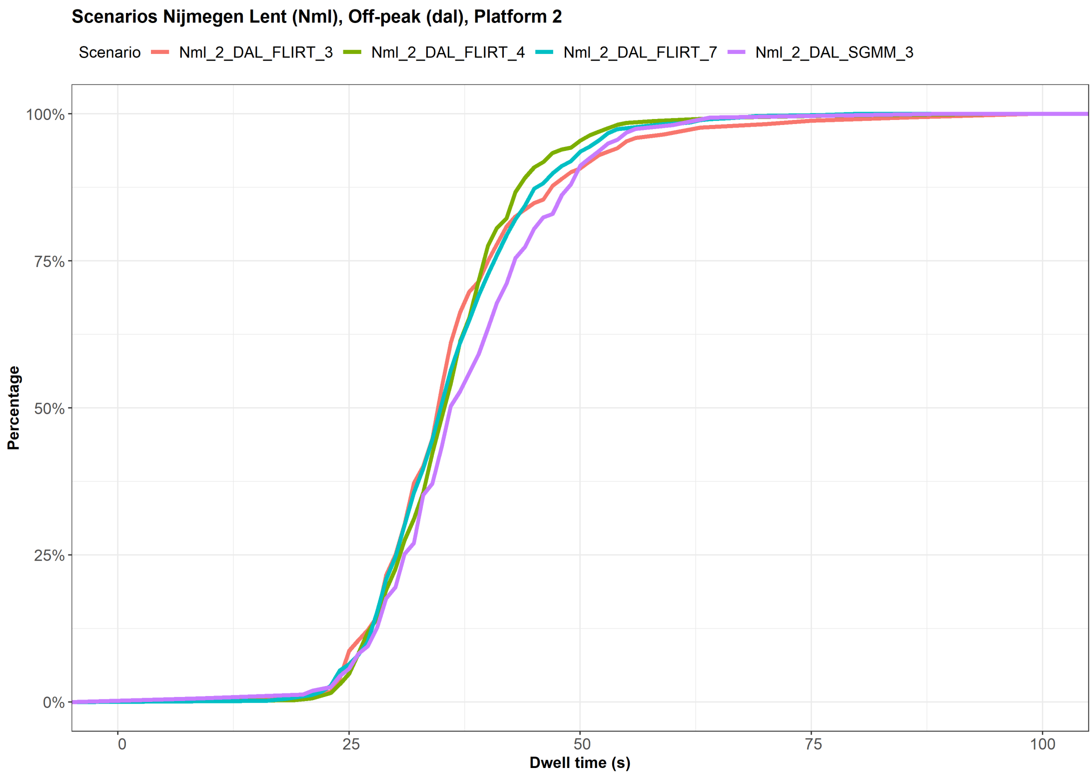
Figure 7.10: Frequency distributions for dwell times, for each scenario (legend omitted for clarity)

Platforms served by trains of different lengths and consisting of different rolling stock types were studied, to isolate the influence of rolling stock type. This analysis was performed using a subset of the scenarios created to study the effect of weather conditions. Of those 76 scenarios, 54 were selected. These scenarios fulfilled two conditions: no significant influence from precipitation *and* multiple rolling stock types and/or train lengths. The stations and platforms concerned were: Almere Parkwijk (Almp; Platform 2), Dordrecht Zuid (Ddzd; Platform 1) and Nijmegen Lent (Nml; Platforms 1 and 2). Figure 7.11a shows the frequency distributions for Platform 2 at Nijmegen Lent, for all train types. This figure appears to indicate that dwell times for SGMM trains are longer than those for trains consisting of FLIRT rolling stock. The shapes of the curves for the three scenarios involving FLIRT trains would appear to indicate that train length has no influence. For similar graphs covering the other stations and platforms, please see Figures J.1a and J.1b in Appendix J. Table J.4 in Appendix J presents the results of the following statistical tests:

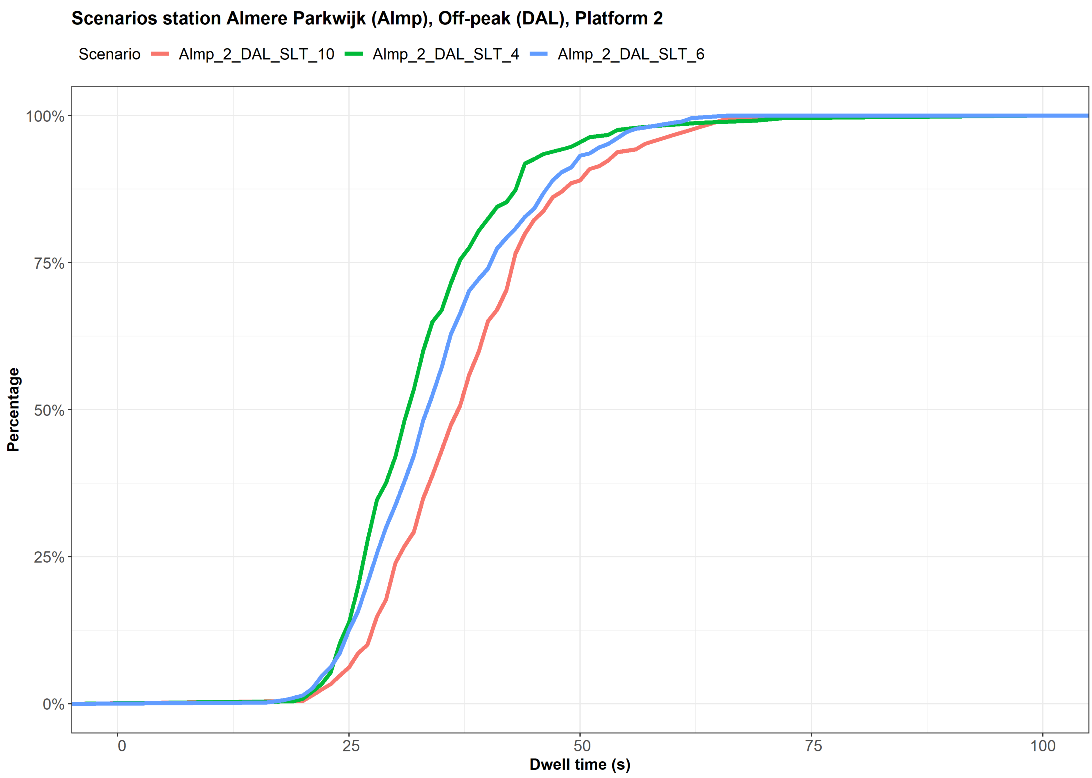
Hypothesis $\mathbf{H_0}$: $\mathbb{P}_A = \mathbb{P}_B$

Hypothesis $\mathbf{H_1}$: $\mathbb{P}_A \neq \mathbb{P}_B$

For these tests, all possible comparisons were made for each station/platform combination between scenarios consisting of variations in rolling stock and/or train length. The test results in Table J.4 clearly show that even when no passengers alight or board, rolling stock type and train length can influence the distribution of dwell times. The even distribution of dwell times for FLIRT trains observed at Nijmegen Lent, Platform 2 (Figure 7.11a) would therefore appear to be something of an exception.



(a) Nijmegen Lent, Platform 2



(b) Almere Parkwijk, Platform 2

Figure 7.11: Frequency distributions for dwell times

Passenger behaviour (Group 3)

This study examines the effect of differences in passenger behaviour by comparing stops during peak periods with stops during off-peak periods. For this part of the study, station, platform, rolling stock, train length and number of alighters and boarders were all kept constant. For certain scenarios, data subsets were available that included observations involving different numbers of passengers. This was the case for both peak and off-peak periods. For instance, stops at Almere Poort (Ampo) with six-coach SLT trains involved different numbers of alighters/boarders per train: 50, 53 and 55. For these scenarios, tests were also conducted on subsets that contained combinations of observations involving different numbers of passengers. Rotterdam Lombardijen (Rlb) was a similar case.

Hypothesis H_0: $\mathbb{P}_{peak} = \mathbb{P}_{off-peak}$

Hypothesis H_1: $\mathbb{P}_{peak} \neq \mathbb{P}_{off-peak}$

Please see Table J.5 (Appendix J) for the results of these tests. In two scenarios at Almere Poort and Rotterdam Lombardijen, there appears to be a statistically significant difference between peak and off-peak periods. However, when these scenarios are merged with observations in which passenger numbers differ only marginally from the original number of passengers in the test, the differences cease to be significant. For the purposes of this study, it was therefore concluded that passenger behaviour has no significant influence on dwell time. Almere Poort and Rotterdam Lombardijen do not constitute exceptions to this rule.

7.4.3 Percentage of dwell time accounted for by the passenger service process

This section examines the percentage of total dwell time accounted for by the passenger service process. This analysis was undertaken using the regression models selected in Section 7.3. For each scenario, the regression coefficients were estimated using the empirical data. In their original form, two of the models incorporate a train-crowding factor. However, earlier analysis conducted as part of this sub-topic showed train crowding to have no significant influence. That factor was therefore omitted from the models used, making the Lin & Wilson model (Equation I.8) identical to that of Lam et al. (Equation I.14).

Analyses in previous sections have shown that station/platform characteristics and train consist (rolling stock and/or length of train) can influence dwell time. For the next step in this study, the percentage of total dwell time accounted for by the passenger service process was therefore determined for a number of scenarios, each consisting of a combination of station, platform, rolling stock and train length. As all trains in a scenario consist of the same rolling stock and are of the same length, the number of doors per train is constant across a given scenario. This makes it possible to derive the results of the Lam et al. model (Equation I.14) from those of the Puong model (Equation I.15) and vice-versa. As a result, only two types of regression model are available for this analysis: Hennige (Equation 7.3), in which alighters and boarders are added together for each stop, and the Lam-Puong model (Equation 7.4 or 7.5), which treat alighters and boarders as distinct independent variables. To eliminate the influence of weather on dwell time, only data from dry days were used.

Hennige model

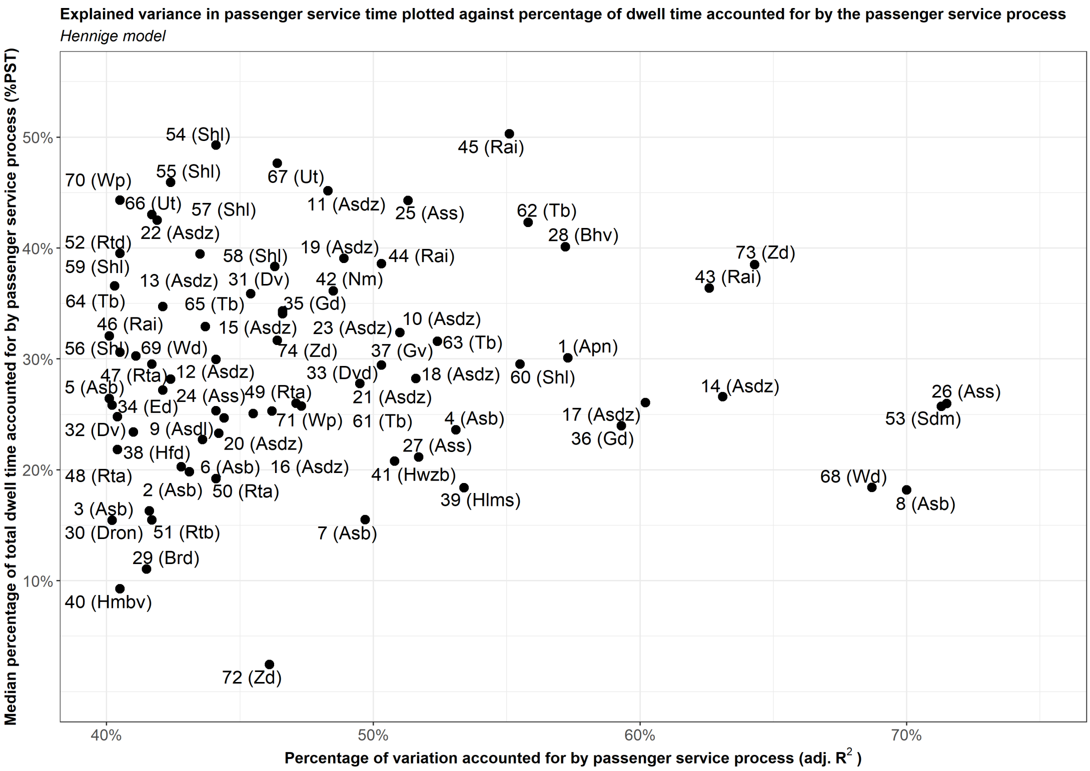
Equation 7.3 is the first of the two regression models. Coefficients β_0 and $\beta_{1;2}$ were estimated for each scenario in the dataset. As explained in Section 7.3, each scenario consists of a set of 50 or more stops at the same platform with the same consist (rolling stock and train length).

$$t_T = \beta_0 + \beta_{1;2}(I_T + U_T) \tag{7.3}$$

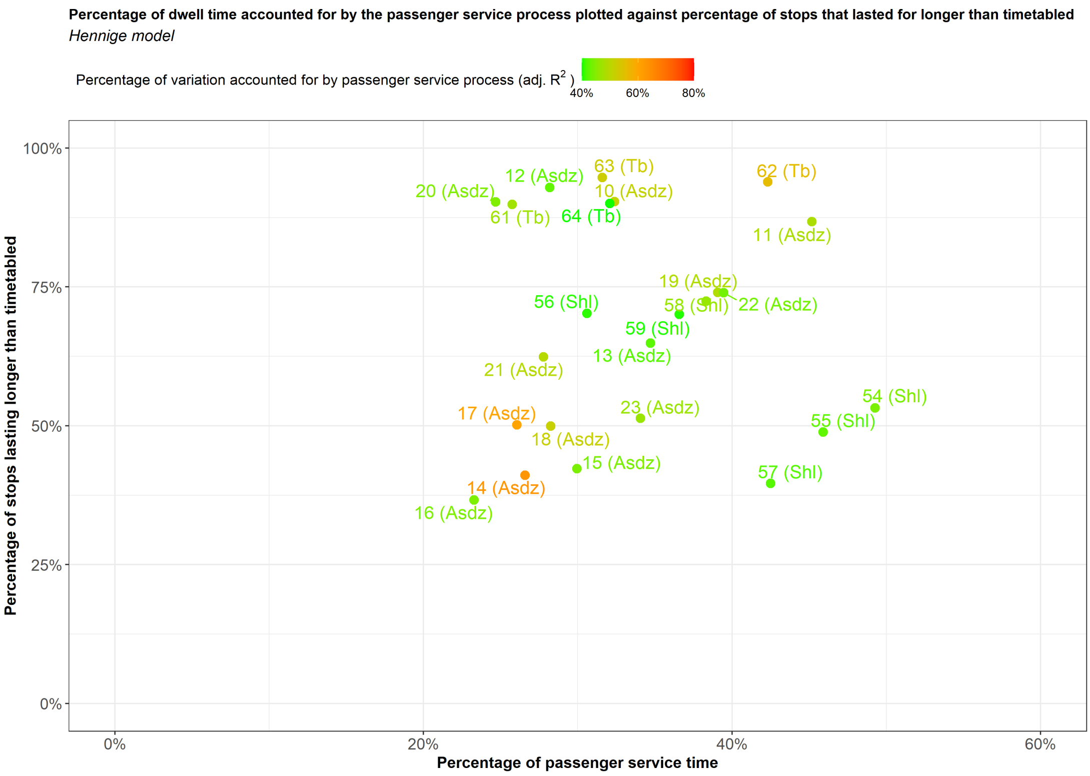
The percentage of dwell time accounted for by the passenger service process ($\%PST$) was then calculated for each stop, using Equation 7.2 and the regression models for each scenario. Figure 7.12a shows the results for 13,282 stops in 74 scenarios at 29 stations for which the explained variance in the regression model was greater than 0.4. The y axis shows the median percentage of dwell time accounted for by the passenger service process across all stops in this scenario. The x axis shows the variance in total dwell time explained by passenger service time ((adjusted) R^2). Please see Table J.6 in Appendix J for a description of the scenarios, coefficients and values of $\%lang$, $\%laat$ en $\%PST$.

Figure 7.12a shows that the percentage of dwell time accounted for by the passenger service process varies from less than 10% to just over 50%. For the vast majority of scenarios, (adjusted) R^2 lies between 40% and 50%. This means that other factors are playing a relatively significant role, in addition to the number of alighters and boarders. This is taken into account when interpreting the results from the following section.

Fig 7.12b plots the percentage of dwell time accounted for by the passenger service process against the percentage of stops that lasted longer than timetabled. That figure shows a selection of scenarios from Figure 7.12a. The selected scenarios all include platforms at stations for which there are three or more scenarios. The thinking behind this selection criterion is that the existence of three or more scenarios for one platform indicates a pattern, whereas a smaller number of scenarios could be coincidence. The data in the selected scenarios indicate that passenger service time made a significant contribution to longer-than-timetabled stops at Amsterdam Zuid (Asdz), Schiphol Airport (Shl) and Tilburg (Tb).

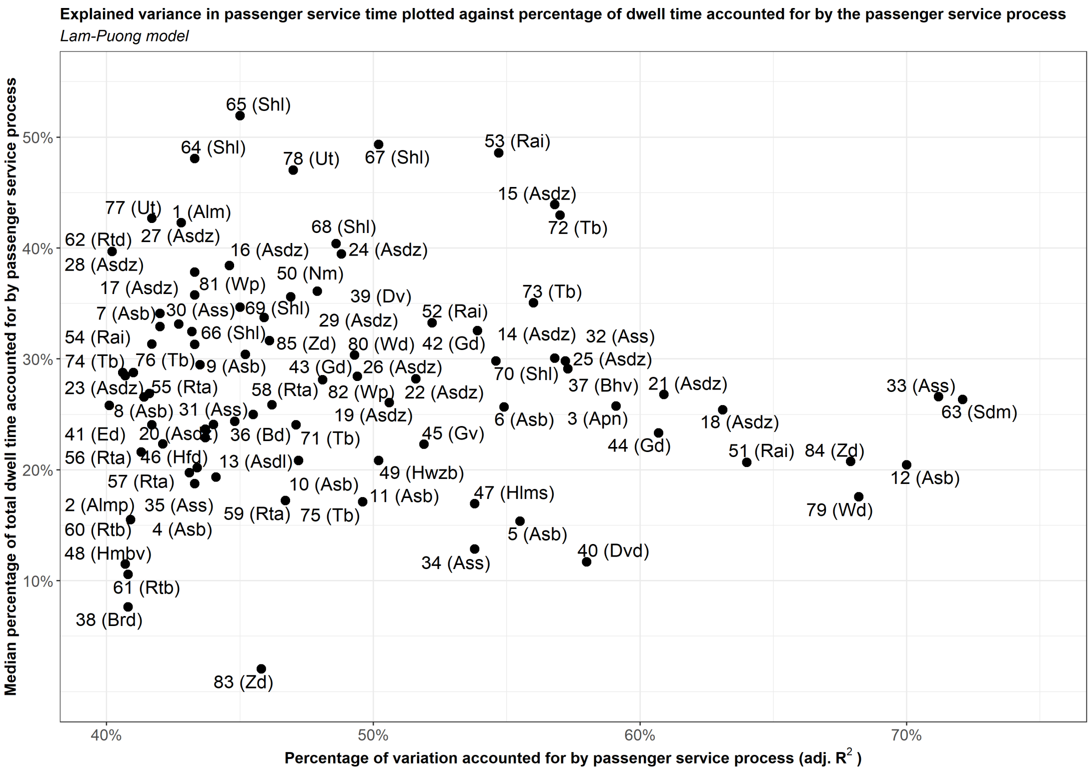


(a) Explained variance in passenger service time plotted against percentage of dwell time accounted for by the passenger service process

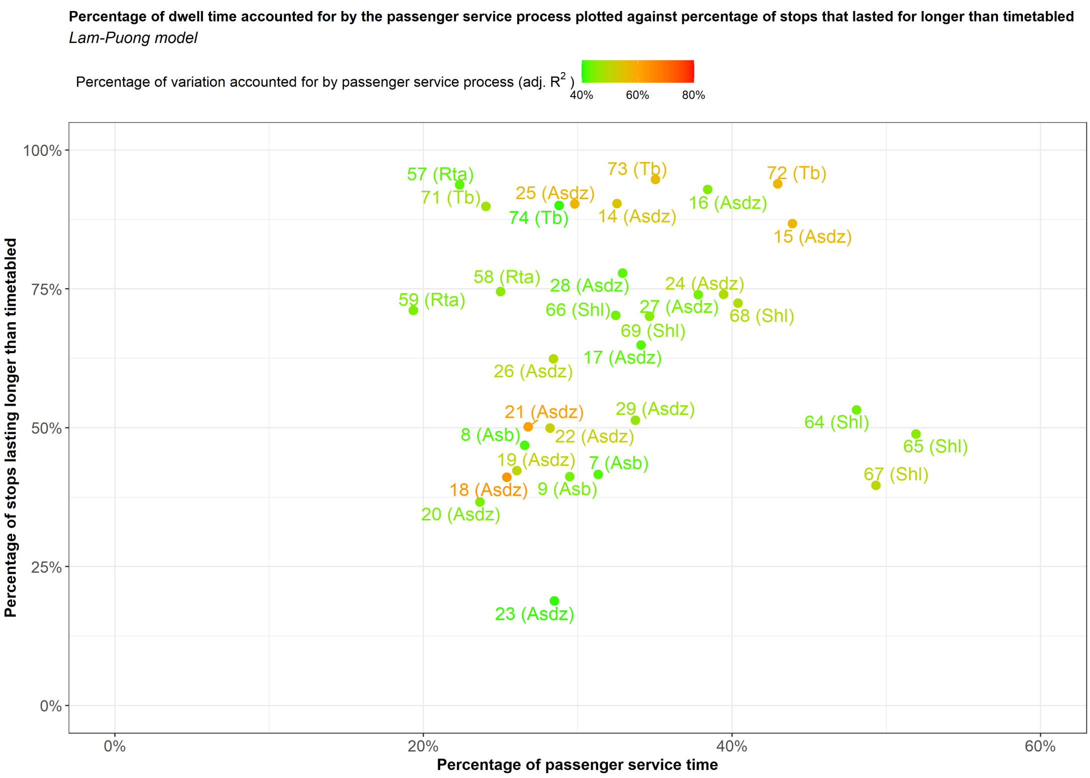


(b) Percentage of dwell time accounted for by the passenger service process plotted against percentage of stops that lasted for longer than timetabled

Figure 7.12: Hennige model: stations with high-relevance, high-significance scenarios



(a) Explained variance in passenger service time plotted against percentage of dwell time accounted for by the passenger service process



(b) Percentage of dwell time accounted for by the passenger service process plotted against percentage of stops that lasted for longer than timetabled

Figure 7.13: Lam-Puong model: stations with high-relevance, high-significance scenarios

Lam-Puong model

As for the Hennige model, the Lam-Puong model (Equation 7.4) and corresponding coefficients were used to calculate the percentage of total dwell time accounted for by the passenger service process, for each scenario. Because it is possible to derive Equations 7.5 (Puong) and 7.4 (Lam) from each other in the case of scenarios based on train type and length, we shall refer to this model as the "Lam-Puong model". The number of train doors is obviously constant for a given type of rolling stock and train length.

$$t_T = \beta_0 + \beta_1 I_T + \beta_2 U_T \tag{7.4}$$

$$t_T = t_{Dgem} = \beta_0 + \beta_1 \frac{I_T}{d} + \beta_2 \frac{U_T}{d} \tag{7.5}$$

Figure 7.13 shows the results for 15,043 stops in 85 scenarios at 31 stations. Please see Table J.7 in Appendix J for a description of the scenarios, coefficients and values of $\%lang$, $\%laat$ en $\%PST$. Rather more scenarios were selected for calculations using the Lam-Puong model than in the case of the Hennige model. Amsterdam Bijlmer ArenA (Asb) en Rotterdam Alexander (Rta) were also selected, in addition to the stations listed above.

Influence of train type and length

Fig 7.14 plots the percentage of dwell time accounted for by the passenger service process against the number of alighters and boarders, for all scenarios at Amsterdam Zuid. That figure shows how train length affects the degree to which passenger service time influences dwell time. The curves were calculated for the range of alighters and boarders in each scenario for which the regression coefficients were estimated.

The figure shows that train consist (rolling stock and length) has a major influence on the percentage of dwell time accounted for by the passenger service process. For a stop with 250 alighters and boarders, that percentage varies between 20% and 75%. The figure also shows that for a given number of alighters and boarders, passenger service time accounts for a smaller percentage of dwell time in the case of longer trains. This is to be expected, as passengers can alight and board via a larger number of doors in the case of a longer train. However, the figure shows that this relationship is not linear. All other things being equal, each extra door results in a smaller increase in the percentage of dwell time accounted for by the passenger service process. Figure J.2 in Appendix J gives a similar picture. That figure shows other stations, multiple rolling stock types and multiple train lengths.

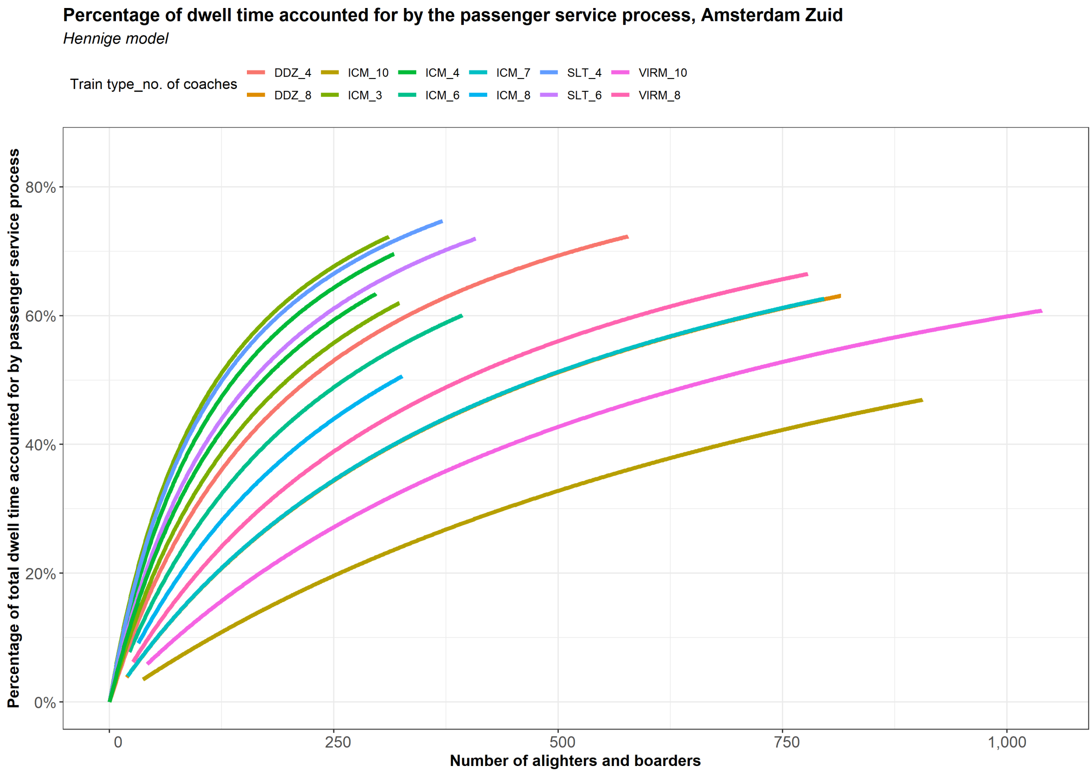


Figure 7.14: Percentage of dwell time accounted for by the passenger service process, as a function of the number of alighters and boarders, Amsterdam Zuid

Influence of platform (and station)

Similarly to the previous analysis, Figure 7.15 plots the percentage of dwell time accounted for by the passenger service process against the number of alighters and boarders, for all scenarios with six-coach SLT (SprinterLightTrain) trains. The figure confirms that the platform/station can have a major influence on the percentage of dwell time accounted for by the passenger service process. For a stop with 250 alighters and boarders, that percentage varies between 50% and 75%. Figure J.3 in Appendix J gives a similar picture. This analysis confirms that the passenger service process depends to a large degree on the station concerned.

7.4.4 Results applied to the timetable as executed in 2018

Amsterdam Zuid, Schiphol Airport, Tilburg, Amsterdam Bijlmer ArenA and Rotterdam Alexander were identified in the previous section as stations at which the passenger service process might have influenced implementation of the timetable. The final step in this analysis is to place all the scenarios for these stations in the context of the timetable as implemented. This involved determining the percentage of trains that departed later than timetabled, for all observations in the original dataset for the 2018 timetable year and for each scenario. This was carried out using the timetabled and actual departure times in TRENTO. Figures 7.16a and 7.16b plot the percentage of trains from each scenario that departed late against the percentage of trains for which

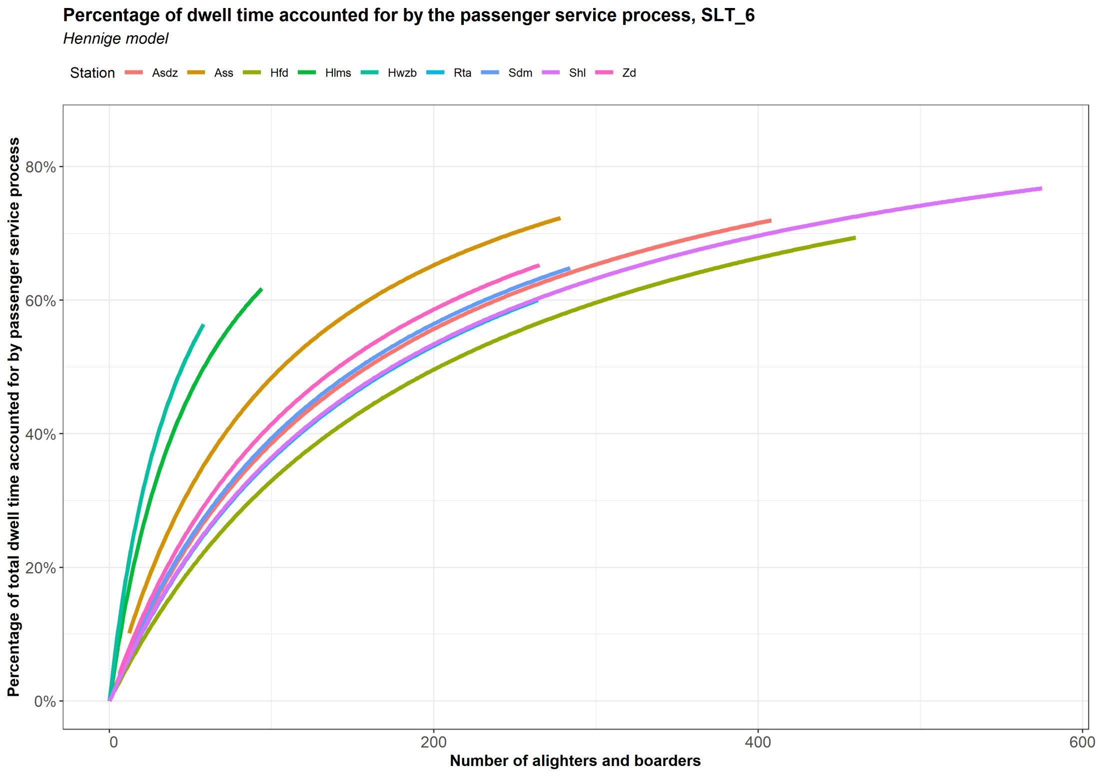


Figure 7.15: Percentage of dwell time accounted for by the passenger service process as a function of the number of alighters and boarders, six-coach SLT

the dwell time was longer than timetabled according to the Hennige and Lam-Puong models respectively.

Figure 7.16 shows four groups of scenarios:

1. Top-right: A large number of trains that departed late *and* for which the stop lasted longer than timetabled. In these scenarios, delays were caused or increased by the length of dwell time.

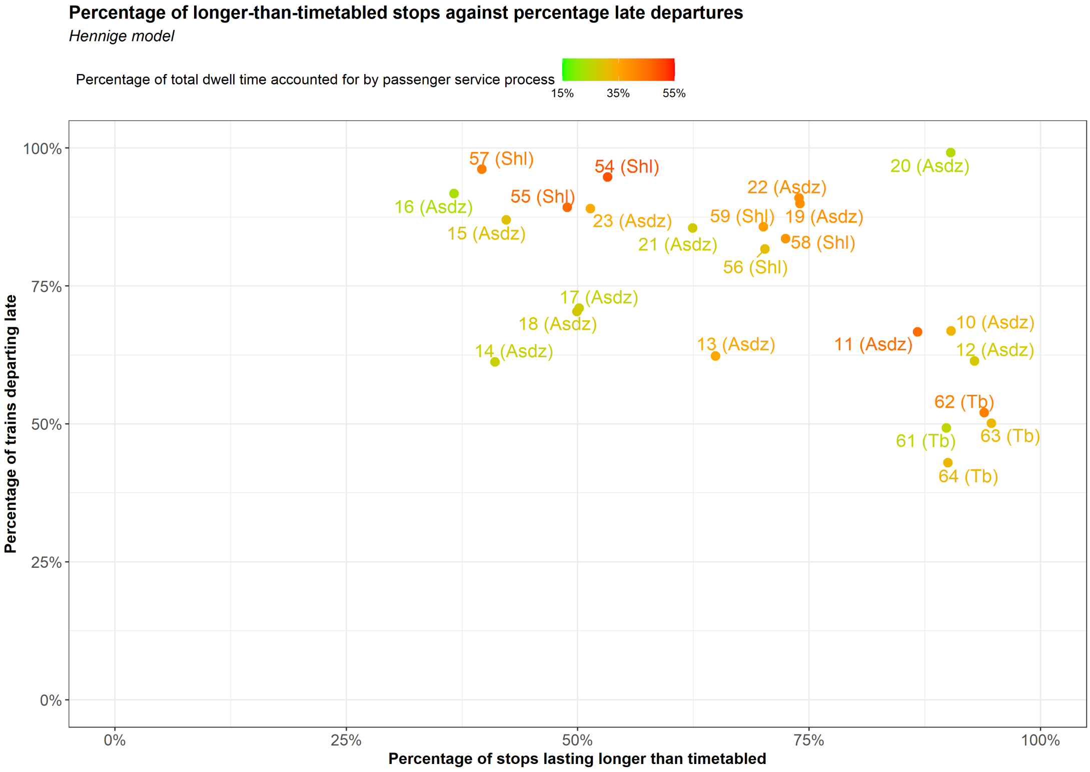
2. Right-centre: Stops lasted longer than timetabled, but the train did not depart late. In these scenarios, the train arrived early, making it possible to compensate for the over-long dwell time.

3. Top-centre: Comparatively few stops lasted longer than planned, but the train nonetheless departed late. These trains departed late because they arrived late.

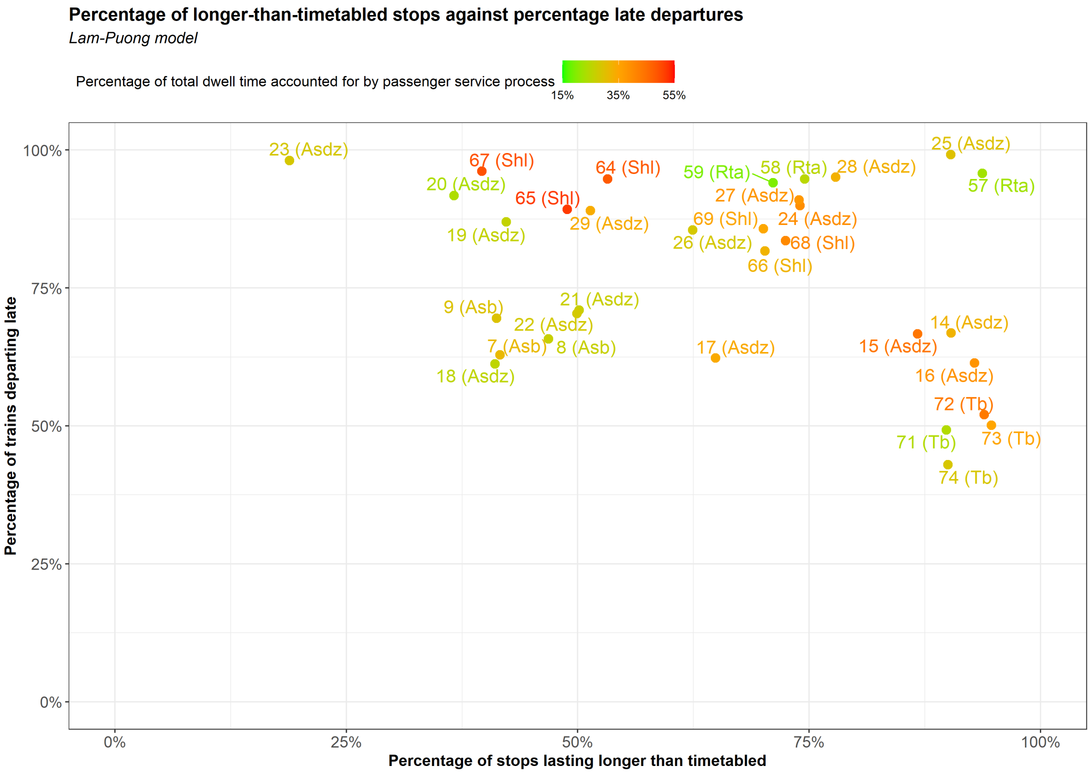
4. Centre: Few trains with over-long dwell times and late departures.

The colours in Figure 7.16 indicate the percentage of dwell time accounted for by the passenger service process. The redder the point, the higher the percentage.

Table 7.6 classifies the stations on the basis of Figure 7.16. Amsterdam Zuid appears in all four groups. In addition to Amsterdam Zuid, Rotterdam Alexander and Schiphol Airport have several scenarios in Group 1. In contrast to Amsterdam Zuid and Schiphol Airport, the passenger service process plays only a minor role at Rotterdam Alexander. All scenarios for Tilburg come under Group 2. Passenger service time



(a) Hennige



(b) Lam-Puong

Figure 7.16: Percentage of longer-than-timetabled stops against percentage late departure and percentage of dwell time accounted for by the passenger service process

Station	Group 1	Group 2	Group 3	Group 4
Amsterdam Bijlmer ArenA (Asb)				Large
Amsterdam Zuid (Asdz)	Large	Large	Large	Small
Rotterdam Alexander (Rta)	Small			
Schiphol Airport (Shl)	Large		Large	
Tilburg (Tb)		Large		

Table 7.6: Stations and scenario groups, indicating fraction of dwell time accounted for by the passenger service process

accounted for a large percentage of dwell time for several scenarios in this group, at both Tilburg and Amsterdam Zuid. Schiphol Airport and Amsterdam Zuid also have scenarios in Group 3 in which the passenger service process accounted for a large percentage of the dwell time. In addition to those for Amsterdam Zuid, all scenarios for Amsterdam Bijlmer ArenA are in Group 4. Passenger service time accounted for only a small percentage of dwell time in the scenarios in that group, for both stations.

This allows us to conclude that passenger service time affected implementation of the timetable at Amsterdam Zuid and Schiphol Airport during 2018.

7.5 Conclusions

This thematic study has focused on the following hypothesis: *As a result of the number of alighting and boarding passengers, trains regularly depart with a delay, or with more delay.* That hypothesis was tested against the answers to the following research questions:

1. Did the other factors, grouped into passenger infrastructure (Group 2), passenger behaviour (Group 3), operating characteristics (Group 4) and weather conditions (Group 5) have a significant influence on dwell time?
2. What is the effect of passenger volume (i.e. the number of alighters and boarders) on dwell time?
3. At what stations was the passenger service process the reason (or one of the reasons) for trains departing late during the 2018 timetable period?

The list of other factors was compiled from earlier research. The aim was to identify factors that influence dwell time in general and passenger service time in particular. In compiling the list of factors, it became apparent that while one could expect many factors to exert an influence, it was not possible to estimate the magnitude of that influence. It also became clear that certain factors can have a major influence on each other. No fully-developed, quantified model existed with which it would have been possible to estimate dwell time on the basis of the most important factors.

In answering **Research Question 1**, the present study has demonstrated that the influence of passenger behaviour (Group 3) is not significant at railway stations in the Netherlands, as no difference was found between stops during peak and off-peak periods. Weather conditions (Group 5) – the presence or absence of rain, as far as this study is concerned – have a significant effect at a number of stations. However, this study concludes that the effect of weather is limited, because an effect was only observed at a limited number of stations. Passenger infrastructure (Group 2) and operating characteristics (Group 4) have a significant and relevant influence. There are large differences in dwell times between platforms and stations, even if all other factors are comparable. Rolling stock and train length also have a significant influence on dwell time.

The above points provide a partial answer to **Research Question 2**. The percentage of dwell time accounted for by the passenger service process varies between scenarios, from 0% to over 80%. For these purposes, a scenario is defined as a subset of all stops made by a given train type at a given platform in 2018. A high percentage of total dwell time accounted for by the passenger service process does not automatically result in an over-long dwell time. A train can still depart punctually if the timetable allows sufficient time for the stop, including the passenger service time.

A selection of scenarios in which the duration of a stop frequently exceeded the time scheduled during the 2018 timetable period highlighted Amsterdam Bijlmer ArenA, Amsterdam Zuid, Schiphol Airport, Tilburg and Rotterdam Alexander. Passenger service time accounted for between 15% and 55% of dwell time in the scenarios for these stations.

To answer **Research Question 3**, the present sub-topic aimed to identify stations at which three conditions were fulfilled: stops lasting for longer than timetabled, passenger service time accounting for a large percentage of dwell time and trains frequently departing late. During the 2018 timetable year, this proved to be the case at Amsterdam Zuid and Schiphol Airport.

Generally speaking, this thematic study indicates that one cannot reject the hypothesis for these two stations. At both stations, the number of alighters and boarders has resulted in stops lasting longer than timetabled. This, in turn, has resulted in trains departing late, or with more delay than they already had on arrival.

7.6 Discussion

There are three important caveats regarding this sub-topic. 1. The manner in which the "other" factors were included (see Sub-section 7.6.1). 2. The filtering method used (see Sub-section 7.6.2). 3. The degree to which the results can be applied to situations other than that of the 2018 timetable (see Sub-section 7.6.3).

7.6.1 Inclusion of other factors

The conceptual model for this study (see Figure 7.5) incorporates a large number of possible influencing factors and a large number of relationships between them. The method used for this sub-topic resulted in considerable simplification of that conceptual model (see Figure 7.6). The main reason for this is that the study was conducted using secondary data.

However, this simplification could result in certain factors being included in the analyses incorrectly, partially or not at all. The relatively low values of (*adjusted*) R^2 for the estimated regression models is an indication that this may have occurred.

The highest values encountered in this study were approximately 70%, and the figures were considerably lower for most scenarios – 40–50%. In previous research, (adjusted) R^2 values ranged from 60% to 90% (see Table 7.3). On the basis of his own operating experience, the author suspects that the relatively low (adjusted) R^2 values in this study were caused by the relatively large variation in the time taken for the departure process in the stops examined for this study. Establishing whether this is the case will require further research with other data sources (see recommendations). The author has no reason to believe that the simplifications have negatively affected the validity of the results (e.g. because of selection bias).

7.6.2 Filter method

A very high threshold was set for the inclusion of observations, to ensure that external factors such as service disruptions and other factors such as weather conditions had as little effect as possible on the estimates of regression coefficients. Using only stops in which the train arrived later than the timetabled departure time was a particularly demanding condition. It is virtually certain that this filtering resulted in fewer observations per scenario and/or fewer scenarios that met the criterion of containing at least 50 observations.

However, it is unlikely that the filter led to selection bias. Applying less demanding criteria would have resulted in more observations per scenario and/or more scenarios, but would probably have reduced the explained variance. This would have meant that scenarios that were close to the limiting values would still have been rejected, on account of the minimum value chosen for (adjusted) R^2. The values of (adjusted) R^2 for the scenarios at Amsterdam Zuid and Schiphol Airport range from over 40% to over 60%, with several scenarios towards the top of this range. It is therefore unlikely that choosing a less demanding arrival time criterion would have altered the results.

7.6.3 General applicability

As for the other sub-topics, one has to consider the degree to which one can apply the results of this study more generally. The fact that the hypothesis for this sub-topic is linked to the 2018 timetable makes that point relevant. The question is therefore "Would other timetables produce different results?" The answer is "probably".

(1) Dwell time is influenced by the number of alighters and boarders. In turn, that figure is influenced by the number of trains timetabled (i.e. service frequency). Increasing service frequency will lower peak passenger loads per train short-term, but will attract new passengers long-term, causing peak loads to rise again. A different timetable could also result in different transfer flows between trains, as the range of possible connections may change. At interchanges in particular, this may lead to larger or smaller numbers of passengers boarding and alighting from particular trains. In other words, a different timetable may result in different numbers of passengers and hence in different dwell times.

(2) The scheduled dwell time plays an important role. A longer scheduled dwell time and the early arrival of a train reduce the risk of late departure (see Figure 7.3). In the 2018 timetable, the majority of scheduled dwell times ranged from 42 seconds to

2 minutes. Short stops by Sprinters on open track were scheduled to last only 42 seconds, whereas the scheduled dwell time for an Intercity was 1 to 2 minutes at most stations. As dwell times are likely to become shorter in future rather than longer, the author expects there to be an increase in the number of stations at which passenger service time will determine overall dwell time. As a result, passenger service time will determine punctuality and/or line capacity. See recommendations for practical application below.

The method used to isolate passenger service time from the total dwell time using the number of alighters and boarders is generally applicable. The passenger service time is not contained in the dataset, whereas the total dwell time and the number of alighters and boarders are. The timetable has no effect on the regression models used for this study.

7.7 Recommendations

This chapter concludes with recommendations for further study (Sub-section 7.7.1) and practical application (Sub-section 7.7.2).

7.7.1 Further study

The low values for the coefficient of determination ($adj.R^2$) in the dwell time models indicated that factors other than the number of alighters and boarders were also playing a significant role in determining dwell time. One indication of this was the wide variation in dwell times for stops involving small numbers of alighters and boarders. Contrary to what the handbooks suggest (e.g. [104] and [114]), no standard values are available for the coefficients used in these models. Furthermore, large quantities of data from a range of sources are needed to determine those coefficients. Further study could therefore usefully include improving dwell time models by looking more closely at the influence of various factors. One option would be to approach factors contained in the conceptual model (Figure 7.5) differently, and to acquire the necessary data via these different approaches. The literature study for this topic revealed that the busiest door(s) (the "dimensioning door(s)") can determine total passenger service time. One obvious approach would therefore be to focus future research on passenger flow via the dimensioning door, rather than on the flow via all doors or via an average door, as was done in the present study.

The models used in previous research and in the present study treat each station as an individual case. However, experience in the United Kingdom [21] points to the existence of a cumulative effect, with small delays owing to longer-than-timetabled stops at several stations adding up to major delays, with consequences for punctuality and line capacity. It is therefore recommended that further development of dwell time models also look at ways of incorporating the cumulative effect of multiple stations.

7.7.2 Practical recommendations

This study has confirmed that passenger service time can affect the timetable. Tight timetabling puts punctuality at risk and increases the risk of overlaps between passenger flows from multiple trains. Increasing scheduled dwell time allows more time for the passenger service process, but reduces the number of trains that can use a given platform per unit time. If this makes it impossible to increase service frequency, dwell times will increase if the number of passengers continues to grow. Vicious circles can therefore arise at both lower and higher service frequencies.

For stations with line capacity and punctuality bottlenecks, it is therefore recommended that passenger service time be included in timetable planning, aiming for a balance between the number of trains, headway and scheduled dwell times. This can be illustrated as follows, using the stations listed in Table 7.6 and Figure 7.16:

- All other things being equal, reducing dwell time would move the scenarios for Tilburg and Amsterdam Zuid from mid-right to top-right. Passenger service time would therefore lead to increased delay in departure time. The scenarios for Amsterdam Bijlmer ArenA and Amsterdam Zuid would move from centre to top-centre. Because passenger service time only accounts for a small percentage of overall dwell time at those stations, this would have little effect.

- All other things being equal, an increase in the number of alighters and boarders at Tilburg, Amsterdam Zuid and Schiphol Airport would increase dwell time, as passenger service time would increase. This would move those stations to the top-right region of the diagram, and platform capacity would affect the timetable.

A second recommendation concerns the type of train used. This sub-topic has shown that train type (rolling stock and length) affects the percentage of dwell time accounted for by the passenger service process. This means that train type affects implementation of the timetable at stations with punctuality and line capacity bottlenecks. It is therefore recommended that train type be taken into account during timetable planning as regards these stations.

Chapter 8

Conclusions and recommendations

This chapter concludes the thesis. It places the results of the three thematic studies in the overall framework of the conceptual model of the passenger capacity of a platform presented in Chapter 3 (see Section 8.1). It then sets out general recommendations for further study (Section 8.2) and practice (Section 8.3). For the underlying specific conclusions and recommendations, please see the last sections of Chapters 5, 6 and 7.

8.1 The results of the thematic studies in perspective

The central research question for this thesis was:

How can we measure the passenger capacity of railway platforms in the Netherlands?

On the basis of earlier research, it is argued that the passenger capacity of a railway station platform is lower than the absolute maximum, or "system" capacity. That system capacity is unknown. What is known, from previous research, is that passenger capacity is lower than system capacity. This is because safety hazards arise for pedestrians if density exceeds passenger capacity. In line with this, and on the basis of previous research, it is argued that the occurrence of platform accidents is not a good indicator for the service capacity of a platform, and nor is it a good indicator of whether service capacity is being exceeded. It is also established that it is not possible to define platform capacity or render it measurable on the basis of existing research.

Analysis of the documentation used for railway operations indicates that the passenger capacity of a platform is specified on the basis of standards. Three limits on the passenger capacity of a platform have been identified from an analysis of standards applied in the Netherlands, Switzerland and the United Kingdom, plus a number of generic handbooks. Those limits are shown in Figure 8.1 and are as follows:

1. As a result of queues forming at an exit escalator immediately following the arrival of a train, passengers stand or walk too close to the platform edge, and/or passengers in the queue for the exit escalator wait in the run-off from the incoming escalator.

2. As a result of crowding on the platform, passengers stand or walk too close to the edge.

3. As a result of the number of alighting and boarding passengers, trains regularly depart with a delay, or with more delay.

In this concept, the first two limits on passenger capacity are related to the passenger perspective, while the third is related to the railway perspective.

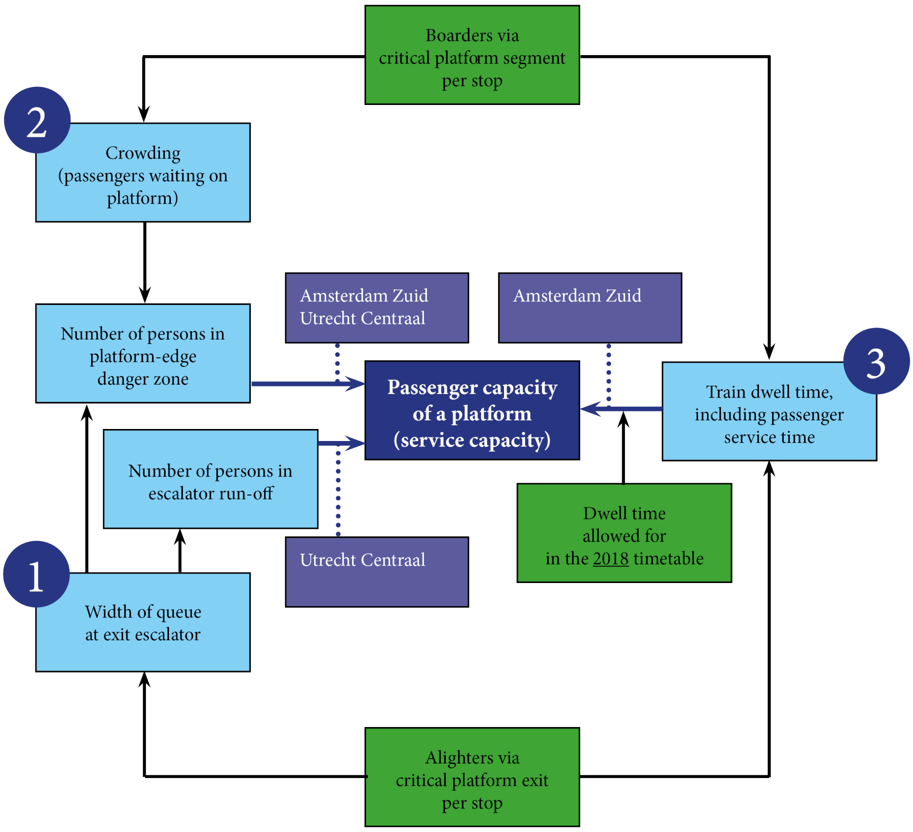


Figure 8.1: The findings of the present thesis as they relate to relationships between the limits on the passenger capacity of a platform

In the course of the three thematic studies, it was established that one or more passenger capacity limits were exceeded at Amsterdam Zuid, Utrecht Centraal and Schiphol Airport during the relatively long period of at least one year (2017–2018) covered by the datasets used.

As regards the passenger perspective: queues that form at the exit escalator following the arrival of trains with large numbers of passengers at Utrecht Centraal, Platform 5, regularly encroach into the area of the run-off from the arriving escalator. Furthermore, density on this platform prior to the arrival of a train is routinely so high (2 persons per square metre or higher) that passengers regularly stand in or walk along the platform-edge buffer zone. The standards also refer to this buffer zone as the "safety" or "danger" zone. On both of the platforms at Amsterdam Zuid that were studied, the queues that form at the exit escalators following the arrival of heavily-loaded trains expand towards the platform-edge buffer zone. As a result, passengers wishing to pass the queue regularly walk along the buffer zone. This situation also arises when trains are departing and have started to move. This is occurring despite the fact that the station operator's standards are intended to ensure that the buffer zone is not used when no train is standing at the platform. This study shows indirectly that the findings cannot be applied to all stations in the Netherlands. Furthermore, it is not possible to exclude the possibility that the situations described only occur on the platforms studied at Utrecht Centraal and Amsterdam Zuid.

As regards the railway perspective, it was established that the passenger service process was a significant and relevant factor in determining train dwell times at one or more platforms at the following stations: Amsterdam Bijlmer ArenA, Amsterdam Zuid, Schiphol Airport, Tilburg and Rotterdam Alexander. Indeed, at Amsterdam Zuid and Schiphol Airport, it was the passenger service process that determined the degree to which trains could depart on time (i.e. in accordance with the timetable). The implication of this is that passenger service time can limit the service capacity of a platform. Whether or not it does so depends on the dwell time allowed for in the timetable.

In a general sense, it is concluded that the passenger capacity of a platform is measurable if the platform-edge buffer zone is standardized and the dwell times provided for in the timetable are known. The present study shows that the three capacity limits were exceeded at the locations studied in the Netherlands. Because only three platform islands and five platform sides were studied during the thematic studies that addressed the passenger perspective, one should be careful about applying the results of those studies more generally. As is apparent from the discussion sections of Chapters 5 and 6, the possibility cannot be discounted of one or both capacity limits being exceeded on other platforms at the larger stations in the Netherlands with high peak loads. In this context, "high" means more than 700 alighters or boarders per stop. As the situations on Platforms 5 and 19 at Utrecht Centraal are similar, this is particularly likely in the case of the Platform 18/19 island at that station.

The results of the third thematic study, which looks at the passenger capacity of a platform from a railway perspective, are dependent on the timetable (which in the case of the present research was that for 2018). However, on the basis of the discussion section of Chapter 7 and of the passenger prognoses (see Chapter 1), one can expect the capacity limit at Amsterdam Zuid and Schiphol Airport to continue to be exceeded under future timetables. That expectation is based on the platforms as they are today. One aim of the rebuilding work planned at both stations is to increase capacity. Time will tell whether the passenger capacity of the modified platforms will be sufficient.

Finally, it is concluded that the passenger capacity of a platform does not only depend on structural factors – platform width, the locations and capacity of platform entrances and the timetable. Passenger capacity is also the result of interactions between factors which, at first sight, appear to be mere details. These include the presence of a divider between escalators moving in opposite directions and the type of train (in terms of rolling stock and length) serving busy stations under a timetable that only allows short dwell times. The choices made by station operators and individual passengers also play an important role in determining the passenger capacity of a platform.

These choices include buffer-zone width (station operators) and whether or not to stand in or walk along that zone (passengers).

8.2 Recommendations for further study

This section sets out general recommendations for further study. The recommended areas for further study are the development of a macroscopic fundamental diagram for railway platforms (Section 8.2.1), the relationship between the capacity limits defined in the present research and (increasing) service frequency (Section 8.2.2) and passenger behaviour (Section 8.2.3).

8.2.1 Development of a macroscopic fundamental diagram for railway platforms

A macroscopic fundamental diagram (MFD) reveals the overall traffic performance of a network without the need for detailed, labour-intensive and time-consuming microscopic pedestrian simulations. An MFD can also be applied to a pedestrian network [201].

A first attempt has been made to develop an MFD for platforms in recent work by Daamen et al. [109]. That research examined traffic in the available platform area immediately following the arrival of a train, by comparison with the (system) capacity of the platform. The results of the thematic studies in Chapters 5 and 6 provide new starting points for further development work on a platform MFD. The first point is that the safety standards of a station operator impose a maximum limit on the passenger traffic in specific platform segments (along the edge of the platform and in the run-off). This maximum is lower than the system capacity (the top of the curve in the fundamental diagram). The second is that a platform MFD must be applicable not only to the situations that arise following the arrival of a train, but also to those that obtain beforehand.

Using a platform MFD, it would be possible to develop systems which, in combination with real-time data from sources such as SMART Station and ROCKT Station, could provide a real-time picture and/or a prediction of pedestrian traffic on a platform. Such systems could then be used in practice, e.g. for crowd management or control.

8.2.2 Relationship between capacity limits and service frequency

In Section 3.5, it is argued that any attempt to make full use of the system capacity of a platform will result in safety hazards that could lead to accidents, and in unpredictable train dwell times. This in turn would make it difficult for a railway to run a stable timetable. It is also pointed out that an unstable timetable may result in safety hazards (or more hazards) for passengers on platforms, via a feedback mechanism. The present study does not examine that feedback mechanism. However, it is important to gain insights into such mechanisms, in view of the ambition to increase service frequency still further in the Netherlands, primarily on existing tracks, by running more trains at shorter headways (see Chapter 2).

All other things being equal, higher service frequencies result in lower peak loads. This helps to prevent or reduce exceedance of platform service capacity. However, higher service frequencies under stable conditions on an intensively-used network demand shorter dwell times. Those shorter dwell times leave less time for handling higher peak platform loads. If timetabled dwell times are regularly being exceeded, increasing service frequency will have a negative impact on punctuality and may lead to delays. In turn, those delays can lead to increased peak loads on platforms, creating a positive feedback loop with negative consequences.

Higher service frequencies can also lead to higher peak loads at the exits via which alighting passengers leave the platform. This is because at higher service frequencies, the passenger flows from multiple trains may overlap as a result of two trains arriving simultaneously (or nearly so) on opposite sides of a platform island. Higher frequencies may thereby cause or exacerbate exceedance of service capacity.

Finally, higher service frequencies at platforms from which trains depart in multiple directions can result in overlap (or more overlap) between incoming passenger flows, i.e. those associated with boarders. This superimposition of passenger flows can result in higher densities than would have been predicted on the basis of individual trains. So once again, higher frequencies may cause or exacerbate exceedance of service capacity.

Further study is required to establish whether – and if so, under what conditions – these feedback mechanisms can arise. As far as the author is aware, there is currently no standard method for determining the probability of feedback mechanisms developing between passenger processes on the platform and train movements. The first step in further study on this topic will therefore be to develop an analysis method, which would also involve identifying the data required. On the basis of the present research, the author recommends including Amsterdam Zuid and Schiphol Airport stations in any such future research involving the Dutch rail network.

8.2.3 Passenger behaviour

This study shows passenger behaviour to be one of the factors affecting the passenger capacity of a platform. Chapters 5 and 6 include recommendations for further study into behaviour in queues at platform exits following the arrival of a train (5) and behaviour on the platform before the train arrives (6). It is recommended that this research form part of a general study regarding passenger behaviour on platforms. The topics for such a study should be as follows:

1. **Preferences** give an insight into assessments that passengers make as concerns maintaining space between themselves and other passengers, and between themselves and the platform edge. One aspect that is highly relevant to platform capacity is the manner in which passengers indicate a risk and then take or avoid that risk. Understanding passengers' perception of risk and their willingness to take risks would enhance understanding of the manner in which passengers experience risk – for themselves and/or for others – near the platform edge and in the run-off from an arriving escalator.

2. On the basis of the literature study in Chapter 3, the author expects some preferences to be contradictory. For instance, a passenger will want to avoid standing

too close to others, but will also want to avoid standing too close to the platform edge. It is therefore necessary to understand how passengers **balance** such factors.

3. It is important to understand how passengers' preferences, decision-making processes and behaviour can be modified by **measures** aimed at influencing their behaviour.

From a research point of view, the results of the recommended further study into behaviour could be used to develop, calibrate and validate pedestrian models. Special attention should be paid to the shape of queues at platform exits (see Sub-section 5.7.1), passenger behaviour regarding the platform edge (see Sub-section 6.7.1) and passenger service time (see Sub-section 7.7.1).

In practical terms, the results of such research could be used when designing, testing and implementing measures to influence passenger choices and behaviour (see Section 8.3.1).

8.3 Practical recommendations

This section contains general practical recommendations and sets out the implications for capacity-creating measures (Sub-section 8.3.1), use of standards, measurements and models (Sub-section 8.3.2), railway policy as regards platform safety (Sub-section 8.3.3) and practical issues that were not included in the present study but to which its results could be relevant (Sub-section 8.3.4).

8.3.1 Implications for capacity-creating measures

In presenting the results of the thematic studies, it was argued that in addition to major, structuring factors, certain decisive details may also affect the passenger capacity of a platform. Chapter 5 shows that the dimensions of a platform, the location of an access point and the presence of a divider can all influence the development of a queue at an exit escalator. Chapter 6 demonstrates the influence of platform width on use of the platform-edge buffer or "danger" zone. That study also shows that the width of the buffer zone itself plays an important role. Chapter 7 identified large differences in dwell times for identical passenger numbers at different platforms. These differences are also the result both of major factors and of important details. Those details include the type of train. Research conducted by the author at Schiphol Airport showed that even the precise stopping position of trains on the platform can have a major influence on dwell time [25].

There is therefore no "one-size-fits-all" solution as regards the interaction between passenger traffic on platforms and the use of that platform by trains. What this study does indicate, however, is that distributing passengers along the platform and the train, and making platforms sufficiently wide, are important steps towards preventing and resolving capacity bottlenecks on platforms.

Distributing boarders along the platform reduces local crowding prior to arrival of the train, thereby reducing use of the buffer zone. It also results in better use of train doors, reducing passenger service time. If passengers are distributed along the train, they will be distributed over multiple platform exits on arrival, reducing queues at the busiest exits.

Ensuring that platforms are sufficiently wide becomes relevant once the options for improving distribution of passengers along the platform and train have been exhausted. All other things being equal, additional platform width results in lower density, which reduces use of the buffer zone in response to local crowding. Widening a platform also creates space for an additional escalator (or stairs of comparable width), thereby reducing queueing at platform exits. One additional metre of width per platform side increases platform capacity significantly.

This thesis indicates that crowding on trains did not have a structural influence on dwell time over the 2018 timetable period, in contrast to what has been observed on certain metro systems (see Chapter 3.3). However, this may change if trains become fuller as a result of expected increases in passenger numbers. That indicator should therefore remain under close observation, even though the thematic study in Chapter 7 did not include this topic. Puong's model (see Chapter 7) could serve as a starting point.

Insights derived from the recommended research on passenger behaviour (see Section 8.2.3) could form a basis for measures to influence that behaviour. Such measures could include hazard markings on platforms, audio-visual signals and awareness-raising campaigns. See Sub-section 3.1.5 for an overview of possible measures. However, the author would point out that the scope for increasing platform capacity by modifying passenger behaviour may well be limited. Research by Hänseler et al. [26] indicates that under crowded conditions, the distribution of passengers along the platform and train on the platforms studied for this thesis (at Utrecht Centraal and Amsterdam Zuid) is already fairly good at a standard train length.

8.3.2 Use of standards, measurements and models

The thematic studies in this thesis have shown traffic flows on platforms to be stochastic rather than deterministic results, with a wide range of possible results. It is therefore important to distinguish between coincidence and patterns when using standards, measurements and models. This will ensure that platform design and operating decisions are not taken on the basis of situations that seldom arise in practice, and that commonly-occurring situations are not ignored. None of the standards or generic handbooks examined in Chapter 3 consider this methodolic factor.

The thematic studies demonstrate the need to examine a large number of different situations when assessing an existing or future situation. If an assessment is to be made on the basis of empirical data (e.g. from sensors), a large number of observations is required, to distinguish underlying patterns from coincidence. This requires longer data-collection periods than are common at present – weeks rather than days. In the case of model studies, it is desirable to carry out a large number of runs, varying the relevant parameters and the known and unknown uncertainties. Currently, the number of runs is often kept small for reasons of cost and/or processing time. It is recommended that standards explicitly state at what probability of exceedance of the standards a situation should be considered hazardous and/or should be considered an actual exceedance of the standard. As standards based on "Fruin densities" are used in the Netherlands (and in other countries), it is recommended that standards require platforms to be divided into 5 m segments. The longer segments that are often used currently (10 m or longer) average away local crowding, thereby masking information regarding relevant portions of a bottleneck.

The microscopic pedestrian models in current use have their limitations when it comes to simulating the form (and hence the width) of queues at platform exits and the use of platform-edge buffer zones. These limitations will continue to apply until such time as improved pedestrian models are developed (see the recommendations in Subsections 5.7.1 and 6.7.1 and Section 8.2.3). In the meantime, the results of the thematic studies in Chapters 5 and 6 can be used to calibrate and validate pedestrian models and when interpreting the results of such models. This requires an additional analysis step and a realization that one cannot blindly accept the results of the ever more detailed and more impressive animations that microscopic pedestrian simulations are capable of producing.

8.3.3 Railway policy

The results presented in this thesis provide four points of departure for railway policy. First, this thesis shows that passenger numbers on the busiest platforms have increased substantially in recent years. At the same time, space around stations is becoming scarce, both because many stations have expanded – partly as a result of building additional platforms – and because cities have grown towards stations. As a result, there will be less space available for creating platform capacity in the future than there was in the past (see Section 2.3). The shortage of space has rendered the widening of existing platforms and the construction of new ones more complex, and such projects now take years or decades. Examples of this include Amsterdam Centraal, Amsterdam Zuid and Schiphol Airport. As regards railway policy, it is recommended that platforms at stations where the numbers of passengers or trains are growing rapidly – or are expected to do so – be treated separately from those of other stations. Station operators' systems of standards serve as a basis for policy regarding all platforms, but do not provide the tailor-made solutions that are required for both operations and projects. Separate design and operating guidelines could be developed for those stations that have been identified as special cases. Specific design guidelines could include making platforms larger than required in the standards. Or reserving space for creating additional capacity in the future. Specific operating guidelines might include the use of crowd management.

Second, this thesis has shown that there is more to platform capacity than safety. It is therefore recommended that railway policy take a broader approach to the concept of platform capacity. Current policy in the Netherlands regarding platform crowding focuses on passenger safety (see Section 1.1). Safety is treated as the precondition for operation of the railway network. This research has shown that dwell time forms part of platform capacity (see Section 7.1, for instance). Platform capacity hence influences the number of trains that can use a particular track, and how punctual they will be. Incorporating dwell time into the concept of platform capacity as a matter of policy is not only a matter of extending the system of standards of Dutch station operators. It also means making platform capacity an explicit factor when allocating line capacity to railway operators.

Third, the results of this research provide several staring points for tightening up both safety standards and risk models. 1. The (standardized) width of the platform-edge buffer zone is not the only factor – real-life passenger behaviour in and near that zone is also of importance. The distribution of passengers along the platform also plays an important role. 2. Furthermore, one could consider setting a standard for the maximum size of a queue at a platform exit, taking account of the available platform width. 3. It would be possible to include dwell times in systems of standards and/or risk models, to make the relationship between platform safety and line capacity explicit.

Finally, the author argues on the basis of this research that the number of accidents is not a suitable indicator for railway policy regarding capacity-related safety on platforms. Establishing a statistical link between accidents and platform capacity would require a large number of platform accidents to occur, whereas current policy focuses on maintaining the current, high level of safety. Furthermore, taking policy-based action in response to accidents implies applying long-term operational measures to prevent further accidents, (e.g. crowd control), as projects aimed at increasing platform capacity take years or even decades to complete. Similar reasoning applies to a situation in which trains are unable to keep to scheduled dwell times because the passenger service process is taking too long.

8.3.4 Topics omitted from this study

Because of the way this study was structured, it is possible that two types of situation have been ignored to which passenger capacity is relevant.

The first is the possibility of higher passenger peaks as a result of events or of disruptions to train services. Those situations were deliberately excluded from this study (see Section 1.3). However, given the high levels of crowding that occur following events, the results of this study could be highly relevant to such situations. Disruptions to train services may lead to cancellations, which may result in high levels of crowding when the next train arrives. As an example, Figure 8.2a gives an impression of the crowding at Amsterdam Bijlmer ArenA following an event. Owing to the proximity of major venues, this station handles a large passenger flow in a short space of time every two weeks on average, in addition to the crowding that occurs at peak times on working days.

The reader of this thesis may not be aware of the situations that arise on very narrow platforms with smaller peak loads, owing to the use of secondary data sources for the analyses in Chapters 5 and 6 (data from SMART Station – see Section 4.1) and the focus on the top ten peak loads according to ROCKT Station data (see Sections 5.5 and 6.5). As an example, Figure 8.2b gives an impression of crowding on the island platform at Tilburg Universiteit, before the platform was widened (see Chapter 1).

It is recommended that the analyses of the thematic studies in Chapters 5 and 6 be repeated for situations on platforms following events and for situations on one or more narrow platforms with low peak loads. It is further recommended that the insights obtained from such follow-up studies be incorporated – along with the results from this thesis – in the existing risk-based approach to platform safety (see [73]).

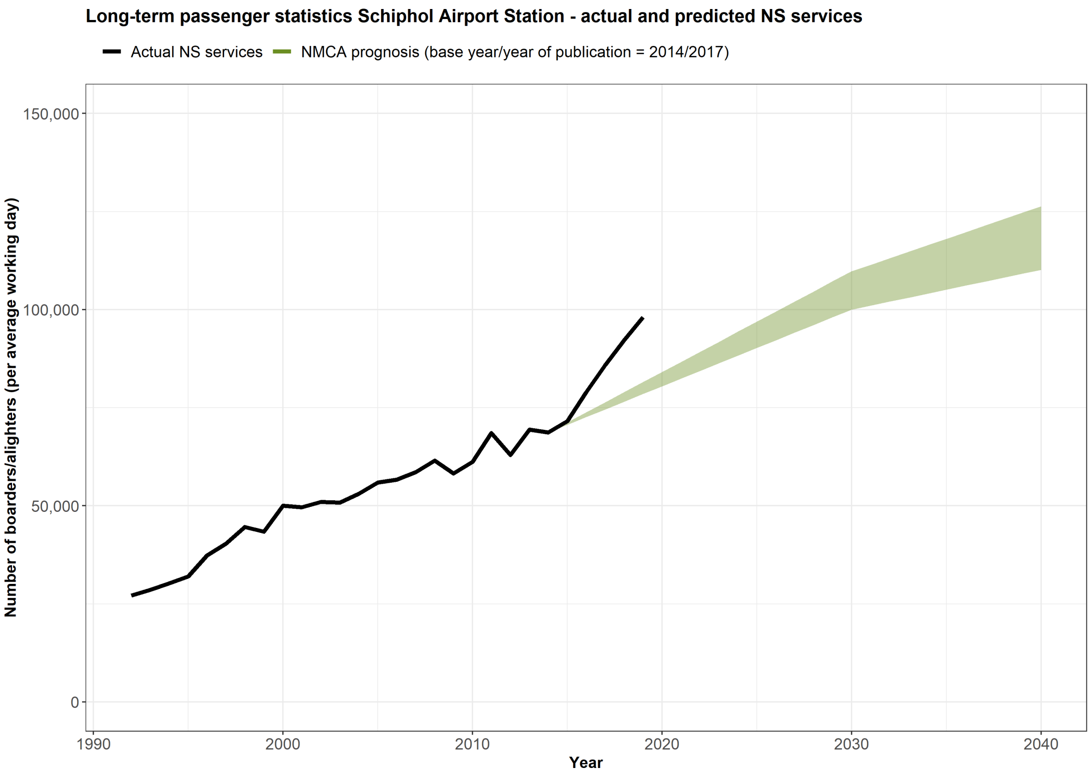
(a) Amsterdam Bijlmer Arena (Platform 8) following an event on 13 February 2019

(b) Tilburg Universiteit on 7 December 2015, 10.12 hrs (Platforms 2/3, old situation)

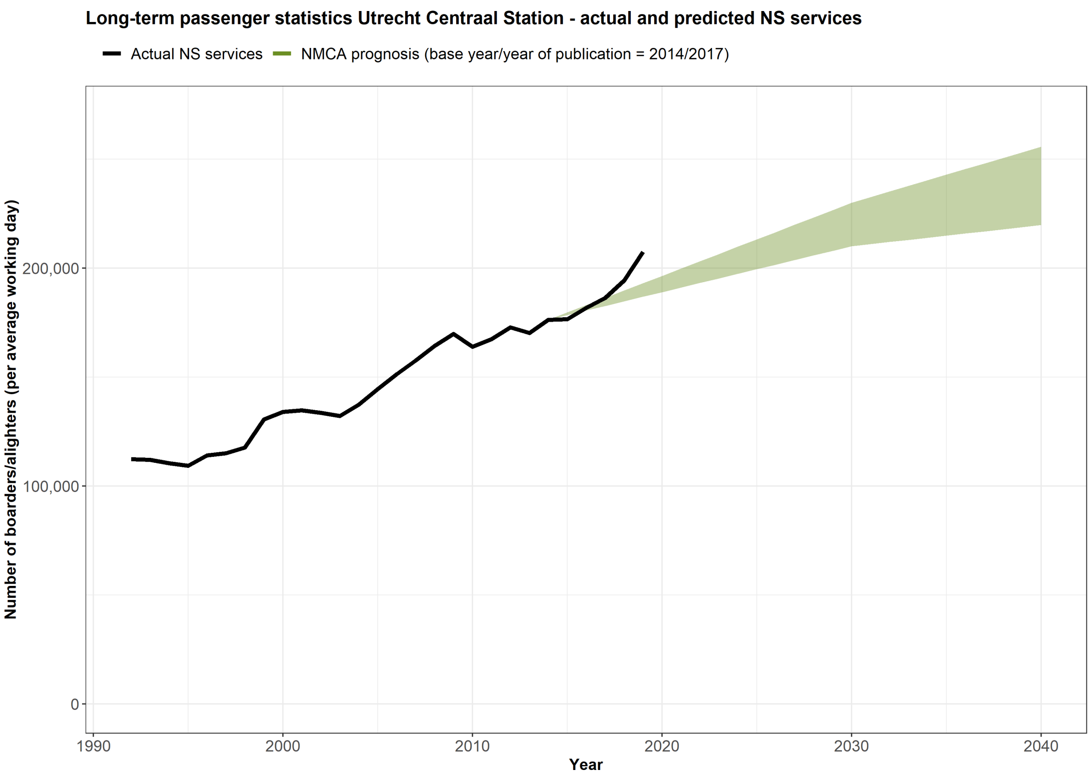
Figure 8.2: Impressions of Amsterdam Bijlmer ArenA and Tilburg Universiteit (Photos: Jeroen van den Heuvel)

Appendix A

Future passenger loads at Schiphol Airport and Utrecht Centraal



(a) Schiphol Airport



(b) Utrecht Centraal

Figure A.1: Future passenger loads at Schiphol Airport and Utrecht Centraal

Appendix B

The development of railway lines and stations in the Netherlands

This analysis takes as its starting point the railway network and large stations as they existed in 2020. It therefore excludes lines and stations that are no longer in service or have taken on other functions. Discussion of station development is limited to those stations that were classified as "large" as of 2020, according to the NS definition of the term. A total of 47 stations fall into this category, i.e. those classified by NS as Type 1, 2 or 3. Type 1: very large stations in city centres. Type 2: large stations in medium-sized towns. Type 3: suburban stations with an interchange function [202]. This classification coincides to a large extent with that used by ProRail in their "network declaration" (*Netverklaring*), in which the larger stations are divided into Kathedraal, Mega and Plus [203]. As regards network development, this overview covers only those infrastructure projects that have resulted in a change in the structure of a timetable, such as new lines, increased service frequency on existing routes and more concentrated train arrivals (simultaneity), or the possibility thereof.

B.1 Changes to station functions

Except where sources are mentioned in the text, this description is based on historical works [204, 205, 206, 207] and the sources listed in Section B.2 of this appendix. The numbers in colour ⟨**n**⟩ correspond to the numbers on the maps in the figures produced for this thesis, Figures B.1, B.2, B.3, B.4 and B.5. Like the sources used, this description is divided into 15-year periods. The year quoted for changes to the network and stations is the year in which the work was delivered.

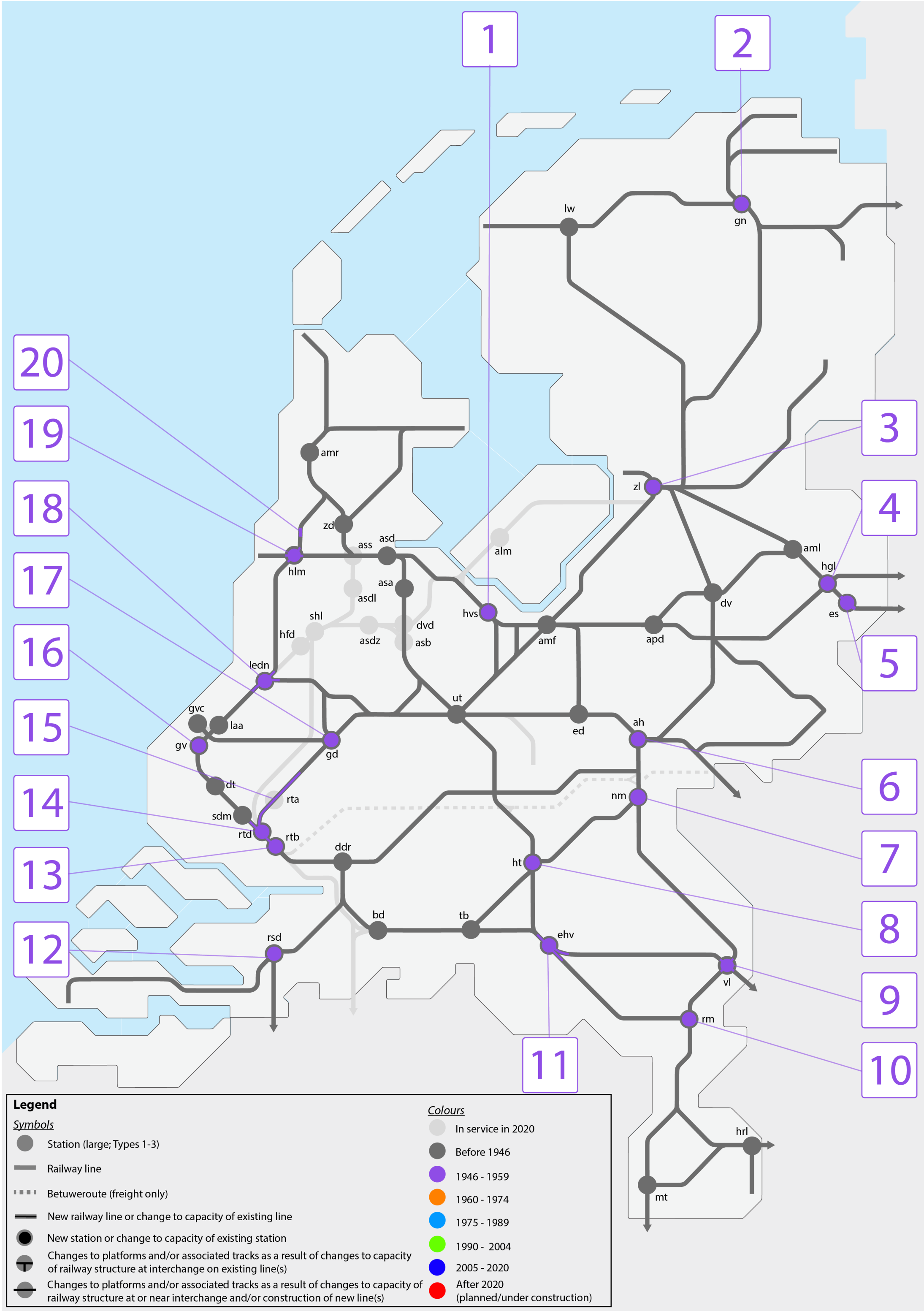


Figure B.1: The Dutch railway network as of 2020, major stations only, showing changes over the period 1946–1959

B.1.1 1946-1959

The period 1946–1959 (see Figure B.1) was devoted to repairing the railway network, following heavy damage during the Second World War. In Rotterdam, rebuilding was combined with the re-routing of the line between Rotterdam's central station and Nieuwerkerk aan den IJssel ⟨15⟩, a project that had already been planned. This project linked up with construction of the new central station (now named Rotterdam Centraal ⟨14⟩) that replaced Rotterdam Delftse Poort, which had been badly damaged by bombing. The station building at Rotterdam Blaak ⟨13⟩ was rebuilt for the same reason. At the same time, the railway line in Rotterdam was re-sited on an embankment, to reduce the barrier effect of the tracks. War damage to stations was repaired at other locations in the Netherlands, with the following stations being rebuilt, entirely or in part: Gouda ⟨17⟩, Roosendaal ⟨12⟩, 's-Hertogenbosch ⟨8⟩, Nijmegen ⟨7⟩, Arnhem Centraal ⟨6⟩ and Hengelo ⟨4⟩. In Venlo, ⟨9⟩ rebuilding provided an opportunity to move the station to a location more convenient for the town centre. New stations were built in Leiden ⟨18⟩ and Eindhoven ⟨11⟩, because tracks had been moved to embankments so that they would constitute less of a barrier. Electrification had started before the war, and now continued. The last NS steam train ran in 1958; from then on, all trains were electric- or diesel-hauled. In Enschede ⟨5⟩ this required major alterations to the track layout, and a new station was built at the same time. The new tracks were built on an embankment, to reduce the barrier effect. The signalling system was updated throughout the country, allowing more trains to run. At Zwolle ⟨3⟩ and Roermond ⟨10⟩ pedestrian level crossings were replaced by subways, because of the increasing number of passengers and trains.

Major railway projects in this period included re-routing the line between Gouda and Rotterdam and building the Velserspoortunnel ⟨20⟩. The tunnel increased the capacity of the line, by obviating the need to open the Velserspoorbrug to allow ships to pass along the Noordzeekanaal. Although no information on the subject has been found, it is possible that the building of an additional platform at Haarlem ⟨19⟩ was related to construction of the Velserspoortunnel. The platform was needed to handle the increased number of trains. When the new (fourth) platform was built, a new station entrance was added, on the side furthest from the town centre. This was necessitated by the northwards expansion of the town.

During the postwar period, stations were also remodelled on account of developments in towns and in railway traffic. A station entrance was added on the east side of Hilversum ⟨1⟩ because of the eastwards expansion of the town, just as Haarlem's northwards expansion had prompted a similar measure on the north side of its station. The entrance to Groningen station ⟨2⟩ was moved to the east side in response to redevelopment of the station area and changes to the roads in the town. As a result, the station building lost its original function as the main station entrance. At Den Haag HS ⟨16⟩ the station entrances were modified on account of increased passenger numbers.

Between 1946 and 1959, the number of passenger-kilometres increased by a quarter, from 6.2 billion to 7.4 billion (see Figure 2.4a) and the number of train-kilometres tripled, from 20 to 57 million per year (see Figure 2.4b).

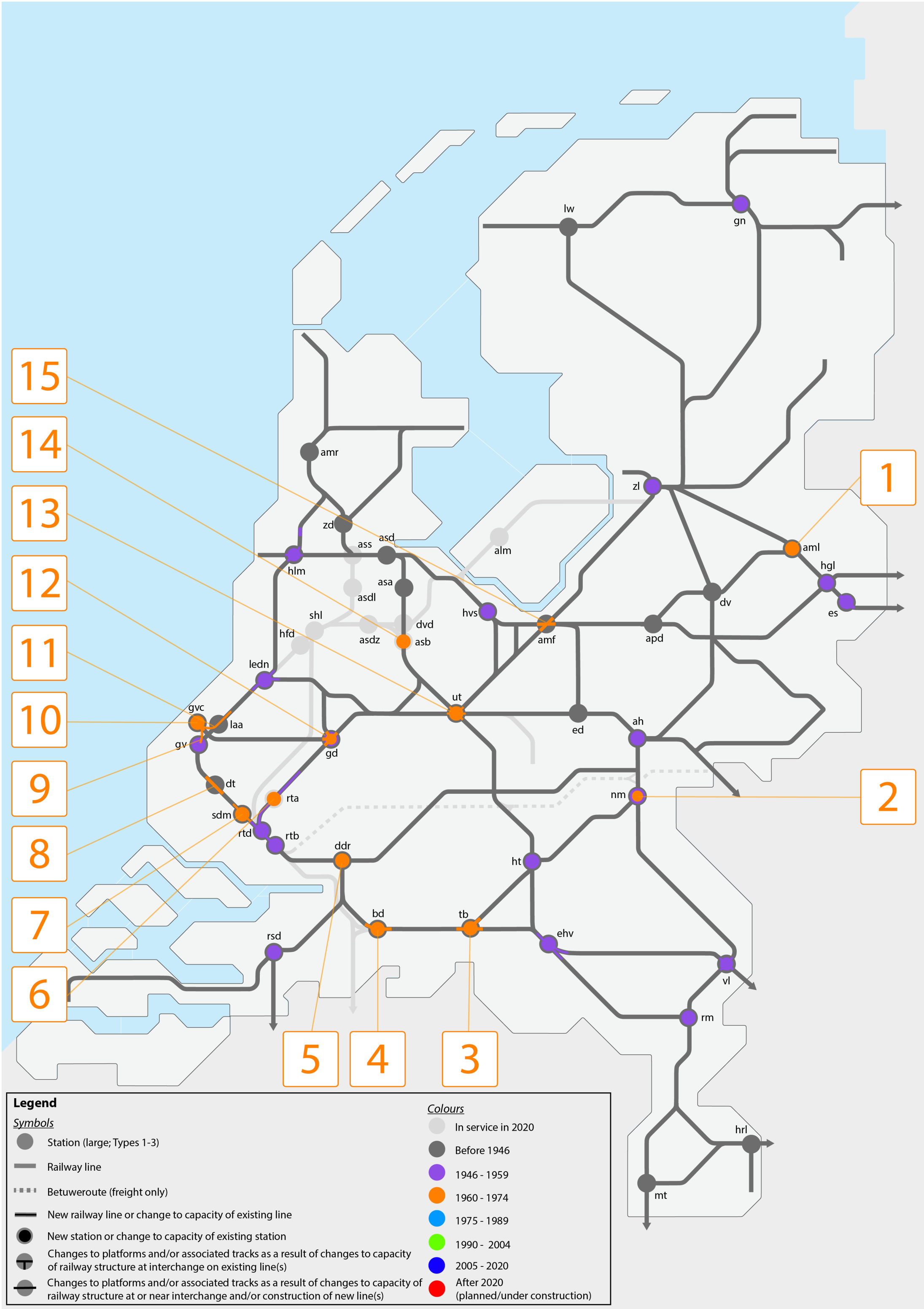


Figure B.2: The Dutch railway network as of 2020, major stations only, showing changes over the period 1960-1974

B.1.2 1960-1974

The new station building at Den Haag Centraal ⟨10⟩ and the rebuilding of Utrecht Centraal ⟨13⟩ were two of the major railway projects undertaken between 1960 and 1975 (see Figure B.2). As early as the 1970s, car traffic in the larger cities was causing traffic jams and parking problems. From an urban perspective, the projects in The Hague and Utrecht were intended to integrate stations into their respective cities, thereby encouraging people to take the train instead of using their cars. For instance, large office complexes were built near or directly above the station in both cities. Integration went furthest at Den Haag Centraal, where all public transport modes were concentrated in a single, new, compact building. The new station replaced the old Den Haag Staatsspoor station, which was only the terminus from the east-west line linking The Hague, Gouda and Utrecht. The new Den Haag Centraal station was connected with the north-south Amsterdam-Leiden-Rotterdam line via two link lines ⟨9⟩ ⟨11⟩. The new station had a different track layout and many more platforms. In Utrecht, the whole platform/track layout was modified to create more through tracks and eliminate a number of dead-end tracks. Both stations were designed for the new railway routes that were planned for after 1975.

The Delft railway viaduct ⟨8⟩ was another of the major railway projects of this period. The purpose of the viaduct was to reduce the barrier effect of the tracks. No functional modifications to the station building or the platforms of Delft station have been identified that could be linked with this project. Because the tracks through the town had been transferred to an embankment, Schiedam Centrum ⟨7⟩, Breda ⟨4⟩ and Tilburg ⟨3⟩ stations were rebuilt. In 1968, a new station was opened at Rotterdam Alexander ⟨6⟩ on the embankment built in the period 1946–1959. In 1971, a temporary station was built in Amsterdam Bijlmer ⟨14⟩ at ground level, pending construction of a permanent station on the embankment planned south-east of Amsterdam (⟨9⟩ in Figure B.3). The track layout at Gouda ⟨13⟩ was remodelled and a new platform was added. At the same time, an entrance was added on the side of the station furthest from the town centre, which also meant extending the pedestrian subway. The pedestrian level crossing at Dordrecht ⟨5⟩ was replaced by a subway in 1965, a new entrance was built on the north side of Nijmegen station ⟨2⟩ and a new station and a pedestrian subway were built in Almelo ⟨1⟩. The subway replaced the footbridge. The dead-end track along the first platform at Amersfoort station ⟨15⟩ was converted into a through track to handle increased rail traffic.

1960–1974 was a time of financial difficulty for NS. The problem lay in a combination of a sharp increase in train-kilometres with only a slight increase in passenger-kilometres, plus a substantial reduction in freight traffic. The problems for passenger operations were caused by the upsurge in car ownership, which led to a fall in the number of railway passengers (see Figure 2.4a). An increase in mean journey length did lead to a 16% increase in passenger-kilometres, to 8.5 billion per year. But what had a greater effect on financial results was that the number of train-kilometres rose dramatically over the same period, from 59 million to 92 million per year, an increase of 60% (see Figure 2.4b).

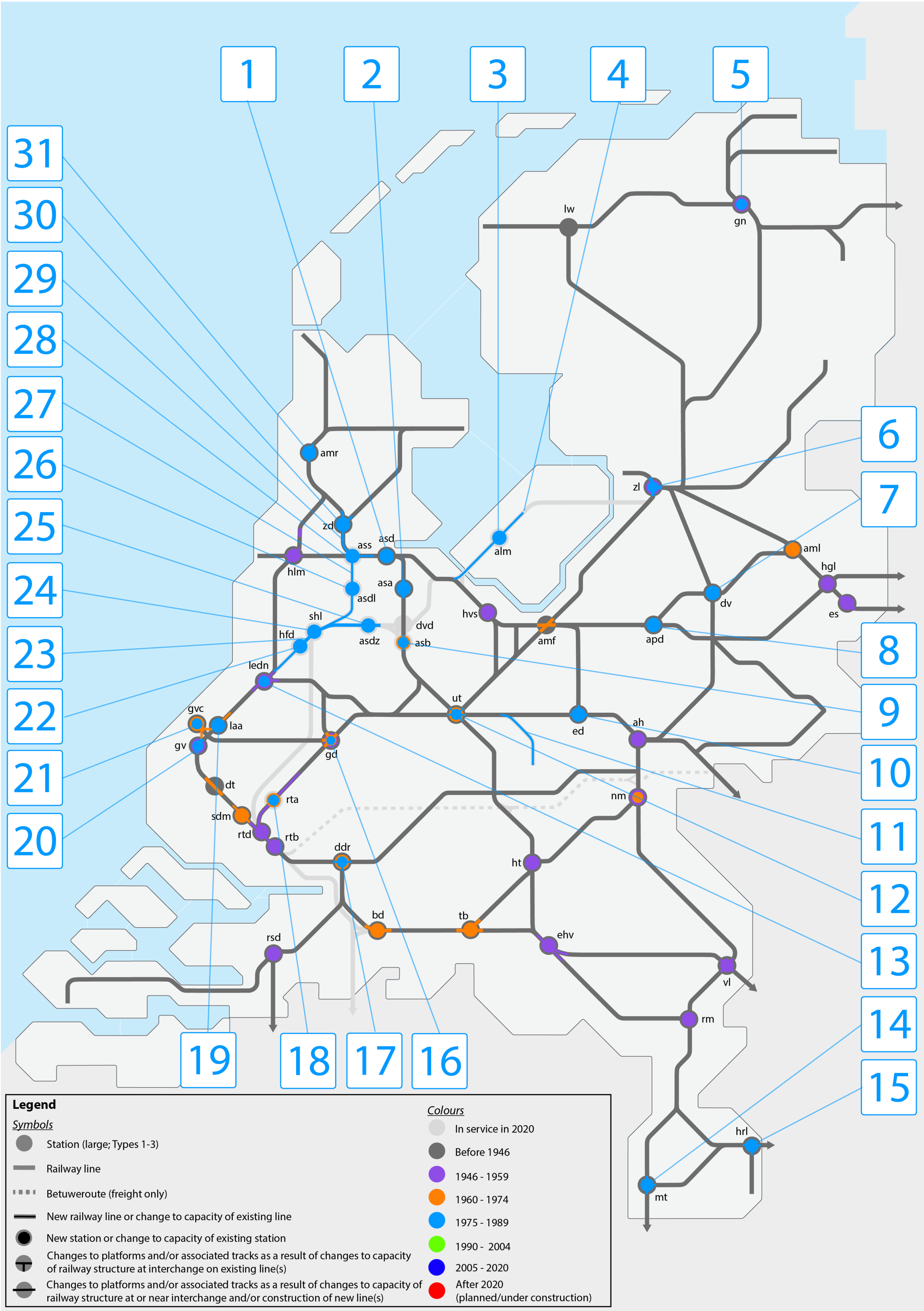


Figure B.3: The Dutch railway network as of 2020, major stations only, showing changes over the period 1975-1989

B.1.3 1975-1989

The period 1975-1989 (see Figure B.3) was dominated by implementation of the *Spoor naar ‘75* (Rail ‘75) expansion plan that NS had unveiled in 1969 [208]. This was a dual approach, combining direct improvements to the train product (*Spoorslag ’70*) and a vision for the railway network, including a number of major expansion projects (*Spoor naar ‘75*). The government welcomed this plan, partly because the disadvantages of car ownership were becoming apparent at a national level – the amount of space that cars were occupying in towns and the huge increase in traffic jams.

Spoorslag ‘70 consisted of introducing fast trains with few stops for longer distances (*Exprestreinen*) and slower trains that stopped at all stations (*Stoptreinen*). The fast trains – which eventually became the Intercity service – were intended to link 40 stations. Spoorslag ‘70 was largely based on the existing rail network.

Spoor naar ‘75 included the building of new lines, the introduction of a new traffic control system and the acquisition of new trains. New lines were planned, to serve areas designated as centres for urban growth: the Zoetermeerstadslijn (new line: Den Haag Centraal-Zoetermeer), the Veenendaallijn (reopening of the Rhenen-Veenendaal-Utrecht line) ⟨11⟩ and the Hofpleinlijn (re-routed from Den Haag HS to Den Haag Centraal). The plan also included the building of the Schiphollijn ⟨23⟩ (The Hague-Leiden-Schiphol-Amsterdam), including the Schipholboog link line near The Hague. The Schiphollijn was built in a number of phases, and links Amsterdam’s Schiphol Airport with Amsterdam Zuid (via the Zuidtak line, completed in 1978), Leiden Centraal and Den Haag Centraal (1981) and Amsterdam Centraal (Westtak line ⟨27⟩; 1986). Following introduction of regional control centres in 1977, more trains could run safely on the same lines, increasing the capacity of the entire network.

The Zoetermeerstadslijn, the re-routed Hofpleinlijn and the Schiphollijn were connected to the new station and tracks at Den Haag Centraal ⟨21⟩, which had been built in the preceding years with these connections in mind. A further platform was also added. A new station was built at Den Haag Laan van NOI ⟨19⟩, with more platforms. The part of Den Haag HS ⟨20⟩ that housed the dead-end tracks of the Hofpleinlijn was demolished, and a new island platform was built to serve the north-south route between Rotterdam and Leiden. This work was carried out concurrently with the re-laying of all the tracks in and around the station. Additional platforms were also needed at Leiden Centraal ⟨13⟩, to cope with the increasing number of trains. Some thirty new stations were planned for the Schiphollijn, including Schiphol Airport (1978) ⟨24⟩, Amsterdam Zuid (1978) ⟨25⟩, Hoofddorp (1981) ⟨22⟩, Amsterdam Lelylaan (1986) ⟨26⟩ and Amsterdam Sloterdijk (1986) ⟨28⟩.

The Hemtunnel ⟨29⟩ was another of the major projects carried out in this period. The tunnel replaced the Hemspoorbrug over the Noordzeekanaal, and formed part of the project to increase the number of tracks between Amsterdam and Zaandam. Because of the increased number of tracks, a new station was built at Zaandam ⟨30⟩ with an additional platform. The tracks at Alkmaar station ⟨31⟩ (located further north) were also renewed during this period, and a further island platform was added.

In addition to creating additional railway capacity through Spoor naar ’75, the government decided in 1977 to build the Flevolijn ⟨4⟩, as part of its new transport policy. This line links Amsterdam via Weesp to the new towns of Almere and Lelystad, which had been built on land created by draining part of the Zuiderzee. A number of stations were built along this line, including Almere Centrum ⟨3⟩.

Many stations were modified between 1975 and 1989. Amsterdam Centraal ⟨1⟩ underwent substantial changes to handle the increasing number of passengers. The central pedestrian subway (the Middentunnel) was widened, and routing through the station building was modified. At Amsterdam Amstel ⟨2⟩, a new entrance was added on the western side and two main-line tracks were converted to metro lines. Gouda station ⟨16⟩ was completely rebuilt, as the post-war building was in poor condition. At Dordrecht ⟨17⟩, an entrance was added on the side away from the town centre (the south side), a new footbridge was built to supplement the existing subway and an island platform was added to handle increased traffic. The station building at Rotterdam Alexander ⟨18⟩ was modified to incorporate a new metro line. Utrecht Centraal ⟨12⟩ was expanded to deal with increasing passenger numbers. Station tracks and platforms were modified in anticipation of an increase in the number of tracks serving the station, which took place in the 1990s.

Track layouts were modified at Maastricht and Heerlen, in the south of the Netherlands. In Maastricht ⟨14⟩ this resulted in changes to the platforms, but the existing station building was retained. In Heerlen ⟨15⟩ the station building was demolished and replaced by a new structure. A new station was built at Ede-Wageningen ⟨10⟩ with an additional single-face platform and a passenger subway. The subway replaced the pedestrian level crossing that had previously been used to cross the tracks and to reach the island platform. To accommodate the expansion of their respective towns, entrances were added on the side of the station away from the town centre and existing subways were extended at Apeldoorn ⟨8⟩, Deventer ⟨7⟩, Zwolle ⟨6⟩ and Groningen ⟨5⟩. In Groningen, a new footbridge was built to provide access to the side of the town away from the centre. In Zwolle, construction of the new entrance was combined with the addition of an island platform, served by the extended subway.

Between 1975 and 1989, the downwards trend in passenger-kilometres of previous years was reversed. The number of passenger-kilometres grew by 18% to over 10 billion in 1989 (see Figure 2.4a) and train-kilometres rose by 16% to 107 million (see Figure 2.4b).

B.1.4 1990-2004

The most significant developments between 1990 and 2004 (see Figure B.4) were the adding of new tracks to existing lines, completion of the Schiphollijn, the Rail21 [209] vision for the railways, introduction of the OV-Studentenkaart (a public transport pass for students) and the beginning of partial privatization [210].

The significant increase in train services had already led to new bottlenecks at the end of the 1970s. Citing eight major bottlenecks, NS successfully lobbied for an additional investment plan, which resulted in additional tracks on a number of routes, sometimes in combination with modifications to stations. Tracks were added to the following lines between 1982 and 1999: Rotterdam-Dordrecht (including the Willemsspoortunnel) ⟨18⟩, Gouda-Gouda Oost (including a railway bridge) ⟨16⟩, Utrecht-Blauwkapel ⟨10⟩, Leiden-Rijswijk (including the Rijswijk railway tunnel) ⟨21⟩, Singelgracht-Amsterdam Centraal ⟨1⟩ and Amersfoort-Schothorst ⟨7⟩. The

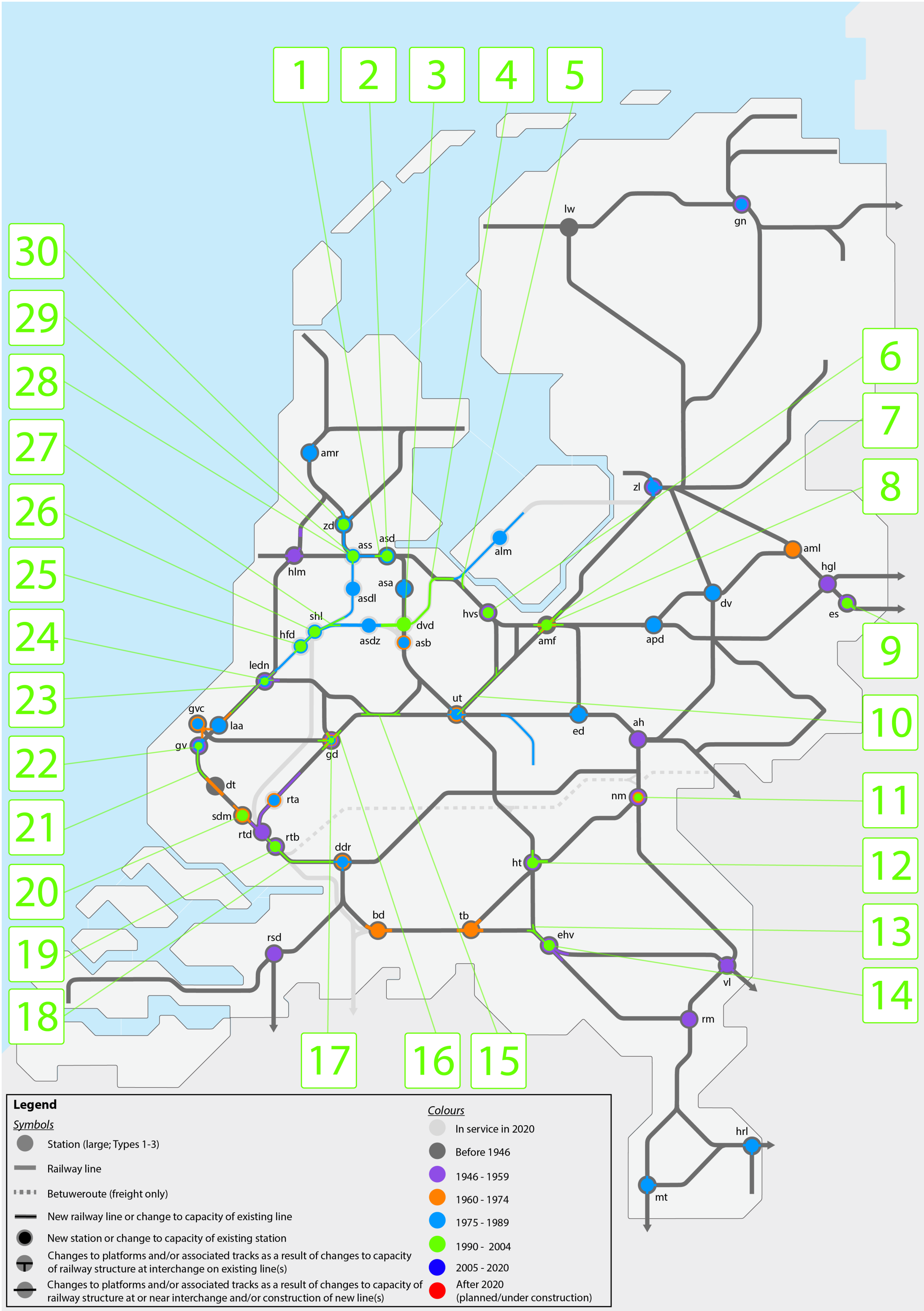


Figure B.4: The Dutch railway network as of 2020, major stations only, showing changes over the period 1990-2004

new tracks in Rotterdam – and the replacement of the railway bridge over the River Meuse by the Willemsspoortunnel – resulted in the rebuilding of Rotterdam Blaak ⟨19⟩. Expanding the Leiden-Rijswijk line ⟨23⟩ involved rebuilding Leiden Centraal ⟨24⟩. The platforms were lengthened, creating two-section platforms and hence enabling two trains to use a platform at the same time. When additional tracks were being laid in the Amersfoort area, the tracks at Amersfoort Centraal ⟨8⟩ were modified and an additional island platform was built. The laying of additional tracks at Amsterdam Centraal ⟨2⟩ was combined with modifications to the tracks west of the station, which included lengthening half of the platforms. This made it possible to accommodate two long Intercity trains on the same platform at the same time, increasing the number of trains that could use the station. In the years preceding this project, and in preparation for the building of the NoordZuidLijn (metro), the western subway was widened and an entrance was added on the side away from the city centre. To increase capacity, the dead-end track at the northern single-face platform over the new station entrance was upgraded to a through track. At the beginning of the 1990s, the Schiphollijn ⟨4⟩ was completed with the construction of the Amsterdam Zuid-Weesp section. New stations opened on this line in 1993, including one at Duivendrecht ⟨3⟩.

At the end of the 1980s/beginning of the 1990s, NS presented their plan entitled *Rail21 – Sporen naar een nieuwe eeuw* (Rail21 – Tracks towards a new century), the successor to Spoor naar ’75. Rail21 was linked to the government’s *Vierde Nota Ruimtelijke Ordening* (Fourth Planning Directive) and the *Structuurschema Verkeer en Vervoer II* (Structural Transport Plan II). The Fourth Planning Directive marked the end of the “focused dispersion policy” that had guided planning in previous decades. That policy had resulted in a number of centres of growth, some of which were now served by rail. The new policy involved boosting the *Stedenring* and enhancing the positions of Schiphol Airport and the Port of Rotterdam as logistics hubs, known as “mainports”. For the purposes of this new policy, the Stedenring was defined as the Randstad (the main conurbations in the west of the Netherlands) plus ’s-Hertogenbosch/Eindhoven and Arnhem/Nijmegen. NS measures to separate passenger and freight traffic were to include the Betuweroute freight-only line linking the Port of Rotterdam directly with Germany. To integrate the Netherlands into the European high-speed network, high-speed lines were to be built in two directions from Amsterdam. TGV trains were to run southwards, linking Amsterdam, Schiphol and Rotterdam with Brussels and Paris via the HSL-Zuid (high-speed line south). ICE trains were to link Schiphol, Amsterdam Zuid, Utrecht and Arnhem with Cologne and Frankfurt via the HSL-Oost (high-speed line east). Rail21 specified three types of train. 1. National and international Intercity services between the major cities in the Randstad and between the Randstad and Groningen, Twente, Arnhem/Nijmegen, the towns of Brabant, Zuid-Limburg and abroad. 2. Inter-regional express trains between the 65 most important centres in the Netherlands. 3. Trains serving the conurbations and regions, which would link the other stations with the inter-regional express network.

Changes in viewpoints and circumstances meant that the Rail21 timetable concept was never fully implemented. What did happen was that the *sneltrein* (fast train) was introduced in 1993/1994. In terms of stations served, the sneltrein provided a service somewhere between that of the Intercity and the Stoptrein – comparable with Rail21’s

"Interregio". The sneltrein was designed to meet the huge demand that had arisen since 1991 with the introduction of the OV-Studentenkaart. This service created a network of four fast trains per hour between the stations on the Stedenring. Various restrictions were applied to the OV-Studentenkaart during the 1990s, damping down the explosive growth in passenger numbers that had followed its introduction.

The first new rail links planned under Rail21 entered service at the start of the 21st century: the Hemboog (Schiphol Airport-Zaandam) ⟨29⟩ and the Gooiboog (Almere-Hilversum/Utrecht) ⟨5⟩. Tracks were added to existing lines: Eindhoven-Boxtel ⟨13⟩, Woerden-Harmelen ⟨15⟩ and Hoofddorp-Riekerpolder (including the Schipholspoor-tunnel) ⟨27⟩. The Hoofddorp-Riekerpolder project involved building new stations at Schiphol Airport ⟨26⟩ and Hoofddorp ⟨25⟩.

In the period between 1990 and 2004, a number of stations were modified to reflect development in their respective towns and cities. A new combined station building/office block was constructed in Hilversum ⟨6⟩ as part of changes to the station area. The same thing happened a couple of years later in 's-Hertogenbosch⟨12⟩ and Amersfoort ⟨8⟩. At Zaandam ⟨30⟩, a new entrance was added on the side furthest from the town centre. A former pedestrian subway on the western side of Den Haag HS ⟨22⟩ was converted into a combined pedestrian and cycle tunnel, for both passengers and non-passengers. This created not only a new means of accessing the platforms, but also a connection between the areas of the town on opposite sides of the railway line. In Eindhoven ⟨14⟩ the timber station building on the side furthest from the town centre was rebuilt at the same time as the bus station. The station building at Amsterdam Sloterdijk ⟨28⟩ was extended, to incorporate the new metro line.

The station building at Schiedam Centrum ⟨20⟩ was demolished to make way for a new metro line. The subway at Nijmegen ⟨11⟩ was widened to accommodate increasing passenger numbers, and new platforms were built at Gouda ⟨17⟩ and Enschede ⟨9⟩ because of the increased number of trains.

Decentralization of passenger services on regional lines began in 1999, as part of a partial privatization programme. This had been decided upon between 1997 and 1999, under the *Derde Eeuw Spoor* (Third Century Rail) directive. In 1999, passenger services on the Almelo-Mariënberg line were taken over from NS by Syntus (then a subsidiary of ConneXXion and NS, now Keolis Nederland). A year later, Syntus took over the lines in the Achterhoek (on the German border) and NoordNed (now Arriva Nederland) took over the lines in Friesland and Groningen. At the same time, government agency ProRail took over operation of railway infrastructure from NS, in a number of phases.

Between 1990 and 2004, NS passenger-kilometres increased by 39% to 14.1 billion (see Figure 2.4a), and train-kilometres by 8% to 115 million (see Figure 2.4b).

B.1.5 2005-2020

The period 2005–2020 (Figure B.5) saw the implementation of major projects set out in Rail21 [209], further decentralization of regional lines [210], conversion of urban railway lines to metro or tram lines, the *Nieuwe Sleutelprojecten* (New Key Projects) at major stations [211], the *Programma Hoogfrequent Spoor* (High-Frequency Rail Programme) [212] and a series of modifications to stations.

The Programma Hoogfrequent Spoor was the successor to Rail21, and was agreed between the Ministry of Transport, Public Works and Water Management and NS in 2010. The aims of the programme were (and are) to increase the frequency of train services on the busiest passenger corridors and to provide reliable routes for freight trains in the future. The passenger corridors are as follows: Schiphol/Amsterdam-Almere-Lelystad (the ”SAAL-corridor”), Alkmaar-Amsterdam-Utrecht-Eindhoven (the ”A2-corridor”), Schiphol-Utrecht-Arnhem-Nijmegen (the ”SUN” or ”A12-corridor”) and The Hague-Rotterdam-Eindhoven. The A2 and A12 are the motorways that follow substantially the same routes as the corresponding railway lines. The programme consists of a package of railway projects to be carried out along these corridors, some of them in combination with modifications to stations.

New rail links opened in 2005-2020: the Utrechtboog (Schiphol/Amsterdam Zuid-Utrecht) ⟨1⟩, the Betuweroute (the freight line linking the Port of Rotterdam with Germany) ⟨18⟩, the High-Speed Line South (Schiphol-Rotterdam-Breda-Belgium/France) ⟨26⟩ ⟨35⟩ and the Hanzelijn (Lelystad-Zwolle) ⟨8⟩. Although the Betuweroute does not normally carry passenger traffic, it is nonetheless of importance for passenger services – and hence for the development of stations – because it leaves more room for passenger trains elsewhere on the (mixed) railway network. This is particularly relevant to the Dordrecht-Breda-Tilburg-Eindhoven line (the Brabantroute). Construction of the Utrechtboog resulted in the building of an extra island platform at Amsterdam Zuid ⟨37⟩ to handle the additional trains and passengers.

Additional tracks have been added to existing lines: Houten-Utrecht ⟨17⟩, the southern branch of the Amsterdam Ringspoorbaan (ring line) between Riekerpolder and Duivendrecht ⟨36⟩, Utrecht-Harmelen (including a rail bridge) ⟨24⟩, Zevenaar-Didam ⟨15⟩ and Amsterdam-Utrecht ⟨4⟩. The last of these projects involved building Amsterdam Bijlmer Arena station ⟨3⟩ and part of the high-speed line eastwards from Amsterdam. The High-Speed Line East from Utrecht to Germany was cancelled, and was replaced by a package of measures allowing more trains to run at normal speed (140 km/h) over the existing tracks between Utrecht and the German border. The lines between Zwolle and Kampen and between Zwolle and Almelo (including the Nijverdal tunnel) ⟨10⟩ were renovated and electrified, allowing more trains to run. Partly on account of the new Hanzelijn and the upgrading of the Zwolle-Kampen and Zwolle-Almelo routes, Zwolle station ⟨9⟩ and its tracks underwent extensive renovation work, which included widening its pedestrian subway and building a new island platform.

The Zoetermeerstadslijn (The Hague-Zoetermeer), the Hofpleinlijn (The Hague-Rotterdam) and the Hoekselijn (Rotterdam-Hoek van Holland) were taken out of the national railway network and converted to an urban light-rail network, RandStadRail. In The Hague, this resulted in converting a number of platforms at Den Haag Laan van NOI ⟨33⟩ and Den Haag Centraal ⟨32⟩ from main-line to urban standards.

The Nieuwe Sleutelprojecten play a prominent role as regards station development. In 1997, the government decided to participate in the redevelopment of six major stations, including the areas immediately around them. This was in addition to the increase in capacity that was already planned. Partly with a view to the introduction of high-speed trains on the HSL-Zuid and HSL-Oost, the idea was to create quality urban centres, including well-integrated public transport terminals. These projects were all

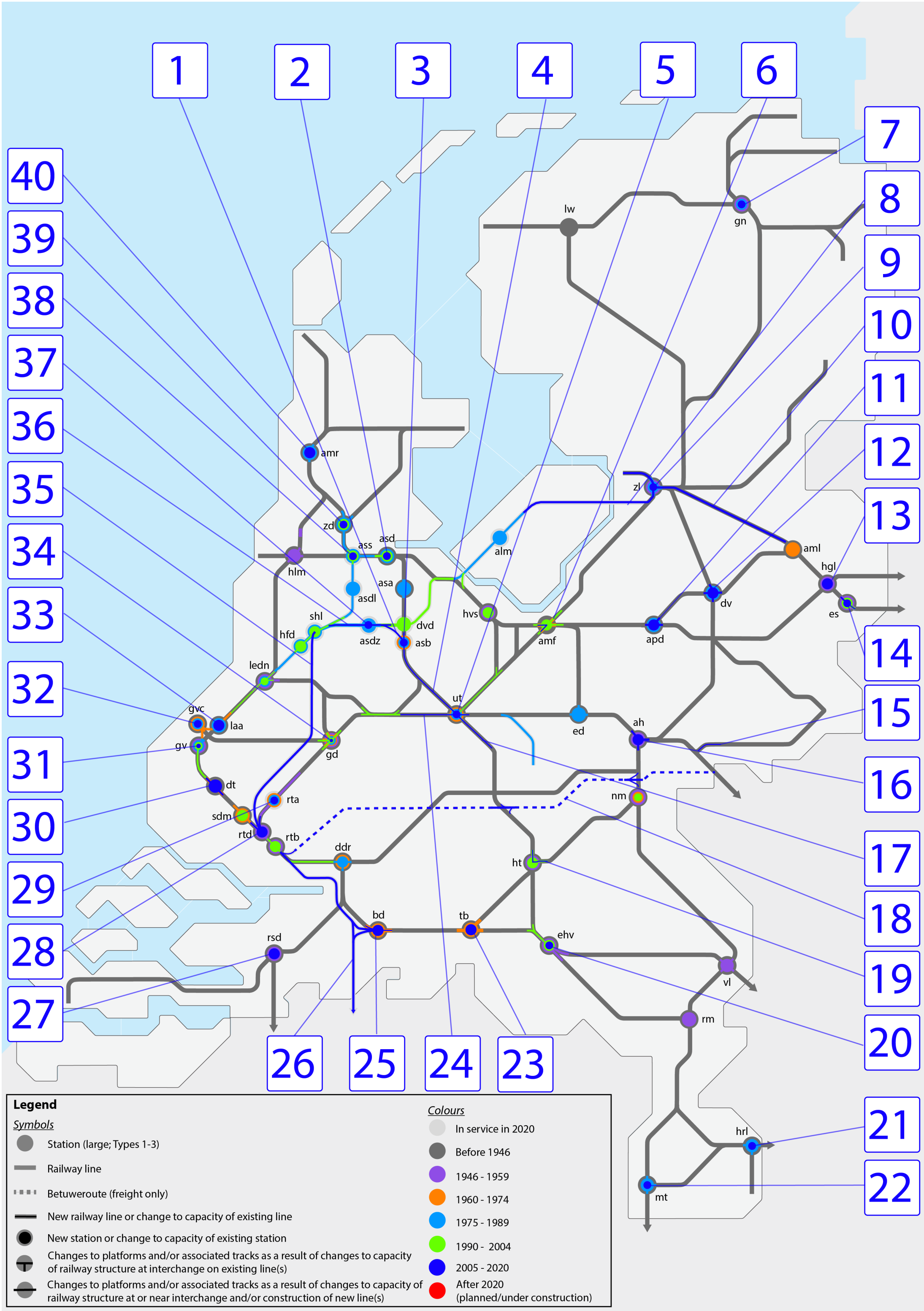


Figure B.5: The Dutch railway network as of 2020, major stations only, showing changes over the period 2005-2020

completed between 2005 and 2020, with the exception of the Amsterdam Zuidas (the new “south axis” business district). At Den Haag Centraal ⟨32⟩, the concourse was rebuilt. New station buildings were constructed at Rotterdam Centraal ⟨28⟩, Utrecht Centraal ⟨5⟩, Arnhem Centraal ⟨16⟩ and Breda ⟨25⟩. This work was accompanied by major rebuilding of the associated tracks and the addition of new platforms. At Utrecht Centraal, this involved widening existing platforms to accommodate increased passenger numbers. To do so, it was necessary to remove the through tracks (not served by platforms) that lay between them. Line speeds were increased on station tracks, and two-section platforms were redesignated as single-section, with only one train stopping at a platform at a time. A grade-separation structure was built on the southern side of Utrecht. As a result of these changes, more trains can arrive at the station at the same time [213]. Figure 2.2 shows aerial photos of Utrecht Centraal before redevelopment of the station area (2010) and after (2020). A grade-separation structure was also built to the west of Arnhem Centraal, with the same aim in mind.

In Delft ⟨30⟩, the 1960s rail viaduct was replaced by a rail tunnel (the Willem van Oranjetunnel), which also houses a new station. Both the tunnel and the station have been designed to accommodate additional tracks planned for some time after 2020. The track layout at Enschede ⟨14⟩ was modified, which also involved modifying the layout of the platforms. grade-separation structures have been built to the west of Amersfoort station ⟨6⟩ and the north of ’s-Hertogenbosch ⟨19⟩, allowing more trains to enter these two stations simultaneously. No changes were made to the stations themselves.

New station entrances have been built at Amsterdam Zuid ⟨37⟩, one of the stations on the city’s Ringspoorbaan (ring line). In 2018, this station was linked to the centre of Amsterdam and Amsterdam Centraal via the NoordZuidLijn metro. At Amsterdam Sloterdijk ⟨38⟩, a new platform was added to accommodate the Hemboog link, which opened in 2003. Amsterdam Centraal ⟨2⟩ underwent substantial changes. The central pedestrian subway, the Middentunnel, was renovated following construction of the new NoordZuid metro line underneath. The bus station was then moved to the side of the station away from the city centre. A new concourse was built under the bus station. Because of the nationwide introduction of OV-chipkaart (smart card) gates, two new pedestrian subways were built between the subways intended for passengers, so that people not travelling by train could pass under the station from one side to the other.

In addition to the major projects, a number of local projects were carried out between 2005 and 2020. In Alkmaar ⟨40⟩ the pedestrian subway was replaced by a footbridge, as it had become to narrow for the growing number of passengers. The subways at Tilburg ⟨23⟩, Apeldoorn ⟨11⟩ and Eindhoven ⟨20⟩ stations were widened, for the same reason. In Roosendaal ⟨27⟩ an old luggage tunnel was converted into a second passenger subway. At Alkmaar, Tilburg, Hengelo ⟨13⟩ and Maastricht ⟨22⟩ stations, a new or upgraded entrance was installed on the side furthest from the town centre. A new single-face platform was built at Apeldoorn following widening of the passenger subway. At Eindhoven Centraal, the station building was renovated and its layout modified. A new single-face platform was added at Deventer ⟨12⟩ to allow the station to handle more trains.

Following redevelopment of the area around Zaandam station ⟨39⟩ the footbridge and the station building were replaced by new buildings directly above the tracks. The station building at Rotterdam Alexander ⟨29⟩ was rebuilt, and a footbridge was added over the metro tracks. The entrance to Gouda station ⟨34⟩ on the side furthest from the town was renovated, and at the same time the temporary single-face platform was replaced by a permanent platform. Because of the increase in passenger numbers, a ground-level crossing was built between two platforms at Groningen station ⟨7⟩ as an alternative to the narrow footbridge. This involved converting a number of through tracks into dead-end tracks. A new quarter was built above the tracks at Heerlen ⟨21⟩, incorporating a station building. The subway under the tracks at Den Haag HS ⟨31⟩ was extended, and the station entrance on the side away from the city was moved to the end of the subway. This removed the direct connection between the platforms and the tunnel that links different parts of the city that had existed since 1998.

The MerwedeLingeLijn (Dordrecht-Geldermalsen), the Valleilijn (Amersfoort-Ede-Wageningen), and various regional lines in Limburg and around Zwolle were put out to tender, under the partial privatization scheme. Between 2005 and 2018, the number of NS passenger-kilometres rose by 31% to 18.5 billion per year (see Figure 2.4a), and train-kilometres increased by 9% to 126 million (see Figure 2.4b).

B.1.6 Plans for 2020 and after

Network development in the period starting in 2020 will focus on the *Programma Hoogfrequent Spoor* (High-Frequency Rail Programme) [212] and the regional rail plan for the northern Netherlands [214]. A new train control system will be introduced nationwide. A new vision for public transport in the Netherlands is to be drawn up as part of the programme entitled “Public Transport in 2040. Outlines of a vision for the future.” [22] . Various station projects are also planned, some of which will involve changes to railway infrastructure.

Following modification of the track layout at Utrecht Centraal as part of the High-Frequency Rail Programme (see previous period), there will be major changes to tracks at and near Amsterdam Centraal ⟨2⟩, Ede-Wageningen ⟨10⟩, Weesp ⟨3⟩, Uitgeest ⟨27⟩, Geldermalsen ⟨11⟩, Driebergen-Zeist ⟨18⟩ and Nijmegen ⟨12⟩. In Amsterdam, changes will involve major alterations to the tracks to the east (Dijksgracht), which will include construction of a grade-separation structure. At Amsterdam Centraal ⟨1⟩ this will be combined with platform widening and lengthening, plus widening of the eastern passenger subway. In a related project, a number of platforms at Amsterdam Sloterdijk ⟨26⟩ will also be modified. Changes to tracks will mean construction of a new station at Ede-Wageningen ⟨10⟩, with an extra single-face platform. Nijmegen ⟨12⟩ is to get a third platform and a station entrance on the side away from the town. That entrance will replace the one added in the 1960s.

Two major projects to add additional tracks to existing lines are also planned under the High-Frequency Rail Programme. The first is on the line between Rijswijk and Delft Zuid ⟨19⟩. The rail tunnel and station built during the previous period were designed for the extra tracks. A new island platform is to be built at Delft station ⟨20⟩ to serve the new tracks. The second is on the line between ’s-Hertogenbosch en Boxtel ⟨15⟩, and will also involve modifications to the platforms and footbridge at ’s-Hertogenbosch station ⟨14⟩. A third track-building project is planned on the line

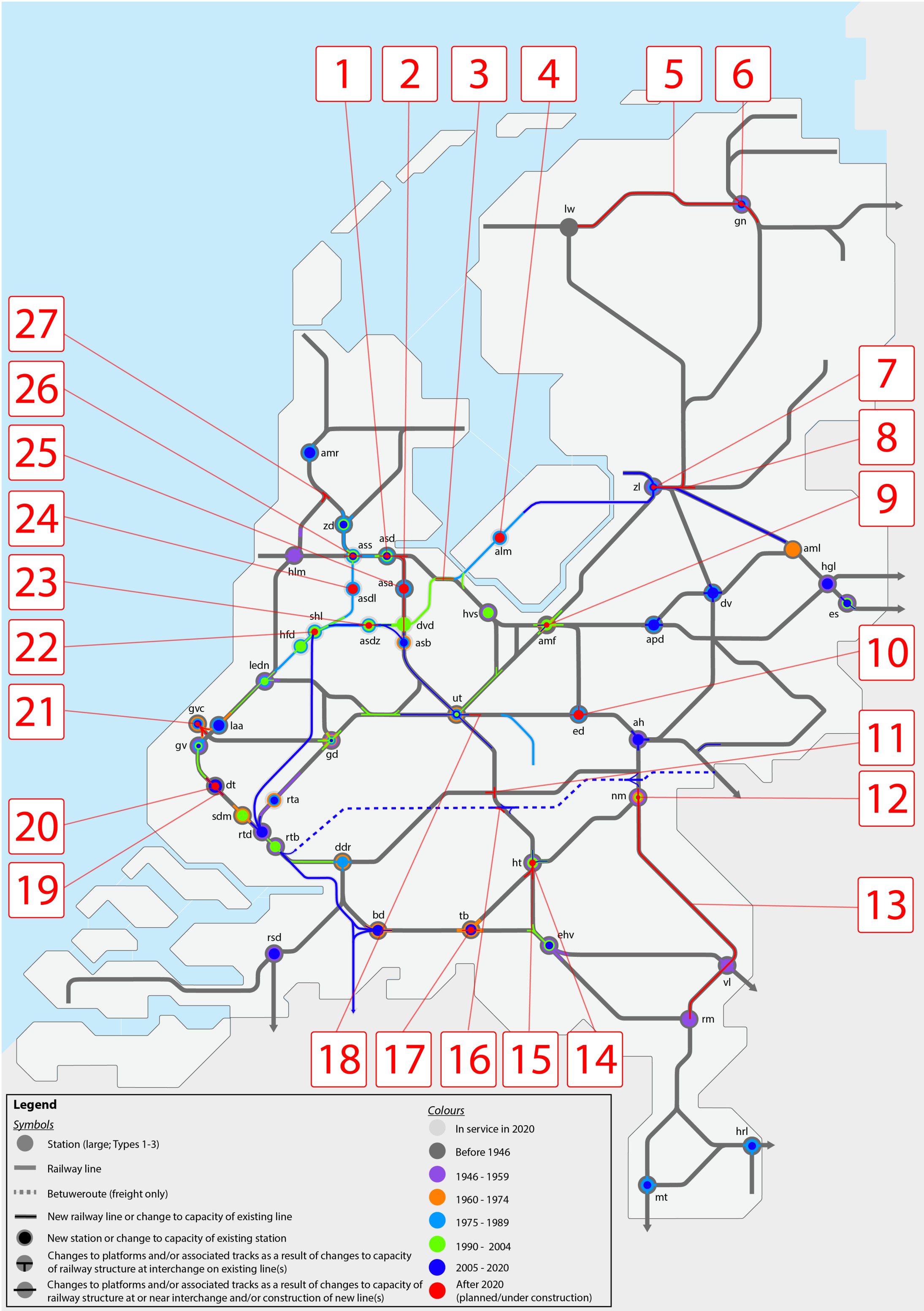


Figure B.6: The Dutch railway network as of 2020, major stations only, showing changes planned from 2020 onwards between Zwolle and Herfte) ⟨8⟩ as part of the regional rail plan for the northern Netherlands. This will allow more trains to stop in Zwolle at the same time. An existing platform in Zwolle ⟨7⟩ will be widened on account of the increase in passenger numbers. In the south of the country, the Maaslijn ⟨13⟩ will receive an upgrade, in the form of electrification and changes to tracks and signalling system.

To increase capacity for passenger trains on the Rotterdam-Tilburg-Eindhoven route (the Brabantroute), a new line ⟨16⟩ will be built near Geldermalsen/Meteren as part of the High-Frequency Rail Programme, linking the Betuweroute with the Utrecht-Eindhoven line towards ’s-Hertogenbosch. This will allow freight trains from Rotterdam to Venlo to use the Betuweroute instead of the Brabantroute. A new single-face platform is to be built at Tilburg ⟨17⟩ to handle the extra passenger trains that will be using the Brabantroute.

Large parts of the network will be equipped (in phases) with the new ERTMS (European Railway Traffic Management System) [215]. This system will allow for shorter headways and hence for more trains on the same lines. There are plans to upgrade the tractive power system, for the same reason [216]

The A10 motorway is to be moved underground on the south side of Amsterdam, and this will be combined with construction of a new Amsterdam Zuid station ⟨23⟩ [217], including provision for international trains [218]. This will mark completion of the sixth Nieuwe Sleutelproject. The new station will have wider platforms and a second pedestrian subway. The platforms, vertical circulation infrastructure and combined airport and station concourse at Schiphol Airport station ⟨22⟩ will be modified to handle rising passenger numbers, pending development of a plan for a large-scale increase in capacity.

The track layout around Groningen station ⟨6⟩ will be modified to enable trains to pass through the station, allowing for a more frequent service. Currently, all trains have to change direction at Groningen. In order to handle the larger number of trains that will be using Groningen station, the number of tracks will be increased on the line between Groningen and Groningen Europapark and the Groningen-Leeuwarden line ⟨5⟩ will be upgraded. A new subway will be added at Groningen station when the track layout is modified. This will shift the main entrance back to the central axis of the station. The track layout at Den Haag Centraal ⟨21⟩ is also to be modified. Once this is complete, what used to be the northern main-line platform (until 2006) and then became a RandStadRail platform (until 2016) will once again form part of the main-line network, allowing a more frequent train service.

At Amsterdam Amstel ⟨25⟩ an extra link will be created between the platform used by trains to Amsterdam Centraal and the subway, to accommodate increased passenger numbers. An additional link is to be built between the first platform at Amersfoort Centraal ⟨9⟩ and the footbridge, for the same reason. The platform layout at Almere Centrum ⟨4⟩ is to be modified, again because of increased numbers of passengers. At the same time, the station building will be renovated and its layout modified. The layout of the station buildings at Amsterdam Lelylaan ⟨24⟩ will be altered, in connection with changes in the area around the station.

B.2 Changes to station functions – sources of information

This appendix describes functional changes to the rail network and stations. This section lists the sources consulted regarding the development of each station.

Information on the Sporenplan website (www.sporenplan.nl) was used for all stations. That site includes maps showing the network in 1965, in 1985 and as it is today (2020). By comparing these maps, it was possible to identify changes in the functions of platforms and station tracks, together with an indication as to when these changes occurred. Figure B.7 gives an example for Den Haag Centraal.

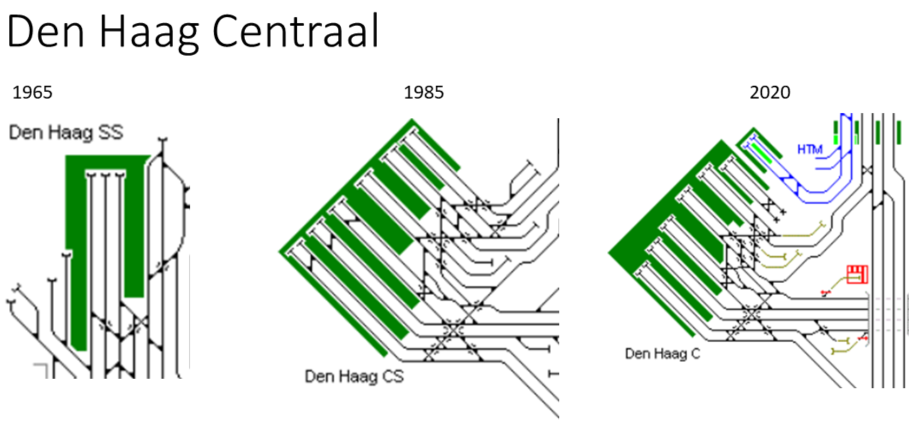


Figure B.7: Den Haag Centraal on Sporenplan (www.sporenplan.nl)

Table B.1 lists the sources consulted for each station. These include books, historical works (WS) and other sources. These "other sources" include media reports, project brochures and websites. The websites consulted were Stationsweb (www.stationsweb.nl; SW), Wikipedia (nl.wikipedia.org; WI) and Stationsinfo (www.stationsinfo.nl; SI).

Station	Number in figure						Source		
Name	B.1	B.2	B.3	B.4	B.5	B.6	Books	WS	Other
Alkmaar			31		40				[219] SW SI
Almelo		1					[220] [207]		
Almere Centrum			3			4	[220]	[221]	[222]
Amersfoort Centraal		15		8	6	9	[220]	[223]	[224] [225]
Amsterdam Amstel			2			25	[220]	[226]	[227] WI
Amsterdam Bijlmer ArenA		14	9		3		[220] [228]		
Amsterdam Centraal			1	2	2	1	[220]	[229]	[230] [231] [232][4]
Amsterdam Lelylaan			26			24	[220]		[233]
Amsterdam Sloterdijk			28	28	38	26	[220] [207]		[234]
Amsterdam Zuid			25		37	23	[220] [207] [217]		[235] [236] [28]
Apeldoorn			8		11				[237] SW
Arnhem Centraal	6				16		[220] [207]		[235] [238]
Breda		4			25		[220] [207]		[235] [239]
Delft	8				30	20		[240]	[241] [242]
Den Haag Centraal		10	21		32	21	[220] [207]		[235] [243] [244]
Den Haag HS	16		20	22	31		[220]	[245]	[243] [246]
Den Haag Laan van NOI			19		33		[220]		
Deventer			7		12			[247]	[248] WI
Dordrecht		5	17					[249]	
Duivendrecht				3			[220]		
Ede-Wageningen			10			10	[220]		[250]
Eindhoven Centraal	11			14	20		[220] [207]	[251]	[252]
Enschede	5			9	14		[220] [207]	[253]	[152]
Gouda	17	12	16	17	34		[220] [207]	[254]	[255]
Groningen	2		5		7	6		[256]	[257]
Haarlem	19							[258]	SW

Continued on next page

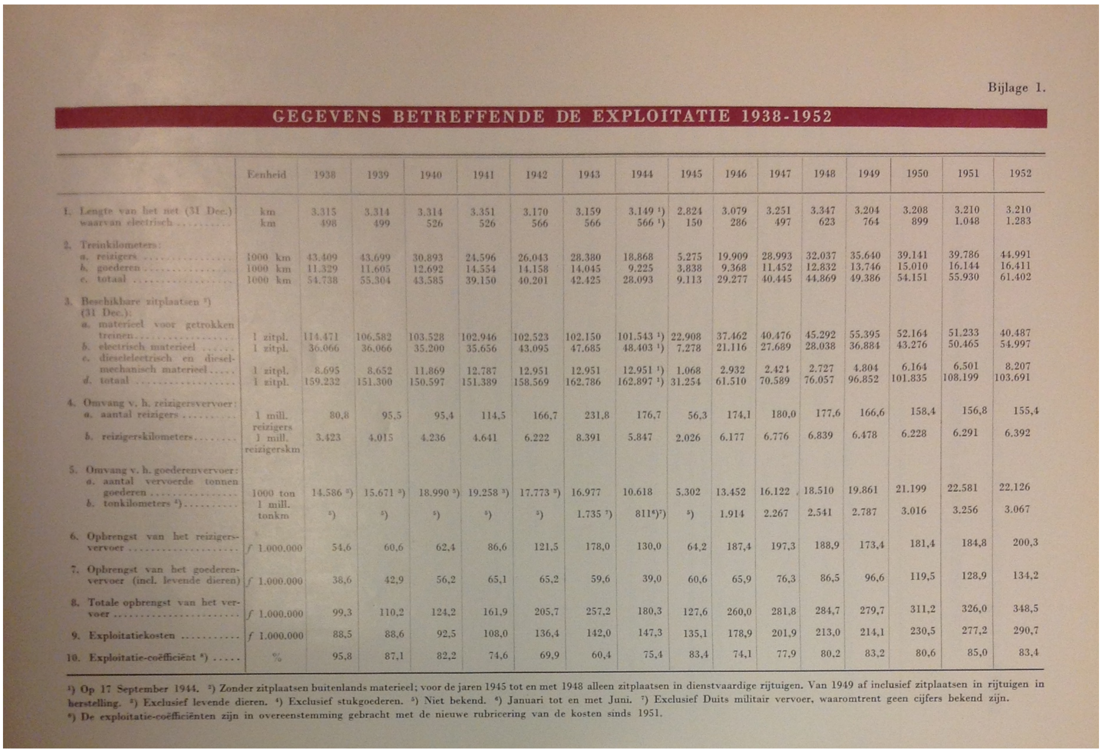
Table B.1 – *Continued from previous page*

Station	**Number in figure**						**Source**		
Name	B.1	B.2	B.3	B.4	B.5	B.6	Books	WS	Other
Heerlen			15		21		[220]		[259]
Hengelo	4				13		[220]		SI
’s-Hertogenbosch	8			12		14	[220] [207]		[260] [261]
Hilversum	1			6			[220]		SW
Hoofddorp			22	25			[220]		
Leeuwarden								[262]	
Leiden Centraal	18		13	24			[220] [207]	[263]	WI
Maastricht			14		22			[264]	
Nijmegen	7	2		11		12	[220] [207]	[265]	[242]
Roermond	10								SW
Roosendaal	12				27		[220] [207]	[266]	
Rotterdam Alexander		6	18		29		[220]		[267]
Rotterdam Blaak	13			19			[220]		
Rotterdam Centraal	14				28		[220] [207]		[235]
Schiedam Centrum		7		20			[220] [207]		
Schiphol Airport			24	26		22	[220] [207] [268]		[269] [29] [130]
Tilburg		3			23	17	[220] [207]	[270]	[271] [272]
Utrecht Centraal		13	12		5		[220] [207]		[235] [273] [274] [275] [8]
Venlo	9						[220] [207]	[276]	
Zaandam			30	30	39		[220] [207]		[234] [277]
Zwolle	3		6		9	7	[220]	[278]	[279] [280] SI

Table B.1: Sources for functional changes at major stations since 1945

B.3 Passenger-kilometres, train-kilometres and train occupancy

Figure 2.4 is based on a dataset compiled from three sources. 1. The figures that NS published in its annual reports between 1945 and 2013. 2. The figures contained in the work by Veenendaal [204]. 3. Railisa, the statistics website of the International Union of Railways: https://uic-stats.uic.org/. That site was used for the years from 2014 onwards, as NS has not published (comparable) figures in its annual reports since 2013.



Bijlage 1.

GEGEVENS BETREFFENDE DE EXPLOITATIE 1938-1952

	Eenheid	1938	1939	1940	1941	1942	1943	1944	1945	1946	1947	1948	1949	1950	1951	1952
1. Lengte van het net (31 Dec.)	km	3.315	3.314	3.314	3.351	3.170	3.159	3.149 1)	2.824	3.079	3.251	3.347	3.204	3.208	3.210	3.210
waarvan electrisch	km	498	499	526	526	566	566	566 1)	150	286	497	623	764	899	1.048	1.283
2. Treinkilometers:																
a. reizigers	1000 km	43.409	43.699	30.893	24.596	26.043	28.380	18.868	5.275	19.909	28.993	32.037	35.640	39.141	39.786	44.991
b. goederen	1000 km	11.329	11.605	12.692	14.554	14.158	14.045	9.225	3.838	9.368	11.452	12.832	13.746	15.010	16.144	16.411
c. totaal	1000 km	54.738	55.304	43.585	39.150	40.201	42.425	28.093	9.113	29.277	40.445	44.869	49.386	54.151	55.930	61.402
3. Beschikbare zitplaatsen 2) (31 Dec.):																
a. materieel voor getrokken treinen	1 zitpl.	114.471	106.582	103.528	102.946	102.523	102.150	101.543 1)	22.908	37.462	40.476	45.292	55.395	52.164	51.233	40.487
b. electrisch materieel	1 zitpl.	36.066	36.066	35.200	35.656	43.095	47.685	48.403 1)	7.278	21.116	27.689	28.038	36.884	43.276	50.465	54.997
c. dieselelectrisch en dieselmechanisch materieel	1 zitpl.	8.695	8.652	11.869	12.787	12.951	12.951	12.951 1)	1.068	2.932	2.421	2.727	4.804	6.164	6.501	8.207
d. totaal	1 zitpl.	159.232	151.300	150.597	151.389	158.569	162.786	162.897 1)	31.254	61.510	70.589	76.057	96.852	101.835	108.199	103.691
4. Omvang v. h. reizigersvervoer:																
a. aantal reizigers	1 mill. reizigers	80,8	95,5	95,4	114,5	166,7	231,8	176,7	56,3	174,1	180,0	177,6	166,6	158,4	156,8	155,4
b. reizigerskilometers	1 mill. reizigerskm	3.423	4.015	4.236	4.641	6.222	8.391	5.847	2.026	6.177	6.776	6.839	6.478	6.228	6.291	6.392
5. Omvang v. h. goederenvervoer:																
a. aantal vervoerde tonnen goederen	1000 ton	14.586 3)	15.671 3)	18.990 3)	19.258 3)	17.773 3)	16.977	10.618	5.302	13.452	16.122	18.510	19.861	21.199	22.581	22.126
b. tonkilometers 4)	1 mill. tonkm	5)	5)	5)	5)	5)	1.735 7)	811 6) 7)	5)	1.914	2.267	2.541	2.787	3.016	3.256	3.067
6. Opbrengst van het reizigersvervoer	f 1.000.000	54,6	60,6	62,4	86,6	121,5	178,0	130,0	64,2	187,4	197,3	188,9	173,4	181,4	184,8	200,3
7. Opbrengst van het goederenvervoer (incl. levende dieren)	f 1.000.000	38,6	42,9	56,2	65,1	65,2	59,6	39,0	60,6	65,9	76,3	86,5	96,6	119,5	128,9	134,2
8. Totale opbrengst van het vervoer	f 1.000.000	99,3	110,2	124,2	161,9	205,7	257,2	180,3	127,6	260,0	281,8	284,7	279,7	311,2	326,0	348,5
9. Exploitatiekosten	f 1.000.000	88,5	88,6	92,5	108,0	136,4	142,0	147,3	135,1	178,9	201,9	213,0	214,1	230,5	277,2	290,7
10. Exploitatie-coëfficiënt 8)	%	95,8	87,1	82,2	74,6	69,9	60,4	75,4	83,4	74,1	77,9	80,2	83,2	80,6	85,0	83,4

1) Op 17 September 1944. 2) Zonder zitplaatsen buitenlands materieel; voor de jaren 1945 tot en met 1948 alleen zitplaatsen in dienstvaardige rijtuigen. Van 1949 af inclusief zitplaatsen in rijtuigen in herstelling. 3) Exclusief levende dieren. 4) Exclusief stukgoederen. 5) Niet bekend. 6) Januari tot en met Juni. 7) Exclusief Duits militair vervoer, waaromtrent geen cijfers bekend zijn.
8) De exploitatie-coëfficiënten zijn in overeenstemming gebracht met de nieuwe rubricering van de kosten sinds 1951.

Figure B.8: NS production figures, 1952 annual report

Figure 2.5 is based on data obtained using Equation B.1:

$$\overline{passengers}_{train} = \frac{passenger - kilometres_{year}}{train - kilometres_{year}} \tag{B.1}$$

B.4 Station numbers and decentralization

Since the start of partial privatization in 1999, NS has ceased to be the sole operator at a number of stations. At other stations, NS no longer operates any trains at all. Failure to take this into account when calculating productivity per station would lead to an underestimation of the mean number of passenger-kilometres per station. Passenger-kilometres and train-kilometres for a station no longer appear in NS production data if NS ceases to operate services at that station. At the same time, the station is included in calculations as it is still open for traffic.

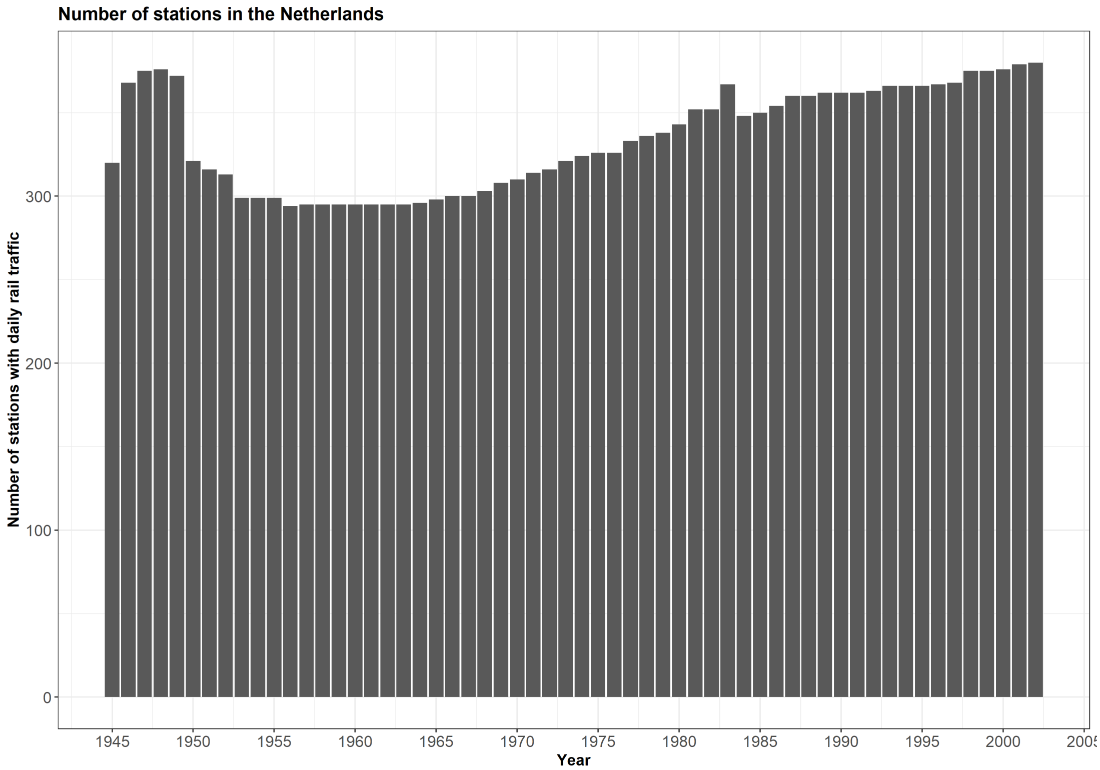


Figure B.9: Number of stations, 1945-2002

To avoid distortion as a result of decentralization, the following procedure was followed. First, the author used NS annual reports for 1945-2002 (Figure B.8) to obtain the number of stations in service for each year (see Figure B.9).

Then, a March 2001 NS network map was used to work out which stations were in use in 2001/2002 (see Table B.2). Where station names have changed in the meantime, the table uses 2020 names.

Station	Station	Station
Aalten	Feanwâlden	Overveen
Abcoude	Franeker	Palenstein
Akkrum	Geerdijk	Pijnacker
Alkmaar	Geldermalsen	Purmerend
Alkmaar Noord	Geldrop	Purmerend Overwhere
Almelo	Geleen Oost	Putten
Almelo De Riet	Geleen-Lutterade	Raalte
Almere Buiten	Gilze-Rijen	Ravenstein
Almere Centrum	Glanerbrug	Reuver
Almere Muziekwijk	Goes	Rheden
Almere Parkwijk	Goor	Rhenen
Alphen aan den Rijn	Gorinchem	Rijssen
Amersfoort Centraal	Gouda	Rijswijk
Amersfoort Schothorst	Gouda Goverwelle	Rilland-Bath
Amsterdam Amstel	Gramsbergen	Roermond
Amsterdam Bijlmer ArenA	Grijpskerk	Roodeschool
Amsterdam Centraal	Groningen	Roosendaal
Amsterdam Lelylaan	Groningen Noord	Rosmalen
Amsterdam Muiderpoort	Grou-Jirnsum	Rotterdam Alexander
Amsterdam RAI	Haarlem	Rotterdam Bergweg
Amsterdam Sloterdijk	Haarlem Spaarnwoude	Rotterdam Blaak
Amsterdam Zuid	Harde (‘t)	Rotterdam Centraal
Anna Paulowna	Hardenberg	Rotterdam Hofplein
Apeldoorn	Harderwijk	Rotterdam Kleiweg
Appingedam	Hardinxveld-Giessendam	Rotterdam Lombardijen
Arkel	Haren	Rotterdam Noord
Arnemuiden	Harlingen	Rotterdam Wilgenplas
Arnhem Centraal	Harlingen Haven	Rotterdam Zuid
Arnhem Presikhaaf	Heemskerk	Ruurlo
Arnhem Velperpoort	Heemstede-Aerdenhout	Santpoort Noord
Assen	Heerenveen	Santpoort Zuid
Baarn	Heerhugowaard	Sappemeer Oost
Bad Nieuweschans	Heerlen	Sauwerd
Baflo	Heeze	Schagen
Barendrecht	Heiloo	Scheemda
Barneveld Centrum	Heino	Schiedam Centrum
Barneveld Noord	Helmond	Schiedam Nieuwland
Bedum	Helmond ‘t Hout	Schin op Geul
Beek-Elsloo	Helmond Brouwhuis	Schinnen
Beesd	Hemmen-Dodewaard	Schiphol Airport
Beilen	Hengelo	Seghwaert
Bergen op Zoom	Hengelo Oost	Sittard
Berkel en Rodenrijs	Hertogenbosch (‘s-)	Sliedrecht

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Table B.2 – *Continued from previous page*

Best	Hertogenbosch Oost (‘s)	Sneek
Beverwijk	Hillegom	Sneek Noord
Bilthoven	Hilversum	Soest
Blerick	Hilversum Media Park	Soest Zuid
Bloemendaal	Hilversum Sportpark	Soestdijk
Bodegraven	Hindeloopen	Spaubeek
Borne	Hoek van Holland Haven	Stadhuis
Boskoop	Hoek van Holland Strand	Stavoren
Bovenkarspel Flora	Hoensbroek	Stedum
Bovenkarspel-Grootebroek	Hollandsche Rading	Steenwijk
Boxmeer	Holten	Susteren
Boxtel	Hoofddorp	Swalmen
Breda	Hoogeveen	Tegelen
Breda Prinsenbeek	Hoogezand-Sappemeer	Terborg
Breukelen	Hoogkarspel	Tiel
Brummen	Hoorn	Tilburg
Buitenpost	Hoorn Kersenboogerd	Tilburg Universiteit
Bunde	Horst-Sevenum	Uitgeest
Bunnik	Houten	Uithuizen
Bussum Zuid	Houten Castellum	Uithuizermeeden
Buytenwegh	Houthem-St.Gerlach	Usquert
Capelle Schollevaar	Hurdegaryp	Utrecht Centraal
Castricum	IJlst	Utrecht Lunetten
Centrum West	Kampen	Utrecht Overvecht
Chevremont	Kapelle-Biezelinge	Valkenburg
Coevorden	Kerkrade Centrum	Varsseveld
Cuijk	Kesteren	Veenendaal Centrum
Culemborg	Klarenbeek	Veenendaal West
Daarlerveen	Klimmen-Ransdaal	Veenendaal-De Klomp
Dalen	Koog aan de Zaan	Velp
Dalfsen	Koudum-Molkwerum	Venlo
De Leyens	Krabbendijke	Venray
De Vink	Krommenie-Assendelft	Vierlingsbeek
De Westereen	Kropswolde	Vlaardingen Centrum
Deinum	Kruiningen-Yerseke	Vlaardingen Oost
Delden	Lage Zwaluwe	Vlaardingen West
Delft	Landgraaf	Vleuten
Delft Campus	Leerdam	Vlissingen
Delftsewallen	Leeuwarden	Vlissingen Souburg
Delfzijl	Leeuwarden Camminghaburen	Voerendaal
Delfzijl West	Leiden Centraal	Voorburg
Den Dolder	Leiden Lammenschans	Voorburg ’t Loo
Den Haag Centraal	Leidschendam-Voorburg	Voorhout
Den Haag HS	Leidsewallen	Voorschoten

Continued on next page

Table B.2 – *Continued from previous page*

Den Haag Laan van NOI	Lelystad Centrum	Voorweg
Den Haag Mariahoeve	Lichtenvoorde-Groenlo	Vorden
Den Haag Moerwijk	Lochem	Vriezenveen
Den Helder	Loppersum	Vroomshoop
Den Helder Zuid	Lunteren	Vught
Deurne	Maarn	Waddinxveen
Deventer	Maarssen	Waddinxveen Noord
Deventer Colmschate	Maassluis	Warffum
Didam	Maassluis West	Weert
Diemen	Maastricht	Weesp
Diemen Zuid	Maastricht Randwyck	Wehl
Dieren	Mantgum	Wezep
Doetinchem	Mariënberg	Wierden
Doetinchem De Huet	Martenshoek	Wijchen
Dordrecht	Meerssen	Wijhe
Dordrecht Stadspolders	Meerzicht	Winschoten
Dordrecht Zuid	Meppel	Winsum
Dorp	Middelburg	Winterswijk
Driebergen-Zeist	Naarden-Bussum	Winterswijk West
Driehuis	Nieuw Amsterdam	Woerden
Driemanspolder	Nieuw Vennep	Wolfheze
Dronryp	Nieuwerkerk a/d IJssel	Wolvega
Duiven	Nijkerk	Workum
Duivendrecht	Nijmegen	Wormerveer
Echt	Nijmegen Dukenburg	Zaandam
Ede Centrum	Nijmegen Heyendaal	Zaandam Kogerveld
Ede-Wageningen	Nijmegen Lent	Zaandijk Zaanse Schans
Eijsden	Nijverdal	Zaltbommel
Eindhoven Centraal	Nunspeet	Zandvoort aan Zee
Eindhoven Strijp-S	Nuth	Zetten-Andelst
Elst	Obdam	Zevenaar
Emmen	Oisterwijk	Zevenbergen
Emmen Bargeres	Oldenzaal	Zoetermeer
Enkhuizen	Olst	Zoetermeer Oost
Enschede	Ommen	Zuidbroek
Enschede De Eschmarke	Oosterbeek	Zuidhorn
Enschede Kennispark	Opheusden	Zutphen
Ermelo	Oss	Zwijndrecht
Etten-Leur	Oss West	Zwolle
Eygelshoven	Oudenbosch	

Table B.2: Stations in use during the 2001/2002 timetable period

Then, data from NS Stations was used to establish which stations opened and closed between 2002 and 2020. Table B.3 shows the stations that closed during that period and Table B.4 shows those that opened.

Station	**Year**	**Station**	**Year**
Berkel en Rodenrijs	2006	Meerzicht	2006
Buytenwegh	2006	Nijverdal West	2013
Centrum West	2006	Palenstein	2006
De Leyens	2006	Pijnacker	2006
Delftsewallen	2006	Rotterdam Bergweg	2006
Dorp	2006	Rotterdam Hofplein	2006
Driemanspolder	2006	Rotterdam Kleiweg	2006
Emmen Bargeres	2011	Rotterdam Wilgenplas	2006
Geerdijk	2016	Schiedam Nieuwland	2017
Heerlen de Kissel	2018	Seghwaert	2006
Hoek van Holland Haven	2017	Stadhuis	2006
Hoek van Holland Strand	2017	Vlaardingen Centrum	2017
Leidschendam-Voorburg	2006	Vlaardingen Oost	2017
Leidsewallen	2006	Vlaardingen West	2017
Maassluis	2017	Voorburg ’t Loo	2006
Maassluis West	2017	Voorweg	2006

Table B.3: Stations closed or converted to urban transit, 2002–2020

Station	Year	Station	Year
Almere Oostvaarders	2004	Hoevelaken	2012
Almere Poort	2012	Kampen Zuid	2012
Amersfoort Vathorst	2006	Krommenie-Assendelft	2008
Amsterdam Holendrecht	2008	Lansingerland-Zoetermeer	2018
Amsterdam Science Park	2009	Maarheeze	2010
Apeldoorn De Maten	2006	Maastricht Noord	2013
Apeldoorn Osseveld	2006	Mook Molenhoek	2009
Arnhem Zuid	2004	Nijmegen Goffert	2014
Barneveld Zuid	2015	Nijverdal West	2009
Boskoop Snijdelwijk	2017	Purmerend Weidevenne	2007
Boven Hardinxveld	2012	Sassenheim	2011
Den Haag Ypenburg	2005	Sliedrecht Baanhoek	2011
Dronten	2012	Tiel Passewaaij	2007
Eemshaven	2018	Tilburg Reeshof	2003
Emmen Zuid	2011	Twello	2006
Eygelshoven Markt	2007	Utrecht Leidsche Rijn	2013
Gaanderen	2006	Utrecht Terwijde	2003
Groningen Europapark	2007	Utrecht Vaartsche Rijn	2016
Halfweg-Zwanenburg	2012	Utrecht Zuilen	2007
Hardinxveld Blauwe Zoom	2011	Veendam	2011
Heerlen de Kissel	2007	Voorst-Empe	2006
Heerlen Woonboulevard	2010	Waddinxveen Triangel	2018
Helmond Brandevoort	2006	Westervoort	2011
Hengelo Gezondheidspark	2012	Zwolle Stadshagen	2019

Table B.4: Stations opened, 2002–2020

Finally, data from NS Stations were used to identify those stations at which NS is no longer the sole operator (Table B.5) and those at which NS no longer operates any services (Table B.6). The year is that in which the change occurred.

Station	**Year**	**Station**	**Year**
Almelo	1999	Groningen Europapark	2007
Almelo De Riet	2018	Heerlen	2007
Amersfoort Centraal	2008	Hengelo	2004
Apeldoorn	2013	Leeuwarden	2001
Arnhem Centraal	2002	Maastricht	2007
Arnhem Velperpoort	2002	Nijmegen	2007
Borne	2018	Roermond	2007
Dordrecht	2008	Sittard	2017
Ede-Wageningen	2008	Tiel	2014
Elst	2014	Venlo	2007
Enschede	2001	Wierden	2018
Enschede Kennispark	2018	Zutphen	2000
Geldermalsen	2008	Zwolle	2013
Groningen	2001		

Table B.5: Stations at which both NS and other operates run services, 1999–2020

Station	Year	Station	Year
Aalten	2000	Koudum-Molkwerum	2001
Apeldoorn De Maten	2013	Kropswolde	2001
Appingedam	2001	Landgraaf	2007
Bad Nieuweschans	2001	Leeuwarden Camminghaburen	2001
Baflo	2001	Lichtenvoorde-Groenlo	2000
Barneveld Zuid	2015	Loppersum	2001
Bedum	2001	Maastricht Noord	2013
Boven Hardinxveld	2012	Mantgum	2001
Boxmeer	2007	Martenshoek	2001
Buitenpost	2001	Mook Molenhoek	2009
Coevorden	2013	Nieuw Amsterdam	2013
Cuijk	2007	Nijmegen Heyendaal	2007
Dalen	2013	Nijverdal	2018
Dalfsen	2013	Ommen	2013
De Westereen	2001	Raalte	2018
Deinum	2001	Reuver	2007
Delfzijl	2001	Roodeschool	2001
Delfzijl West	2001	Ruurlo	2000
Dronryp	2001	Sappemeer Oost	2001
Eemshaven	2018	Sauwerd	2001
Eijsden	2012	Scheemda	2001
Emmen	2013	Sliedrecht Baanhoek	2011
Emmen Zuid	2013	Sneek	2001
Enschede De Eschmarke	2001	Sneek Noord	2001
Eygelshoven	2007	Stavoren	2001
Eygelshoven Markt	2007	Stedum	2001
Feanwâlden	2001	Swalmen	2007
Franeker	2001	Tegelen	2007
Gaanderen	2000	Terborg	2000
Glanerbrug	2001	Uithuizen	2001
Gramsbergen	2013	Uithuizermeeden	2001
Grijpskerk	2001	Usquert	2001
Groningen Noord	2001	Varsseveld	2000
Hardenberg	2013	Veendam	2011
Hardinxveld Blauwe Zoom	2011	Venray	2007
Harlingen	2001	Vierlingsbeek	2007
Harlingen Haven	2001	Voorst-Empe	2013
Heerlen de Kissel	2007	Vorden	2000
Heerlen Woonboulevard	2010	Warffum	2001
Heino	2018	Westervoort	2001
Hengelo Gezondheidspark	2012	Winschoten	2001
Hindeloopen	2001	Winsum	2001
Hoevelaken	2012	Winterswijk	2000

Continued on next page

Table B.6 – *Continued from previous page*

Station	**Year**	**Station**	**Year**
Hoogezand-Sappemeer	2001	Winterswijk West	2001
Hurdegaryp	2001	Workum	2001
IJlst	2001	Zuidbroek	2001
Kampen	2018	Zuidhorn	2001
Klarenbeek	2013	Zwolle Stadshagen	2019

Table B.6: Stations at which services are provided by other operators, but not by NS, 1999–2020

While carrying out this analysis, the author encountered a number of exceptions that do not fit into the production and station data. For the sake of completeness, these stations are shown in Table B.7.

Station	**Opened**	**Closed**	**Comments**
Almere Strand		2012	Special-event halt
Amsterdam ArenA			Special-event halt
Doetinchem Stadion		2005	Special-event halt
Eindhoven Stadion			Special-event halt
Heerenveen IJsstadion		2015	Special-event halt
Achter de Hoven (Leeuwarden)		2018	A few services per day
Onze Lieve Vrouwe Ter Nood		2013	Special-event halt
Rotterdam Stadion			Special-event halt
Utrecht Maliebaan	2005		Railway museum

Table B.7: Other changes in status after 1999

Appendix C

Fundamental diagram and level of service

Legend **Figures 3.7 and C.1**	**Speed** (u in m/s)	**A**	**B**	**Capacity** (q_{max} in P/ms)	**Reference**
Fruin (1971)	C.1	1.43	0.35	1.46	[95] [106] [107]
Navin & Wheeler (1969)	C.1	1.63	0.60	1.10	[95]
Oeding (1963)	C.1	1.50	0.39	1.44	[95]
Older (1968)	C.1	1.31	0.34	1.26	[95]
Sarkar & Janardhan (1997)	C.1	1.46	0.35	1.52	[106]
SFPE (2002)	C.1	1.40	0.37	1.31	[107]
Tariboon et al. (1986)	C.1	1.23	0.26	1.45	[106]
Virkler & Elayadath (1994)	C.2	-	-	0.96	[106]
Weidmann (1993)	C.3	-	-	1.22	[106] [107]

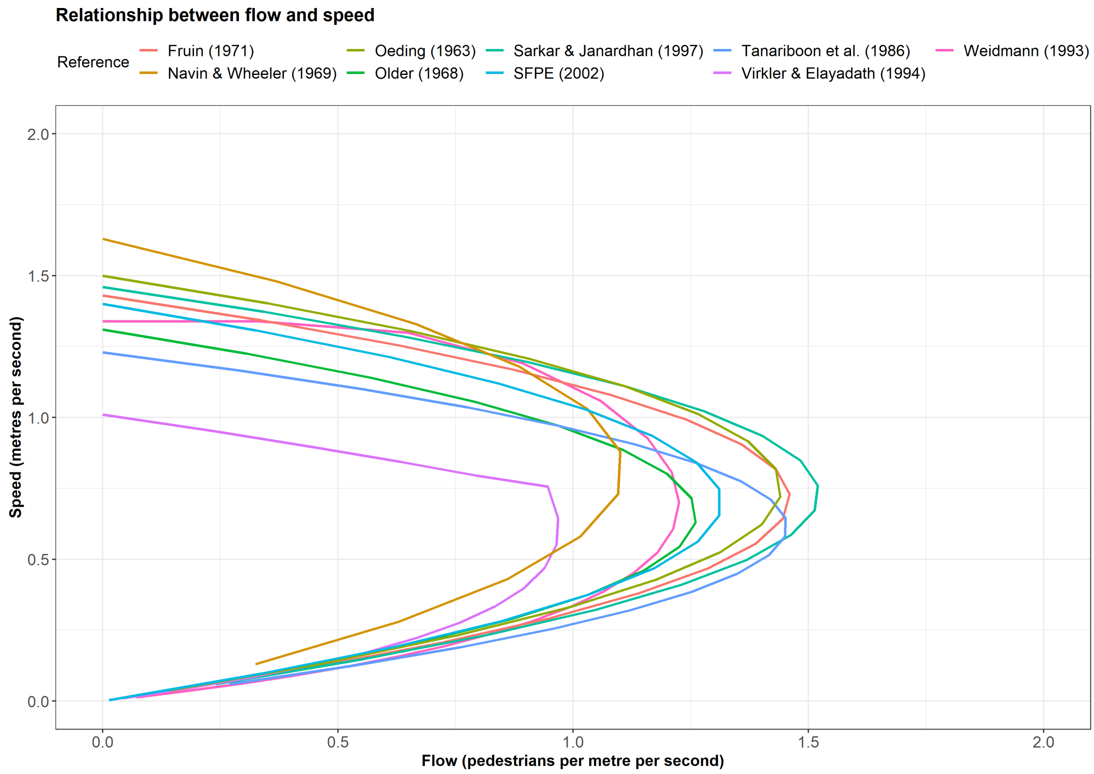
Table C.1: Overview of FD functions for speed

With the following functions for speed (u):

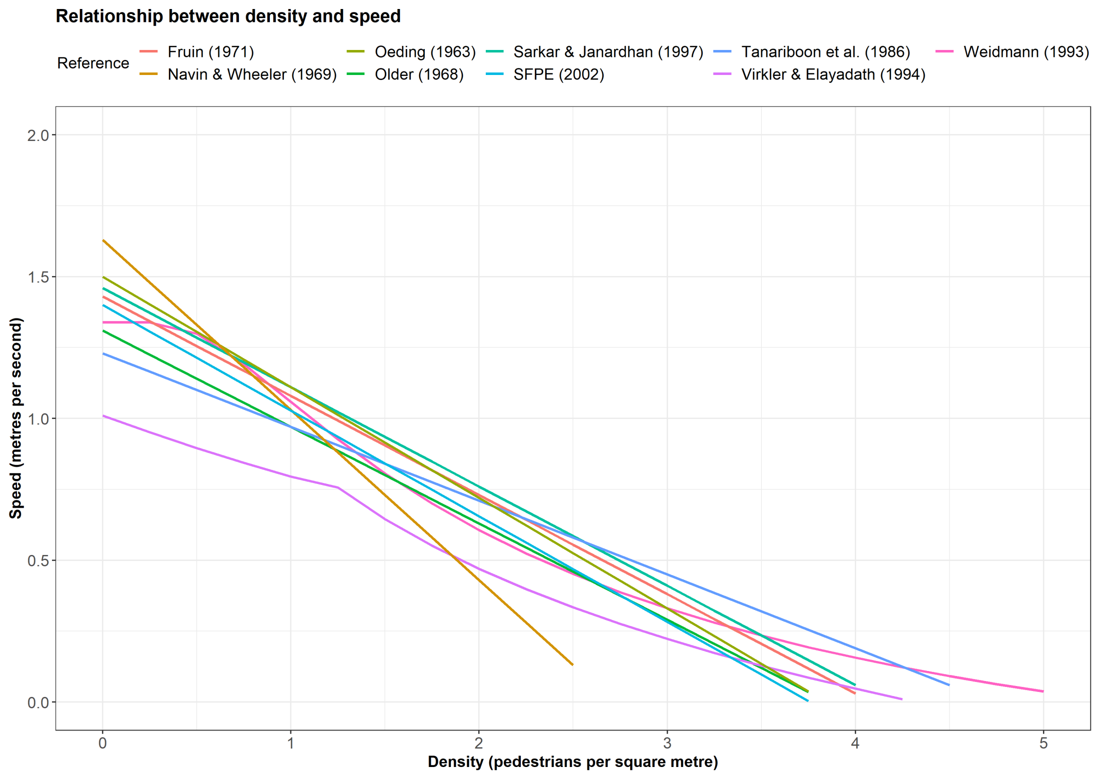
$$u = A - B \cdot k \tag{C.1}$$

$$u = \begin{cases} 1.01 \cdot e^{\left(\frac{-k}{4.17}\right)}, \text{where } k < 1.07 \\ 0.61 \cdot ln\left(\frac{4.32}{k}\right), \text{where } k \geq 1.07 \end{cases} \tag{C.2}$$

$$u = 1.34 \cdot \left(1 - e^{-1.913 \cdot \left(\frac{1}{k} - \frac{1}{5.4}\right)}\right) \tag{C.3}$$



(a) Flow-speed relation



(b) Density-speed relation

Figure C.1: Fundamental diagram for pedestrian traffic – other relations

LEVEL-OF-SERVICE DESCRIPTIONS FOR WALKWAYS

Level of Service A

Average Pedestrian Area Occupancy: 35 square feet per person, or greater.
Average Flow Volume: 7 PFM, or less. *

At walkway level-of-service A, sufficient area is provided for pedestrians to freely select their own walking speed, to bypass slower pedestrians, and to avoid crossing conflicts with others. Designs consistent with this level-of-service would include public buildings or plazas without severe peaking characteristics or space restrictions.

Level of Service B

Average Pedestrian Area Occupancy: 25-35 square feet per person.
Average Flow Volume: 7-10 PFM.

At walkway level-of-service B, sufficient space is available to select normal walking speed, and to bypass other pedestrians in primarily one-directional flows. Where reverse-direction or pedestrian crossing movements exist, minor conflicts will occur, slightly lowering mean pedestrian speeds and potential volumes. Designs consistent with this level-of-service would be of reasonably high type, for transportation terminals and buildings in which recurrent, but not severe, peaks are likely to occur.

Level of Service C

Average Pedestrian Area Occupancy: 15-25 square feet per person.
Average Flow Volume: 10-15 PFM.

At walkway level-of-service C, freedom to select individual walking speed and freely pass other pedestrians is restricted. Where pedestrian cross movements and reverse flows exist, there is a high probability of conflict requiring frequent adjustment of speed and direction to avoid contact. Designs consistent with this level-of-service would represent reasonably fluid flow; however, considerable friction and interaction between pedestrians is likely to occur, particularly in multi-directional flow situations. Examples of this type of design would be heavily used transportation terminals, public buildings, or open spaces where severe peaking, combined with space restrictions, limit design flexibility.

***PFM = Pedestrians per foot width of walkway, per minute.**

(a) LOS A, B and C

Level of Service D

Average Pedestrian Area Occupancy: 10-15 square feet per person.
Average Flow Volume: 15-20 PFM.

At walkway level-of-service D, the majority of persons would have their normal walking speeds restricted and reduced, due to difficulties in bypassing slower-moving pedestrians and avoiding conflicts. Pedestrians involved in reverse-flow and crossing movements would be severely restricted, with the occurrence of multiple conflicts with others. Designs at this level-of-service would be representative of the most crowded public areas, where it is necessary to continually alter walking stride and direction to maintain reasonable forward progress. At this level-of-service there is some probability of intermittently reaching critical density, causing momentary stoppages of flow. Designs consistent with this level-of-service would represent only the most crowded public areas.

Level of Service E

Average Pedestrian Area Occupancy: 5-10 square feet per person.
Average Flow Volume: 20-25 PFM.

At walkway level-of-service E, virtually all pedestrians would have their normal walking speeds restricted, requiring frequent adjustments of gait. At the lower end of the range, forward progress would only be made by shuffling. Insufficient area would be available to bypass slower-moving pedestrians. Extreme difficulties would be experienced by pedestrians attempting reverse-flow and cross-flow movements. The design volume approaches the maximum attainable capacity of the walkway, with resulting frequent stoppages and interruptions of flow. This design range should only be employed for short peaks in the most crowded areas. This design level would occur naturally with a bulk arrival traffic pattern that immediately exceeds available capacity, and this is the only design situation for which it would be recommended. Examples would include sports-stadium design, or rail transit facilities where there may be a large but short-term exiting of passengers from a train. When this level-of-service is assumed for these design conditions, the adequacy of pedestrian holding areas at critical design sections, and all supplementary pedestrian facilities, must be carefully evaluated.

(b) LOS D and E

Level of Service F

Average Pedestrian Area Occupancy: 5 square feet per person, or less.

Average Flow Volume: Variable, up to 25 PFM.

At walkway level-of-service F, all pedestrian walking speeds are extremely restricted, and forward progress can only be made by shuffling. There would be frequent, unavoidable contact with other pedestrians, and reverse or crossing movements would be virtually impossible. Traffic flow would be sporadic, with forward progress based on the movement of those in front. This level-of-service is representative of a loss of control, and a complete breakdown in traffic flow. Pedestrian areas below 5 square feet are more representative of a queuing, rather than a traffic-flow situation, and this level-of-service is not recommended for walkway design.

(c) LOS F

Figure C.2: Fruin levels of service for walkways [36]

Appendix D

Notes regarding stations with SMART Station sensors

To complement Figure 4.6, Table D.1 shows the types of sensor used, classified by type, period and purpose of measurement. In line with the SMART Station concept (Figure 4.1), the table distinguishes between trackers and counters.

- Trackers
  - Bluetooth (BT). Initially, the trackers used only Bluetooth antennas. These antennas were phased out at the end of 2018, as it was possible to obtain better data using WiFi tracking.
  - WiFi (WF). In 2013, WiFi antennas were added to the existing trackers. From that year onwards, all new trackers were fitted with WiFi antennas, as an increasing number of devices could be detected using WiFi [24].
- Counters
  1. First generation (gen 1): Infrared technology that recorded flows at predefined counting lines.
  2. Second generation (gen 2): Stereo camera technology that recorded flows at predefined counting lines, plus the number of persons in predefined floor fields.
  3. Third generation (gen 3): Stereo camera technology that incorporates the features of second-generation devices and records the positions (trajectories) of all individual pedestrians in the area covered by the sensor, 10 times per second.

The data used for this research was acquired using the third-generation counters shown with the symbol **x** in Table D.1.

Station	**Period**	**Locations**	**Trackers**		**Counters**			**Purpose**
	Measurements	Sensors	BT	WF	gen 1	gen 2	gen 3	
Utrecht C.	2011-2012	Concourse	x		x			Tests for development of
		Subway(s)						SMART Station measuring concept
		Platform(s)						
	2013-2015	Concourse	x	x	x			Development of SMART
		Subway(s)	x	x				Station measuring concept during
		Platform(s)	x	x				rebuilding of concourse [23] [24]
	2015-2016	Concourse						Use of station entrances
		Subway(s)	x	x	x			for planning of
		Platform(s)	x	x				Noordertunnel renovation
	2017-2019	Concourse	x				x	Crowd control because of
		Subway(s)	x					overcrowding declaration,
		Platform(s)	x				x	Plat. 5 [5] [8]
Groningen	2013	Concourse	x					Use of station entrances
								for planning of
		Platform(s)						passenger subway
Leiden C.	2013-2015	Concourse	x	x				Tracker development tests
		Subway(s)	x	x	x	x		as part of SMART Station
		Platform(s)						measuring concept
	2015-2018	Concourse	x	x				Use of subway
		Subway(s)	x	x		x		as part of
		Platform(s)						bottleneck analysis
Schiphol Airport	2013-2014	Concourse	x					Use of station and platform
		Platform(s)	x					entrances, in connection with
			x					introduction of OV-chipkaart
	2014-2015	Concourse	x	x				Passenger flows,

Continued on next page

Table D.1 – *Continued from previous page*

Station	**Period**	**Locations**	**Trackers**		**Counters**			**Purpose**
	Measurements	Sensors	BT	WF	gen 1	gen 2	gen 3	
		Platform(s)	x	x				for station
			x	x				planning [130]
	2016-2019	Concourse	x	x				Crowd control because of
								overcrowding on Plat. 1-2
		Platform(s)	x	x		x	x	[6]
Amsterdam C.	2016-2019	Concourse						Crowd control because of
		Subway(s)				x	x	crowding in subways
		Platform(s)						at OV-chipkaart gates
	2017-2019	Concourse	x	x				Use of station entrances and
		Subway(s)	x	x				subways, for
		Platform(s)						station planning [218] [4]
Amsterdam Zuid	2017-2019	Concourse	x	x				Crowd control because of
		Subway(s)	x	x			x	increased crowding after
		Platform(s)	x	x			x	opening of NoordZuidLijn metro [7]
's Hertogenbosch	2017-2019	Concourse	x	x			x	Use of station entrances
		Footbridge(s)	x	x				for station
		Platform(s)	x	x				planning
Amsterdam Bijlmer Arena	2019	Concourse					x	Crowd control because of
								crowding on concourse after
		Platform(s)						events in Arena zone [11]

Table D.1: Stations in the Netherlands that were equipped with SMART Station between 2011 and 2019

Appendix E

Examples of data

timestampms	tracked_object	x_pos	y_pos	sensor_id
1.4899644000E+12	2799509	-89770.8	-2776.0	8
1.4899644001E+12	2799509	-89874.5	-2764.6	8
1.4899644002E+12	2799509	-89975.8	-2757.3	8
1.4899644003E+12	2799509	-90018.6	-2774.6	8
1.4899644004E+12	2799509	-90078.9	-2741.1	8
1.4899644005E+12	2799509	-90198.8	-2725.4	8
1.4899644006E+12	2799509	-90300.3	-2706.1	8
1.4899644007E+12	2799509	-90382.6	-2691.3	8
1.4899644008E+12	2799509	-90510.2	-2639.0	8
1.4899644009E+12	2799509	-90602.9	-2576.1	8

Table E.1: Example data, SMART Station Trajectory data

Datumtijd	Vloerveld	Aantal
2018-07-16 00:05:08	qut11At	1
2018-07-16 00:05:15	qut11At	0
2018-07-16 00:19:04	qut11At	1
2018-07-16 00:23:11	qut11At	0
2018-07-16 00:52:43	qut11At	1
2018-07-16 00:52:56	qut11At	0
2018-07-16 01:18:24	qut11At	1
2018-07-16 02:20:32	qut11At	0
2018-07-16 06:18:42	qut11At	1
2018-07-16 06:24:43	qut11At	0

Table E.2: Example data, SMART Station Train detection data

station	stationID	treinnummer	av_verkeersdatum	treinmoment	in_of_uit	aantal_reizigers
Asdz	61	4342	2017-09-01	2017-09-01T13:56:40	U	6.768
Asdz	61	11658	2017-09-01	2017-09-01T17:47:13	I	38.858
Ut	621	872	2017-09-01	2017-09-01T20:53:29	I	100.769
Asdz	61	3520	2017-09-01	2017-09-01T08:05:37	I	28.132
Ut	621	5531	2017-09-01	2017-09-01T09:36:56	I	21.342
Ut	621	11789	2017-08-31	2017-09-01T00:06:25	I	12.042
Ut	621	3576	2017-09-01	2017-09-01T21:44:07	I	50.758
Asdz	61	1673	2017-09-01	2017-09-01T19:41:33	U	5.999
Ut	621	8876	2017-09-01	2017-09-01T21:54:00	I	47.986
Ut	621	3018	2017-09-01	2017-09-01T07:40:47	I	202.641
Ut	621	886	2017-09-01	2017-09-02T00:23:24	U	68.572
Asdz	61	3125	2017-09-01	2017-09-01T07:37:08	U	9.239
Ut	621	875	2017-09-01	2017-09-01T20:37:13	U	119.323
Ut	621	6964	2017-09-01	2017-09-01T19:07:28	U	26.774
Ut	621	6134	2017-09-01	2017-09-01T11:27:37	I	24.375
Ut	621	1762	2017-09-01	2017-09-01T18:31:42	U	53.303
Asdz	61	2448	2017-09-01	2017-09-01T16:25:48	U	76.550
Ut	621	856	2017-09-01	2017-09-01T16:50:22	U	95.016
Ut	621	3027	2017-09-01	2017-09-01T08:54:19	I	54.937
Ut	621	3164	2017-09-01	2017-09-01T18:49:16	U	69.248
Ut	621	7454	2017-09-01	2017-09-01T16:30:26	U	18.453
Asdz	61	303124	2017-09-01	2017-09-01T09:23:06	I	12.237
Ut	621	7425	2017-09-01	2017-09-01T08:25:16	I	40.060
Ut	621	871	2017-09-01	2017-09-01T19:37:55	U	177.914
Ut	621	4970	2017-09-01	2017-09-01T19:52:51	I	30.546

Table E.3: Example data, ROCKT Station

TRENTO_VERKEERSDATUM	TRENTO_TREINNR	TRENTO_SERIE	TRENTO_DRGLPT	TRENTO_SPOOR	TRENTO_HALTEERSECTIE	TRENTO_MAT_A_SRT	TRENTO_MAT_A_TYPE	TRENTO_MAT_A_BAKKEN	TRENTO_MAT_A_LENGTE	TRENTO_MAT_V_SRT	TRENTO_MAT_V_TYPE	TRENTO_MAT_V_BAKKEN	TRENTO_MAT_V_LENGTE
2018-09-01	3069	3000	Ut	19	UT$2652T	VIRM	6	6	162	VIRM	6	6	162
2018-09-01	3577	3500	Asdz	2	ASDZO$744AT	VIRM	4	4	109	VIRM	4	4	109
2018-09-01	583	500	Ut	11	UT$A2672T	DDZ	6	6	154	DDZ	6	6	154
2018-09-01	2077	2000	Ut	12	UT$2612BT	DDZ	4	4	101				0
2018-09-01	8831	8800	Ut	9	UT$2602DT	ICM ICM	3 4	7	188				0
2018-09-01	77387	77300	Ut	14	UT$2614BT	SGMM	3	3	79				0
2018-09-01	618	600	Ut	8	UT$2608T	ICM	4	4	107	ICM	4	4	107
2018-09-01	80444	80000	Ut	1	UT$2556BT				0	DD-AR	3	3	101
2018-09-01	3083	3000	Ut	19	UT$2652T	VIRM	6	6	162	VIRM	6	6	162
2018-09-01	2069	2000	Ut	12	UT$2612BT	ICM ICM	4 3	7	188				0
2018-09-01	8889	8800	Ut	9	UT$2602DT	DDZ	4	4	101				0
2018-09-01	5559	5500	Ut	3	UT$2560T				0	SLT	4	4	69
2018-09-01	5742	5700	Ut	1	UT$2556BT				0	SLT	4	4	69
2018-09-01	8833	8800	Ut	9	UT$2602DT	ICM ICM	4 3	7	188				0
2018-09-01	6977	6900	Ut	20	UT$2620BT				0	SLT	4	4	69

Table E.4: Example data, Trento (part 1 of 4)

TRENTO_VERKEERSDATUM	TRENTO_TREINNR	TRENTO_AANK_TIJD_DT	TRENTO_VERTR_TIJD_DT	TRENTO_VGB_B_APLANTIJD_DT	TRENTO_VGB_E_APLANTIJD_DT	TRENTO_VGB_ACT	TRENTO_VGB_VOLGNR
2018-09-01	3069	2018-09-01 19:22:38	2018-09-01 19:23:51	2018-09-01 19:22:00	2018-09-01 19:24:00	AV	55
2018-09-01	3577	2018-09-01 20:54:34	2018-09-01 20:56:48	2018-09-01 20:55:00	2018-09-01 20:56:00	AV	6
2018-09-01	583	2018-09-01 22:41:50	2018-09-01 22:48:13	2018-09-01 22:42:00	2018-09-01 22:48:00	AV	28
2018-09-01	2077	2018-09-01 20:44:35		2018-09-01 20:45:00		A	22
2018-09-01	8831	2018-09-01 09:33:21		2018-09-01 09:34:00		A	23
2018-09-01	77387	2018-09-02 00:50:06		2018-09-02 00:58:00		A	12
2018-09-01	618	2018-09-01 07:41:44	2018-09-01 07:48:40	2018-09-01 07:42:00	2018-09-01 07:48:00	AV	23
2018-09-01	80444		2018-09-01 19:58:07		2018-09-01 19:59:00	V	1
2018-09-01	3083	2018-09-01 22:50:28	2018-09-01 22:54:12	2018-09-01 22:52:00	2018-09-01 22:54:00	AV	50
2018-09-01	2069	2018-09-01 18:44:08		2018-09-01 18:45:00		A	22
2018-09-01	8889	2018-09-02 00:03:43		2018-09-02 00:04:00		A	23
2018-09-01	5559		2018-09-01 16:36:40		2018-09-01 16:36:00	V	1
2018-09-01	5742		2018-09-01 13:10:13		2018-09-01 13:10:00	V	1
2018-09-01	8833	2018-09-01 10:03:14		2018-09-01 10:04:00		A	23
2018-09-01	6977		2018-09-01 20:52:16		2018-09-01 20:52:00	V	1

Table E.5: Example data, Trento (part 2 of 4)

TRENTO_VERKEERSDATUM	TRENTO_TREINNR	TRENTO_VERTREKSEIN_ID	TRENTO_VERTREKSEIN_VEILIG_DT	TRENTO_VERTREKSEIN_STOP_DT	TRENTO_INRIJSEIN_ID	TRENTO_INRIJSEIN_VEILIG_DT
2018-09-01	3069	UT$2718	2018-09-01 19:19:31	2018-09-01 19:24:32	UT$2652	2018-09-01 19:19:19
2018-09-01	3577	ASDZO$764			ASDZO$744	
2018-09-01	583	UT$2672	2018-09-01 22:47:03	2018-09-01 22:48:42	UT$2612	2018-09-01 22:38:44
2018-09-01	2077				UT$2612	2018-09-01 20:41:29
2018-09-01	8831				UT$2612	2018-09-01 09:30:09
2018-09-01	77387				UT$2756	2018-09-02 00:48:26
2018-09-01	618	UT$2676	2018-09-01 07:47:49	2018-09-01 07:49:08	UT$2608	2018-09-01 07:38:51
2018-09-01	80444	UT$2688	2018-09-01 19:58:07	2018-09-01 19:58:35		
2018-09-01	3083	UT$2718	2018-09-01 22:46:59	2018-09-01 22:54:53	UT$2652	2018-09-01 22:46:57
2018-09-01	2069				UT$2612	2018-09-01 18:40:55
2018-09-01	8889				UT$2612	2018-09-02 00:00:25
2018-09-01	5559	UT$2684	2018-09-01 16:35:07	2018-09-01 16:37:04		
2018-09-01	5742	UT$2688	2018-09-01 13:09:07	2018-09-01 13:10:37		
2018-09-01	8833				UT$2612	2018-09-01 09:59:56
2018-09-01	6977	UT$2720	2018-09-01 20:51:11	2018-09-01 20:52:44		

Table E.6: Example data, Trento (part 3 of 4)

TRENTO_VERKEERSDATUM	TRENTO_TREINNR	TRENTO_INRIJSEIN_STOP_DT	TRENTO_TREINNR_OMNR_AN	TRENTO_TREINNR_COMB_AN	TRENTO_TREINNR_SPLITS_AN	TRENTO_KERING_IND
2018-09-01	3069	2018-09-01 19:22:09				
2018-09-01	3577					
2018-09-01	583	2018-09-01 22:40:51				K
2018-09-01	2077	2018-09-01 20:43:36	8872			O
2018-09-01	8831	2018-09-01 09:32:09	2026			O
2018-09-01	77387	2018-09-02 00:48:53		77389 407787		O
2018-09-01	618	2018-09-01 07:40:42				K
2018-09-01	80444		408044			O
2018-09-01	3083	2018-09-01 22:49:51				
2018-09-01	2069	2018-09-01 18:43:04	8864			O
2018-09-01	8889	2018-09-02 00:02:37	8886			O
2018-09-01	5559		5552			O
2018-09-01	5742		405742			O
2018-09-01	8833	2018-09-01 10:02:05	2028			O
2018-09-01	6977		7877			

Table E.7: Example data, Trento (part 4 of 4)

Appendix F

Weather stations and railway stations

Railway station		*Weather station*		*Distance*
Abbreviation	**Name**	**Number**	**Name**	**(m)**
Ac	Abcoude	240	SCHIPHOL	13468
Ah	Arnhem	275	DEELEN	8104
Ahp	Arnhem Velperpoort	275	DEELEN	8491
Ahpr	Arnhem Presikhaaf	275	DEELEN	8988
Akm	Akkrum	270	LEEUWARDEN	20696
Alm	Almere Centrum	269	LELYSTAD	22511
Almb	Almere Buiten	269	LELYSTAD	17895
Almm	Almere Muziekwijk	269	LELYSTAD	24551
Almp	Almere Parkwijk	269	LELYSTAD	20767
Aml	Almelo	290	TWENTHE	18652
Ampo	Almere Poort	240	SCHIPHOL	24776
Amr	Alkmaar	249	BERKHOUT	16178
Amri	Almelo de Riet	290	TWENTHE	17039
Amrn	Alkmaar Noord	249	BERKHOUT	14511
Ana	Anna Paulowna	235	DE KOOY	7061
Apd	Apeldoorn	275	DEELEN	18300
Apn	Alphen a/d Rijn	215	VOORSCHOTEN	15198
Arn	Arnemuiden	310	VLISSINGEN	8358
Asa	Amsterdam Amstel	240	SCHIPHOL	9259
Asb	Amsterdam Bijlmer ArenA	240	SCHIPHOL	10700
Asd	Amsterdam Centraal	240	SCHIPHOL	10108
Asdl	Amsterdam Lelylaan	240	SCHIPHOL	5340
Asdm	Amsterdam Muiderpoort	240	SCHIPHOL	10703
Asdz	Amsterdam Zuid	240	SCHIPHOL	6023
Ashd	Amsterdam Holendrecht	240	SCHIPHOL	11755
Asn	Assen	280	EELDE	14873
Ass	Amsterdam Sloterdijk	240	SCHIPHOL	8534
Assp	Amsterdam Science Park	240	SCHIPHOL	11425
Bd	Breda	350	GILZE-RIJEN	11282
Bdg	Bodegraven	348	CABAUW	17481
Bdpb	Breda-Prinsenbeek	350	GILZE-RIJEN	15547

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Table F.1 – *Continued from previous page*

Railway station		***Weather station***		***Distance***
Abbreviation	**Name**	**Number**	**Name**	**(m)**
Bet	Best	370	EINDHOVEN	6622
Bgn	Bergen op Zoom	340	WOENSDRECHT	5924
Bhv	Bilthoven	260	DE BILT	3718
Bkl	Breukelen	260	DE BILT	15192
Bl	Beilen	279	HOOGEVEEN	12189
Bnk	Bunnik	260	DE BILT	4230
Br	Blerick	391	ARCEN	14271
Brd	Barendrecht	344	ROTTERDAM	13998
Bsk	Boskoop	215	VOORSCHOTEN	15986
Btl	Boxtel	370	EINDHOVEN	15374
Bv	Beverwijk	257	WIJK AAN ZEE	4766
Cas	Castricum	257	WIJK AAN ZEE	5818
Cl	Culemborg	356	HERWIJNEN	11232
Cps	Capelle Schollevaar	344	ROTTERDAM	9450
Db	Driebergen-Zeist	260	DE BILT	6623
Ddr	Dordrecht	344	ROTTERDAM	22982
Ddzd	Dordrecht Zuid	344	ROTTERDAM	24585
Dmn	Diemen	240	SCHIPHOL	12338
Dmnz	Diemen Zuid	240	SCHIPHOL	11365
Dn	Deurne	375	VOLKEL	23316
Dr	Dieren	275	DEELEN	15797
Dron	Dronten	269	LELYSTAD	16053
Dt	Delft	344	ROTTERDAM	7957
Dtz	Delft Zuid	344	ROTTERDAM	6491
Dv	Deventer	278	HEINO	20863
Dvc	Deventer Colmschate	278	HEINO	20785
Dvd	Duivendrecht	240	SCHIPHOL	9978
Dvnk	De Vink	215	VOORSCHOTEN	1495
Ed	Ede-Wageningen	275	DEELEN	14046
Ehs	Eindhoven Strijp-S	370	EINDHOVEN	5469
Ehv	Eindhoven	370	EINDHOVEN	7292
Eml	Ermelo	269	LELYSTAD	18555
Esk	Enschede Kennispark	290	TWENTHE	5396
Est	Elst	275	DEELEN	15529
Gd	Gouda	348	CABAUW	16081
Gdg	Gouda Goverwelle	348	CABAUW	13645
Gdm	Geldermalsen	356	HERWIJNEN	9015
Gerp	Groningen Europapark	280	EELDE	8883
Gp	Geldrop	370	EINDHOVEN	12537
Gv	Den Haag HS	215	VOORSCHOTEN	11147
Gvm	Den Haag Mariahoeve	215	VOORSCHOTEN	7270
Gvmw	Den Haag Moerwijk	215	VOORSCHOTEN	13081
Gw	Grou-Jirnsum	270	LEEUWARDEN	15759
Gz	Gilze-Rijen	350	GILZE-RIJEN	2076
Hd	Harderwijk	269	LELYSTAD	15027

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Table F.1 – *Continued from previous page*

Railway station		***Weather station***		***Distance***
Abbreviation	**Name**	**Number**	**Name**	**(m)**
Hde	t Harde	278	HEINO	24971
Hdrz	Den Helder Zuid	235	DE KOOY	1236
Hfd	Hoofddorp	240	SCHIPHOL	6679
Hgl	Hengelo	290	TWENTHE	6757
Hgv	Hoogeveen	279	HOOGEVEEN	6999
Hil	Hillegom	240	SCHIPHOL	15373
Hk	Heemskerk	257	WIJK AAN ZEE	5812
Hlms	Haarlem Spaarnwoude	240	SCHIPHOL	10735
Hlo	Heiloo	257	WIJK AAN ZEE	12321
Hm	Helmond	370	EINDHOVEN	19950
Hmbh	Helmond Brouwhuis	375	VOLKEL	20967
Hmbv	Helmond Brandevoort	370	EINDHOVEN	16018
Hmh	Helmond ’t Hout	370	EINDHOVEN	17708
Hr	Heerenveen	273	MARKNESSE	28817
Hrn	Haren	280	EELDE	6083
Hrt	Horst-Sevenum	391	ARCEN	13371
Ht	s-Hertogenbosch	356	HERWIJNEN	21338
Htn	Houten	260	DE BILT	7389
Htnc	Houten Castellum	260	DE BILT	9238
Hto	s-Hertogenbosch Oost	356	HERWIJNEN	21260
Hwd	Heerhugowaard	249	BERKHOUT	10931
Hwzb	Halfweg-Zwanenburg	240	SCHIPHOL	8104
Hze	Heeze	370	EINDHOVEN	15247
Kma	Krommenie-Assendelft	257	WIJK AAN ZEE	10316
Kpnz	Kampen Zuid	273	MARKNESSE	18989
Laa	Den Haag Laan v NOI	215	VOORSCHOTEN	9473
Ldl	Leiden Lammenschans	215	VOORSCHOTEN	3849
Lls	Lelystad Centrum	269	LELYSTAD	6400
Mas	Maarssen	260	DE BILT	10749
Mdb	Middelburg	310	VLISSINGEN	6051
Mp	Meppel	273	MARKNESSE	20924
Mz	Maarheeze	377	ELL	14968
Nm	Nijmegen	375	VOLKEL	22858
Nmd	Nijmegen Dukenburg	375	VOLKEL	19373
Nmgo	Nijmegen Goffert	375	VOLKEL	20362
Nml	Nijmegen Lent	275	DEELEN	21636
Ns	Nunspeet	269	LELYSTAD	20459
Nvp	Nieuw Vennep	240	SCHIPHOL	11834
Nwk	Nieuwerkerk a/d IJssel	344	ROTTERDAM	11662
Obd	Obdam	249	BERKHOUT	6153
Odb	Oudenbosch	340	WOENSDRECHT	20355
Ost	Olst	278	HEINO	14931
Ot	Oisterwijk	350	GILZE-RIJEN	17952
Otb	Oosterbeek	275	DEELEN	7157
Ow	Oss West	375	VOLKEL	17739

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Table F.1 – *Continued from previous page*

Railway station		***Weather station***		***Distance***
Abbreviation	**Name**	**Number**	**Name**	**(m)**
Pmo	Purmerend Overwhere	249	BERKHOUT	14780
Pmr	Purmerend	249	BERKHOUT	15784
Pmw	Purmerend Weidevenne	249	BERKHOUT	16670
Pt	Putten	269	LELYSTAD	21811
Rai	Amsterdam RAI	240	SCHIPHOL	7150
Rlb	Rotterdam Lombardijen	344	ROTTERDAM	10812
Rm	Roermond	377	ELL	16136
Rsd	Roosendaal	340	WOENSDRECHT	12971
Rsn	Rijssen	278	HEINO	22408
Rsw	Rijswijk	344	ROTTERDAM	12313
Rta	Rotterdam Alexander	344	ROTTERDAM	7399
Rtb	Rotterdam Blaak	344	ROTTERDAM	5462
Rtd	Rotterdam Centraal	344	ROTTERDAM	4384
Rtn	Rotterdam Noord	344	ROTTERDAM	3241
Rtz	Rotterdam Zuid	344	ROTTERDAM	7740
Rvs	Ravenstein	375	VOLKEL	15827
Sdm	Schiedam Centrum	344	ROTTERDAM	5233
Sgn	Schagen	235	DE KOOY	16064
Shl	Schiphol	240	SCHIPHOL	2134
Std	Sittard	380	MAASTRICHT	12622
Swk	Steenwijk	273	MARKNESSE	18170
Tb	Tilburg	350	GILZE-RIJEN	10233
Tbr	Tilburg Reeshof	350	GILZE-RIJEN	4132
Tbu	Tilburg Universiteit	350	GILZE-RIJEN	7966
Tpsw	Tiel Passewaaij	356	HERWIJNEN	17006
Ut	Utrecht Centraal	260	DE BILT	4926
Utg	Uitgeest	257	WIJK AAN ZEE	6908
Utlr	Utrecht Leidsche Rijn	260	DE BILT	7849
Uto	Utrecht Overvecht	260	DE BILT	3940
Utt	Utrecht Terwijde	260	DE BILT	9460
Utzl	Utrecht Zuilen	260	DE BILT	6164
Vb	Voorburg	215	VOORSCHOTEN	9828
Vg	Vught	370	EINDHOVEN	23520
Vss	Vlissingen Souburg	310	VLISSINGEN	2530
Vst	Voorschoten	215	VOORSCHOTEN	1777
Vtn	Vleuten	260	DE BILT	11573
Wad	Waddinxveen	344	ROTTERDAM	16633
Wadn	Waddinxveen Noord	344	ROTTERDAM	17248
Wd	Woerden	348	CABAUW	12992
Wdn	Wierden	290	TWENTHE	22573
Wf	Wolfheze	275	DEELEN	7817
Wm	Wormerveer	257	WIJK AAN ZEE	12960
Wp	Weesp	240	SCHIPHOL	17231
Wt	Weert	377	ELL	6992
Wv	Wolvega	273	MARKNESSE	21271

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Table F.1 – *Continued from previous page*

Railway station		***Weather station***		***Distance***
Abbreviation	**Name**	**Number**	**Name**	**(m)**
Ypb	Den Haag Ypenburg	215	VOORSCHOTEN	10022
Zbm	Zaltbommel	356	HERWIJNEN	9811
Zd	Zaandam	240	SCHIPHOL	13553
Zdk	Zaandam Kogerveld	240	SCHIPHOL	15573
Zl	Zwolle	278	HEINO	13732
Zlw	Lage Zwaluwe	350	GILZE-RIJEN	23446
Zp	Zutphen	275	DEELEN	24106
Ztm	Zoetermeer	344	ROTTERDAM	9741
Ztmo	Zoetermeer Oost	344	ROTTERDAM	9904
Zvb	Zevenbergen	350	GILZE-RIJEN	24076
Zwd	Zwijndrecht	344	ROTTERDAM	21134

Table F.1: Straight-line distance in metres between railway station and closest KNMI weather station

Appendix G

Queue formation at escalators: validation

(a) 08:41:15

(b) 08:41:16

(c) 08:41:17

(d) 08:41:18

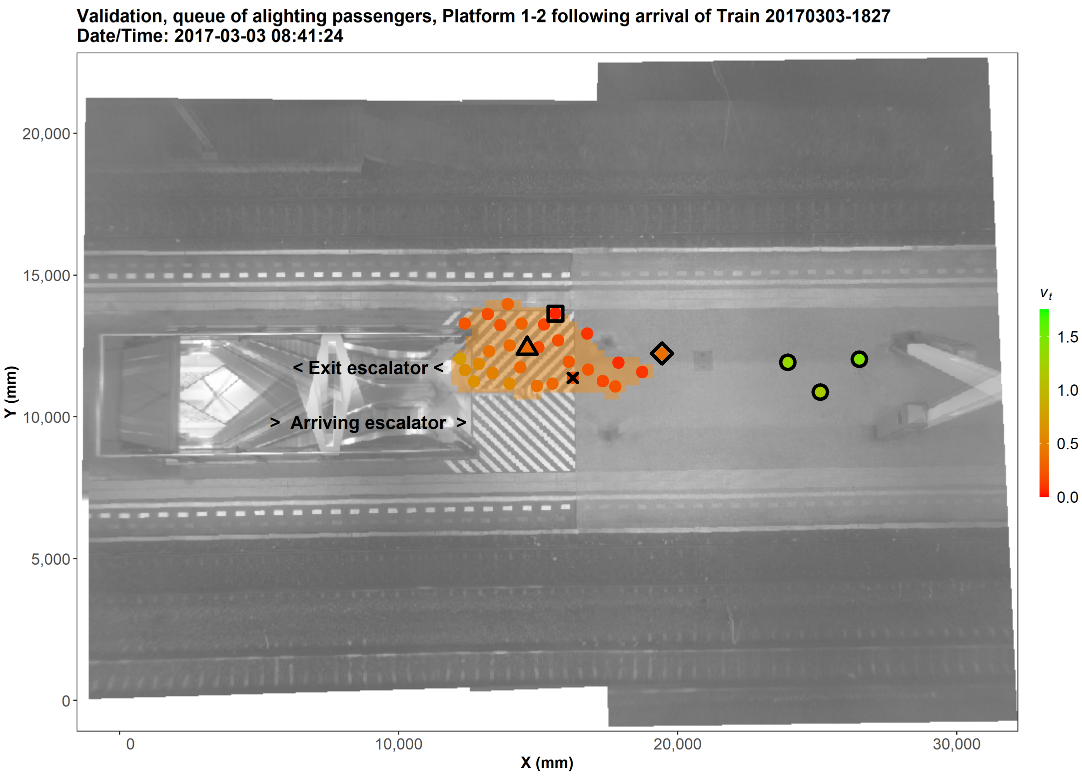
(e) 08:41:19

(f) 08:41:20

(g) 08:41:21

(h) 08:41:22

(i) 08:41:23



(j) 08:41:24

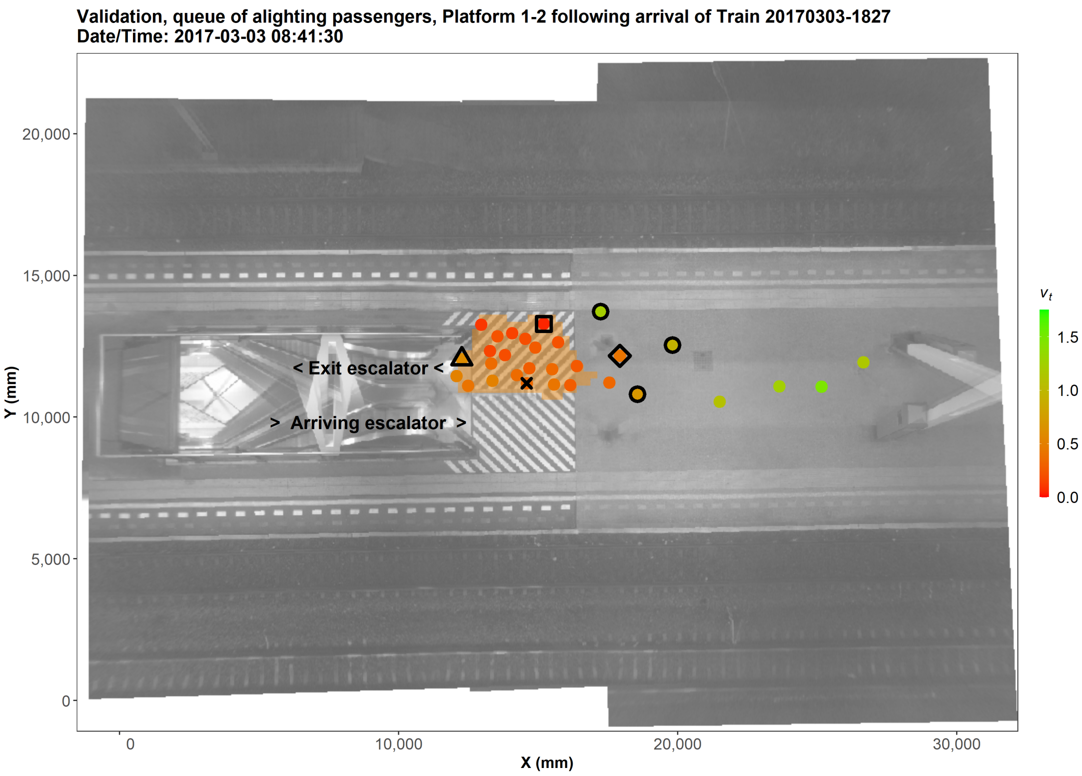
(k) 08:41:25

(l) 08:41:26

(m) 08:41:27

(n) 08:41:28

(o) 08:41:29



(p) 08:41:30

Figure G.1: Queue validation, descending pedestrians, following the arrival of Train 20170303-1827, Platform 1-2

Appendix H

Segments, sample sizes and distributions for platform-edge analyses

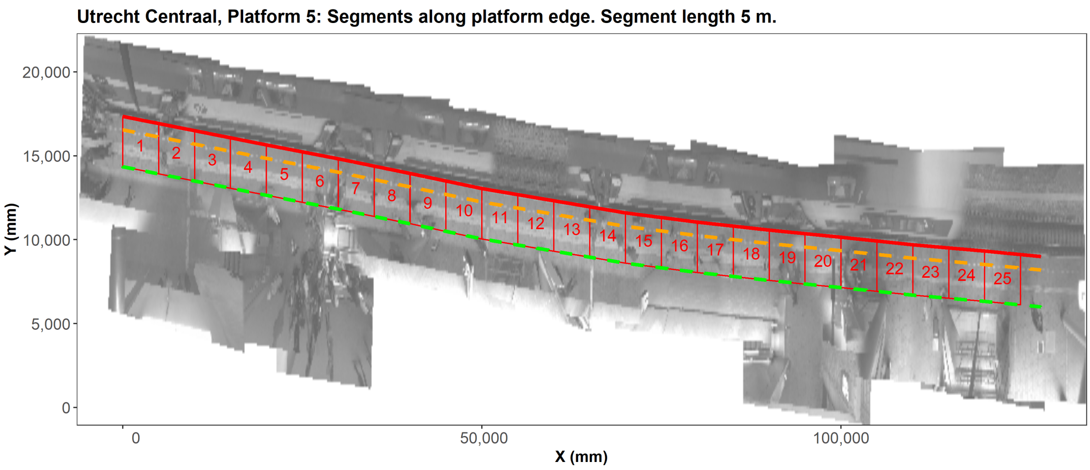


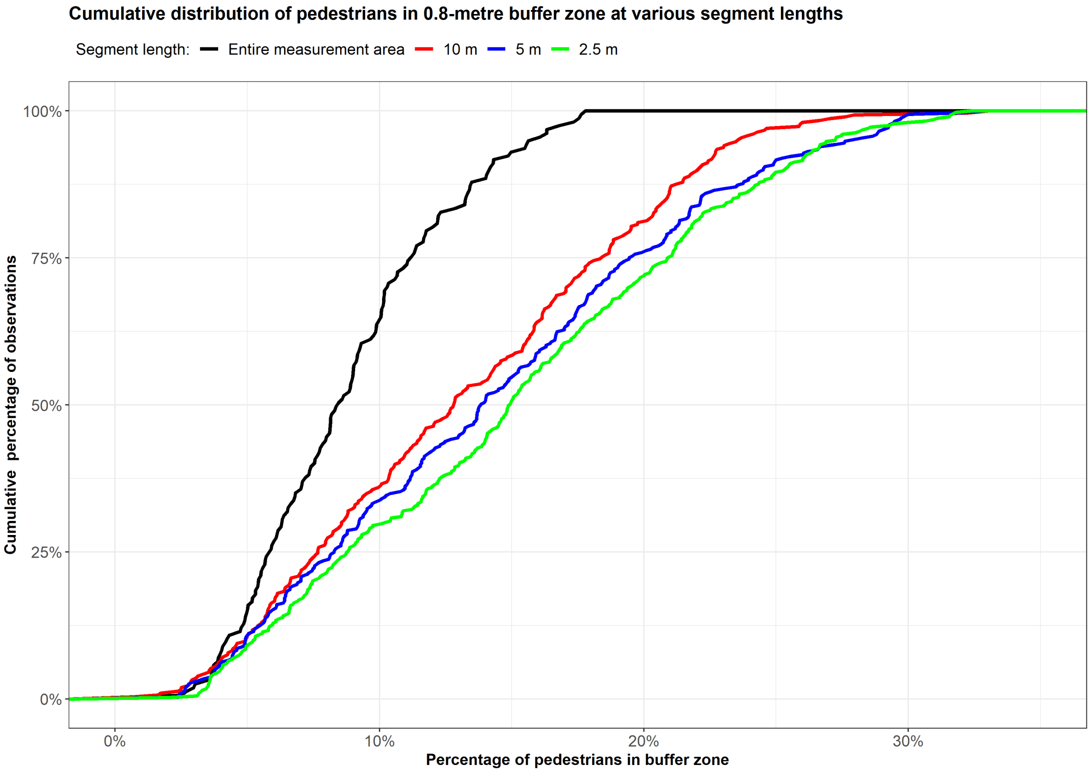
Figure H.1: Segment numbers, Platform 5, Utrecht Centraal, segment length = 5 m

Segment No.	1	2	3	4	5	6	7	8	9	10	11	12
Density												
0.07	2328	1085	693	852	772	477	645	1024	1172	1396	1591	1709
0.13	1084	1120	858	1109	980	785	855	1179	1286	1360	1374	1370
0.20	420	952	853	1005	1037	849	855	1113	1119	1038	911	840
0.27	140	769	780	843	894	842	797	959	820	707	642	518
0.33	36	582	679	670	699	747	732	655	546	446	358	331
0.40	10	444	602	495	555	660	660	440	399	306	258	213
0.47	2	299	469	363	401	563	460	321	235	229	143	106
0.53	0	202	358	275	306	426	414	206	175	145	97	73
0.60	0	161	252	182	227	350	307	138	128	89	60	47
0.67	0	109	206	144	167	242	214	91	82	52	41	23
0.73	0	64	165	120	114	189	163	59	50	34	24	16
0.80	0	60	131	80	84	124	104	40	32	20	16	9
0.87	0	34	93	52	53	98	68	27	32	13	12	7
0.93	0	19	50	33	32	73	48	14	9	10	8	4
1	0	9	48	28	30	37	21	8	12	6	9	2
1.07	0	5	27	24	9	26	13	5	7	4	0	3
1.13	0	3	18	9	7	16	12	2	4	5	1	2
1.20	0	4	11	9	9	8	14	3	2	1	4	2
1.27	0	0	5	3	3	3	1	4	2	2	2	2
1.33	0	1	4	1	4	3	1	1	3	3	3	2
1.40	0	1	2	1	2	1	1	0	2	0	1	1
1.47	0	2	2	1	1	1	2	1	1	2	4	3
1.53	0	1	2	0	2	5	0	0	2	0	0	1
1.60	0	1	3	3	2	2	2	0	0	1	0	1
1.67	0	0	0	2	0	0	2	0	0	3	0	1
1.73	0	2	0	1	2	1	0	1	0	2	0	1
1.80	0	0	1	1	0	2	1	0	1	0	1	0
1.87	0	3	2	2	2	1	1	1	0	0	1	0
1.93	0	1	0	1	1	1	1	0	1	0	0	0
2	0	0	1	0	2	2	0	1	0	1	0	0

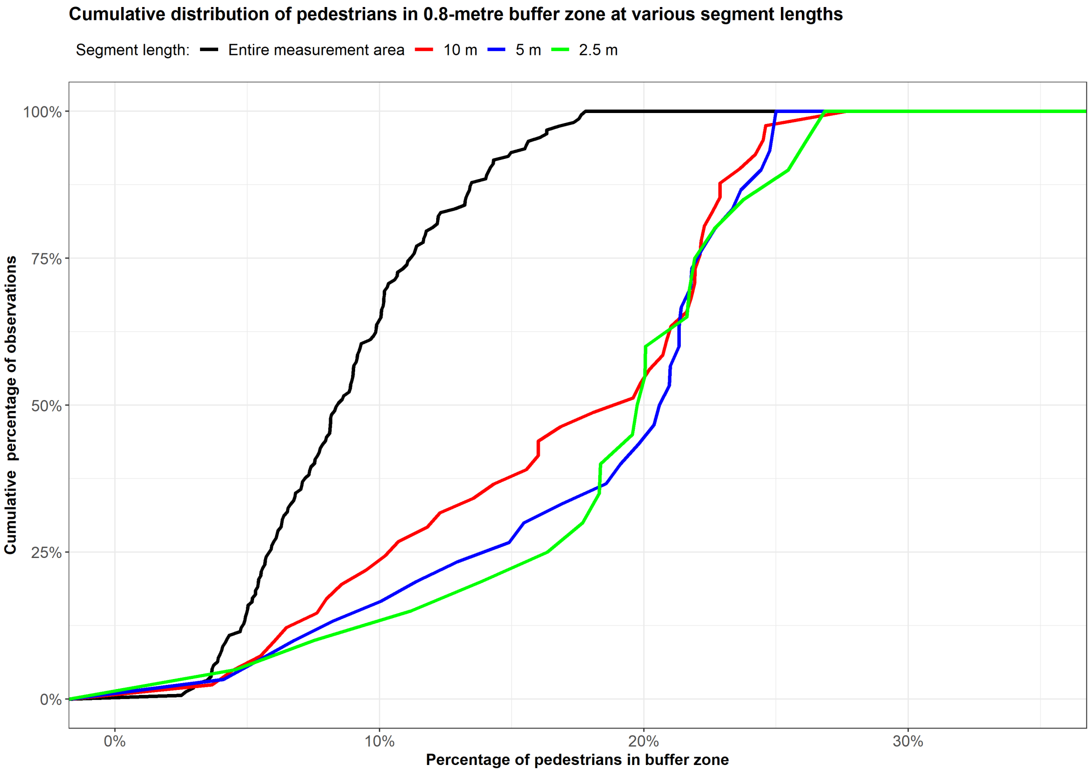
Table H.1: Number of stops per density value per segment, segment length = 5 m (continued in Table H.2)

Segment No. Density	13	14	15	16	17	18	19	20	21	22	23	24	25	Total
0.07	1821	1677	1716	1620	1384	1355	973	1092	1198	1004	1101	1786	1551	32133
0.13	1226	1215	1193	1188	1251	1198	951	1004	1048	872	938	1062	790	27296
0.20	783	748	763	777	842	914	758	981	849	782	618	564	448	20819
0.27	464	514	449	473	634	672	679	796	733	600	454	359	262	15800
0.33	296	319	286	301	383	447	529	498	488	457	309	233	157	11184
0.40	172	198	210	221	281	325	453	373	406	359	231	168	62	8501
0.47	113	143	152	157	181	227	363	316	289	280	170	119	52	6153
0.53	52	92	118	100	143	166	257	200	214	195	113	63	23	4413
0.60	39	64	63	71	88	96	178	158	136	142	66	40	16	3098
0.67	19	38	42	42	70	82	174	101	120	125	34	27	6	2251
0.73	26	24	33	30	46	47	132	76	69	87	29	22	5	1624
0.80	5	11	18	18	30	19	76	49	72	52	22	15	1	1088
0.87	7	12	7	12	10	26	56	16	54	46	9	6	0	750
0.93	4	8	10	4	4	10	46	23	26	37	6	2	2	482
1	4	4	3	2	2	5	35	12	23	27	5	3	1	336
1.07	4	4	4	2	6	4	22	12	12	17	9	1	1	221
1.13	1	1	3	2	0	3	19	6	13	11	1	1	0	140
1.20	1	4	2	0	5	3	7	3	2	11	3	0	0	108
1.27	1	0	1	3	2	1	5	1	5	7	0	1	0	54
1.33	1	1	1	5	2	0	9	1	3	2	1	0	0	52
1.40	2	3	1	0	2	2	4	0	1	4	2	0	0	33
1.47	3	0	0	0	1	2	1	3	1	0	1	0	0	32
1.53	0	0	1	0	0	2	3	3	2	2	0	0	0	26
1.60	0	0	1	2	0	2	5	3	0	1	0	0	0	29
1.67	0	1	0	0	0	0	0	1	2	0	0	0	0	12
1.73	0	1	1	1	1	1	0	0	3	1	0	0	0	19
1.80	0	0	0	0	1	0	3	2	1	2	0	0	0	16
1.87	0	0	0	0	1	0	1	1	0	1	0	0	0	17
1.93	0	0	0	0	0	1	3	0	1	2	0	0	0	13
2	0	0	0	0	0	3	0	1	0	2	0	0	0	13

Table H.2: Number of stops per density value per segment, segment length = 5 m (continued from Table H.1)



(a) Percentages as a function of density ρ and segment *s*



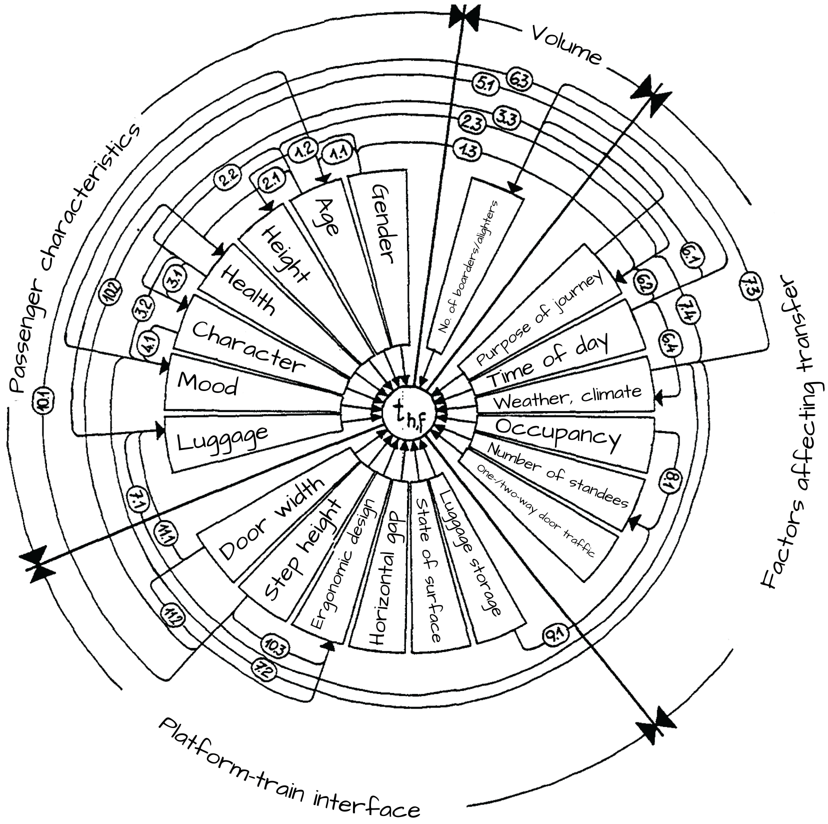
(b) Percentages as a function of density ρ (all segments)

Figure H.2: Cumulative distribution of pedestrians in 0.8-metre buffer zone at various segment lengths

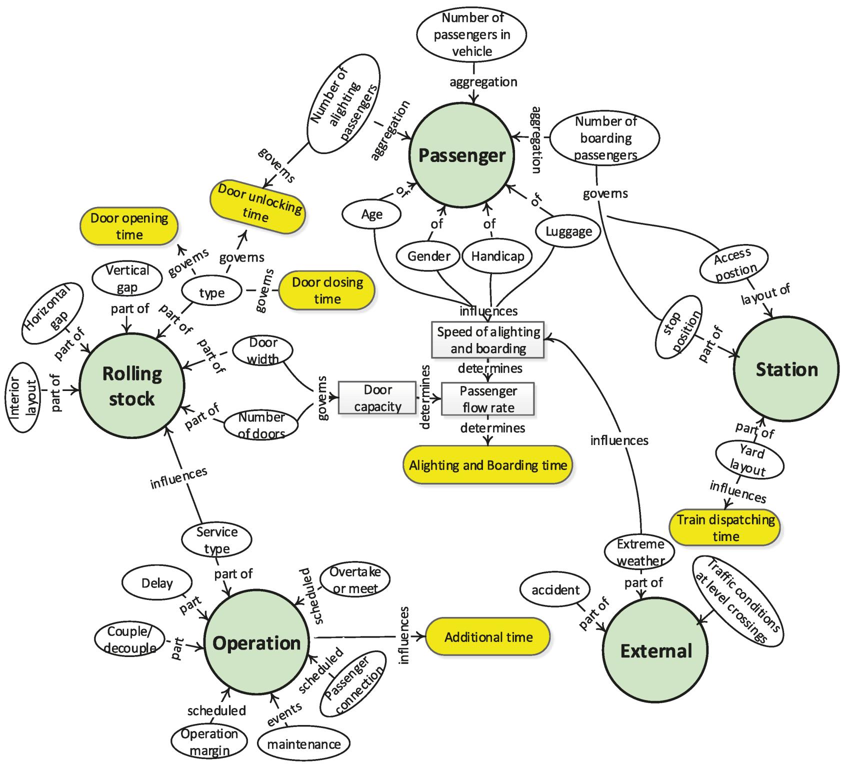
Appendix I

Existing models of passenger-dependent dwell time

I.1 Conceptual models from earlier research



(a) Weidmann [113]



(b) Li et al. [195]

Figure I.1: Conceptual models from earlier research

I.2 Regression models from earlier research

To enable comparison between the different models, the notation for the commonly-used model parameters has been standardized. See Table I.1 below. Table I.2 at the end of this appendix presents a summary of the models from earlier research described below.

Parameter	Definition
t_T	Vehicle dwell time
t_{Di}	Dwell time for passenger service at door *i*
t_{Dgem}	Dwell time for passenger service at average door
t_{Dmax}	Dwell time for passenger service at dimensioning door
d	Number of doors in vehicle (usually on one side)
I_t	Number of boarders per vehicle
U_t	Number of alighters per vehicle
A_t	Number of standing passengers per vehicle before stop (on arrival)
U_t	Number of standing passengers per vehicle following stop (on departure)
I_d	Number of boarders per door
U_d	Number of alighters per door
β_0	Constant component of dwell time
β_1	Coefficient for boarder parameter (process time per unit)
β_2	Coefficient for alighter parameter (process time per unit)
β_3	Coefficient for standing passenger parameter, (process time per unit)
β_4 β_5	Coefficient for interaction (friction) between alighters and boarders
$\beta_{1;2}$	Coefficient for alighter and boarder parameter
α_1	Power coefficient for boarder parameter
α_2	Power coefficient for alighter parameter

Table I.1: Standardized definitions of parameters and coefficients

Equation I.1 is the result of research by Dirmeier [175], based on measurements made during 270 stops by three-car trains, each with a total length of 65 m, on the Frankfurt S-Bahn (Germany) around 1978. The exact dates are not mentioned, nor are the stations involved. The equation applies to the busiest door, and the assumption is that passenger service time at that door determines dwell time. The researcher recommends assigning a fixed value to the constant of 2 seconds between the train coming to a halt and the first passenger alighting, and 16 seconds between the end of the boarding process and the time at which the train starts to move.

$$t_T = t_{Dmax} = \beta_0 + \beta_1 I_d + \beta_2 U_d \tag{I.1}$$

On the basis of a study of dwell times on the light rail network in Calgary (Canada) – which at that time used three- and two-car trains with total lengths of 50 or 75 m – Wirasinghe and Szplett [169] [168] propose an equation (Equation I.2) for passenger service time at door *i* as a function of a constant, the number of boarders, the number of alighters and coefficients for the average service time per boarder and alighter. The values of these coefficients are determined by the percentage of total alighters and boarders at door (ψ_{di}) that is accounted for by boarders. A distinction is made between three situations ((ψ_d; β_1; β_2): alighting flow dominant ($\psi_d < 33\%$; β_1 = 2.4; β_2 = 1), alighting and boarding flows approximately balanced ($33\% \leq \psi_d \leq 67\%$; β_1 = 1.4; β_2 = 0.4)) and boarding flow dominant ($\psi_d > 67\%$; $\beta_1 = \beta_2$ = 1.4)). Constant: β_0 = 2.

$$t_{Di} = \beta_0 + \beta_1(\psi_d)U_d + \beta_2(\psi_d)I_d \tag{I.2}$$

To calculate dwell time (Equation I.3), the researchers calculated the number of passengers at the busiest door at two stations, on the basis of the distribution of passengers over all the doors of the train [169]. One station has an island platform with a single entrance at one end, whereas the other station has a side-loading platform with several entrances, distributed along the full length of the platform.

$$t_T = t_{Dmax} = max(t_{Di}) = \beta_0 + [\beta_1(\psi_d)\psi_t + \beta_2(\psi_d)(1-\psi_t)]\frac{I_t + U_t}{d}E[\Phi_d] \tag{I.3}$$

$$\psi_t = f\frac{I_t}{I_t + U_t} \tag{I.4}$$

On the basis of statistical analyses of their empirical data, Wirasinghe and Szplett established that it is necessary to multiply ψ_t (Equation I.4) by a factor f of 1.15 in the case of platforms with a single entrance at one end (i.e. the case in which all passengers have to walk to or from one or both ends of the train to leave the platform), in order to obtain a representative fraction of boarders at the busiest door (ψ_d). For platforms with multiple entrances, this factor is 1. The factor accounts for the fact that boarders do not distribute themselves evenly along the platform, but are concentrated near the platform entrance.

The researchers also discovered that the distribution of passengers along the train could be modelled by a negative exponential distribution in the case of the platform with an entrance at one end and by a normal distribution in the case of the platform with multiple entrances. On this basis, they derive an expected value for the ratio (Φ_d) between the number of passengers at the busiest door and the mean number of passengers per door (on the basis of the number of doors in the train, d). The researchers propose Equation I.5 for the negative exponential distribution. For the normal distribution, they refer to Gumbel [**?**].

$$E[\Phi_d] = \ln d + 0.58 \tag{I.5}$$

Lin [179] and Lin and Wilson [180] estimated a large number of regression models on the basis of data from the *Green Line* of the *Massachusetts Bay Transportation Authority* (MBTA). This line is part of the light rail network of Boston, USA. The data covers 122 stops made by one-car trains (25 m) and 51 stops made by two-car trains (approximately 50 m) in spring 1988 and 1989.

The independent variables for the linear models were the number of boarders (I_t), number of alighters (U_t), number of standing passengers on arrival (A_t) and number of standing passengers on departure (V_t), for the entire train. For certain models, the last two of these variables were used as a measure of crowding in the vehicle, yielding Equations I.6 and I.7.

$$t_T = \beta_0 + \beta_1 I_t + \beta_2 U_t + \beta_3 A_t \tag{I.6}$$

$$t_T = \beta_0 + \beta_1 I_t + \beta_2 U_t + \beta_3 V_t \tag{I.7}$$

For other regression models, Lin and Wilson constructed a crowding term from the sum of the product of (1) the number of alighters and the number of standees on arrival and (2) the number of boarders and the number of standees on departure. This resulted in Equation I.8, which was deemed to be a good model on the basis of the explained variation (*adjusted* R^2). Lin and Wilson indicate that the station does not affect dwell time. By contrast, the differences in the estimated coefficients for the one-car and two-car trains indicated that distribution of passengers along the train did have a significant effect.

$$t_T = \beta_0 + \beta_1 I_t + \beta_2 U_t + \beta_3 (I_t V_t + U_t A_t) \tag{I.8}$$

In their study using data from almost 7,000 observations on the Stuttgart S-Bahn, Hennige and Weiger [181] found that peak-time passengers require an average of 0.81 s to board or alight. The trains were either "short" (one train set, 65 m, 12 doors per side) or "long" (three sets). Each observation covered all the doors of one set. In the case of long trains, the set used was varied. The implicit assumption was that the set from which the observation was taken determined the dwell time of the train. A value of 13 s was found for the constant component of dwell time (β_0 = 13). Hennige and Weiger's work resulted in Equation I.9.

$$t_T = \beta_0 + \beta_{1;2}(I_t + U_t) \tag{I.9}$$

Weidmann [113] built up his generic model of dwell time for public transport – bus, tram, metro and train – from a partial model per door, a partial model per stop and a partial model for all stops in a single trip. The last two models serve as the basis for the previous model or for the two previous models. Following extensive research, Weidmann identified the following as independent variables for dwell time:

- The number of passengers alighting and boarding
- Door width (b_{di})
- Door capacity per linear metre (c_{di})
- A large number of parameters, which were merged into one general parameter (F). Those parameters were: difference in height between platform and vehicle, passenger density in the vehicle in the vicinity of the doors, door capacity usage rate, door width, number of doors and distribution of passengers over the doors. In turn, those parameters were dependent upon the number of alighters and boarders. Certain parameters were also dependent on each other.

Equation I.10 is a highly simplified form of Weidmann's model. In the introduction to his thesis, Weidmann writes that the passenger service time is the most uncertain element and hence the most difficult to predict [113]. Later in his thesis, he emphasizes the importance of good data. Wiggenraad [193] and Lehnhoff & Janssen [184] express the same idea in different words. Their research shows that passenger service time can account for very different percentages of total dwell time.

$$t_T = \frac{I_t + U_t}{\sum b_{di} c_{di}} F \tag{I.10}$$

In their standard work produced for practical use, Parkinson & Fisher [104] describe generic models for passenger service time at the dimensioning door. Their models are based on regression analyses using empirical data from eight rail systems in the US and Canada. The researchers transformed the independent variable to obtain a good fit. The researchers propose three different models, for the following situations: mainly boarding (Equation I.11), mainly alighting (Equation I.12) and mixed (Equation I.13).

$$ln(t_{Dmax}) = \beta_0 + \beta_{1a} I_t - \beta_{1b} I_t^2 \tag{I.11}$$

$$ln(t_{Dmax}) = \beta_0 + \beta_{2a} U_t - \beta_{2b} U_t^2 \tag{I.12}$$

$$ln(t_{Dmax}) = \beta_0 + \beta_{2a} U_t - \beta_{1a} I_t - \beta_{2b} U_t^2 - \beta_{1b} U_t^2 \tag{I.13}$$

Lam et al. [182] used 40 to 45 observations from each of three stations in Hong Kong (1998) to estimate the model in Equation I.14, for eight-car metro trains with five doors per car. In contrast to Lin and Wilson, Lam et al. concluded on the basis of correlation and regression analysis that crowding on board the vehicles was not a determining factor. It is not clear from the above publication how they reached this conclusion. One year later, the same authors repeated the procedure for two other stations in Hong Kong, using 80 to 90 observations per station [183]. This study also resulted in a regression model in the form of Equation I.14. Vuchic proposes the same function in his standard work [114].

$$t_T = \beta_0 + \beta_1 I_t + \beta_2 U_t \tag{I.14}$$

As a follow-up to the work of Lin and Wilson, Puong [197] used data from 54 stops at two MBTA *Red Line* stations to estimate a regression model I.15 that took a different approach to modelling crowding on board the train. The independent variables in this model are the number of alighters, boarders and standees at time of departure, for each door. Because the congestion factor plays a greater role in this model, on-board congestion will strongly influence dwell time if there are large numbers of standees. The researcher acknowledges that using average values per door results in under-estimation of dwell times, as passengers are not evenly distributed over the doors in practice. He therefore states that the results of his model will describe the lower end of the actual range of dwell times.

$$t_T = t_{Dgem} = \beta_0 + \beta_1 \frac{I_t}{d} + \beta_2 \frac{U_t}{d} + \beta_3 (\frac{V_t}{d})^3 \frac{I_t}{d} \tag{I.15}$$

Harris [185] [**?**] investigated whether the London Underground dwell time model used for their system gave valid results for the very busy trains on the overground network covering the area south-west of London (*South West Trains*). The model takes the form of Equation I.16, where H_t is the number of standing passengers in the vehicle (excluding alighters and boarders), the coefficient γ is a constant, coefficient F is a peak door/average door factor, coefficient β_5 describes the interaction between alighters and boarders and coefficient δ is used to correct for differences in door widths and space around the doors by comparison with the reference vehicle type. In his 2006 work [185], Harris takes a value of 1.4 for γ and shows that the standard value for β_5 (0.027) leads to over-estimates at high numbers of alighters and boarders. He states that the value of 0.011 found in other research gives better results. This model uses power coefficients α_1 and α_2 to render the average time per boarder and alighter dependent on the number of boarders and alighters. In his 2007 publication [**?**], Harris states that while a value of 0.7 is used for α_1 and α_2 in the case of the London Underground, the values of those two coefficients can range from 0.45 to 0.9 and 0.7 to 0.9 respectively in other situations. Harris does not explicitly include coefficients β_1 and β_2 in his model; they have been added to Equation I.16 to facilitate comparison between this model and others. In this instance, both coefficients have a value of 1.

$$t_T = t_{Dmax} = \beta_0 + \left[\gamma(1+\frac{F}{35})\frac{H_t}{d}\right]\cdot\left[\beta_1\left(F\frac{I_t}{d}\right)^{\alpha_1} + \beta_2\left(F\frac{U_t}{d}\right)^{\alpha_2} + \beta_5\left(F\frac{I_t}{d}\right)\left(F\frac{U_t}{d}\right)\right]\delta \tag{I.16}$$

Douglas [198] developed the model in Equation I.17 on the basis of the regression models proposed by Puong [197] and Harris [185] [**?**]. In a manner analogous to that of Puong, Douglas includes a congestion factor in his model, incorporating congestion in the form of a separate block of variables with a corresponding coefficient β_3. Like Harris, he uses power coefficients α_1 and α_2 to render the average time per boarder and alighter dependent on the number of boarders and alighters. Similarly to Wirasinghe en Szplett [168], Douglas also includes the degree of interaction between alighters and boarders in his model. His approach is once again to use a block of variables with a corresponding coefficient, β_4 in this case.

$$t_T = t_{Dmax} = max(t_{Di}) = \beta_0 + \beta_1 {I_d}^{\alpha_1} + \beta_2 {U_d}^{\alpha_2} + \beta_3(U_d + I_d)H_d + \beta_4 U_d I_d \tag{I.17}$$

Name	System	Rolling stock	Coaches	Doors	Aggr	Function
Dirmeier [175]	S-Bahn Frankfurt	DB Baureihe 420	2	24	Busiest door	I.1
Wirasinghe & Szplett [168]	LRT Calgary	Siemns/Duewg U2	2/3	8/12	Busiest door	I.2 I.3 I.4 I.5
Lin & Wilson [180]	MBTA Boston	LRV	1/2	3/6	Whole vehicle	I.6 I.7 I.8
Hennige & Weiger [181]	S-Bahn Stuttgart	DB Baureihe 420	1/3	12/36	Whole vehicle	I.9
Parkinson & Fisher [104]	8 systems, USA/CDN	Various	Unk.	Unk.	Busiest door	I.11 I.12 I.13
Lam et al. [182]	MTRC Hong Kong	Metro Cammell	8	40	Whole vehicle	I.14
Lam et al. [183]	LRT Hong Kong	LRV	1	3	Whole vehicle	I.14
Puong [197]	MBTA Boston	-	6	18-24	Average door	I.15
Harris [185]	SouthWestTrains	Class 455	Test	-	Busiest door	I.16
Douglas [198]	Railcorp Australia	Millennium	Test	-	Busiest door	I.17

Table I.2: Regression models in existing research

Appendix J

Analyses of passenger-related dwell time

J.1 Puong's regression model (Equation I.15) with data for station/platform combinations

Case			***In/out range***			***Regression model coefficients***				
Station	Platform	n	min	med	max	$adj.R^2$	β_0 (SD)	β_1 (SD)	β_2 (SD)	β_3 (SD)
Hvsp	1	3575	0	3	55	0.45	43.15 (0.35)	2.26 (0.09)	1.88 (0.06)	0 (0)
Asdz	3	6199	0	8	84	0.38	41.3 (0.36)	1.89 (0.07)	1.53 (0.03)	n.s.
Asdl	1	12057	0	5	56	0.36	37.53 (0.19)	1.97 (0.04)	1.11 (0.09)	0 (0)
Shl	2	3293	0	10	63	0.36	47.61 (0.7)	2.46 (0.07)	1.89 (0.08)	n.s.
Asb	2	2543	0	7	88	0.35	40.4 (0.55)	1.6 (0.07)	1.47 (0.06)	0 (0)
Tb	1e	8070	0	8	87	0.35	48.66 (0.3)	1.55 (0.04)	1.6 (0.05)	0 (0)
Ass	8B	1385	0	5	35	0.33	31.56 (0.44)	2.2 (0.16)	1.16 (0.08)	0 (0)
Hvs	2e	2650	0	9	59	0.33	38.22 (0.56)	1.47 (0.07)	1.66 (0.09)	0 (0)
Asb	6	4941	0	5	64	0.33	36.52 (0.27)	1.57 (0.05)	1.13 (0.03)	0 (0)
Asdz	1	3711	0	12	71	0.33	42.33 (0.6)	1.69 (0.07)	1.29 (0.04)	n.s.
Ledn	9B	1484	0	12	87	0.32	51.26 (1.17)	1.74 (0.13)	1.51 (0.12)	0 (0)
Asb	7	1749	0	8	86	0.31	42.44 (0.71)	1.68 (0.07)	1.01 (0.1)	n.s.
Ass	8BA	16873	0	6	60	0.31	42.76 (0.16)	3.07 (0.06)	1.26 (0.02)	n.s.
Shl	4	3587	0	8	85	0.31	42.41 (0.46)	2.72 (0.16)	1.21 (0.04)	0 (0)
Ledn	9Bm	1676	0	10	54	0.30	53.8 (0.97)	1.41 (0.13)	1.96 (0.12)	0 (0)
Sdm	2BA	559	0	3	29	0.30	45.39 (0.84)	2.22 (0.58)	2.12 (0.25)	n.s.
Uto	2	6674	0	4	30	0.30	35.72 (0.22)	2.4 (0.09)	1.71 (0.08)	0 (0)
Ahpr	2	9060	0	1	47	0.30	42.4 (0.15)	1.01 (0.1)	1.75 (0.03)	n.s.
Asdz	4	5632	0	13	95	0.29	44.27 (0.51)	1.21 (0.04)	1.57 (0.05)	0 (0)
Asb	8	605	0	4	58	0.29	39.27 (1.74)	1.76 (0.13)	3 (0.72)	n.s.
Amf	6Am	1037	0	14	78	0.29	60.43 (1.27)	2.12 (0.12)	0.41 (0.11)	n.s.
Rtb	2	11681	0	5	56	0.29	41.37 (0.17)	1.09 (0.05)	1.96 (0.04)	0 (0)
Tb	2	2097	0	8	55	0.28	50.41 (0.68)	2.36 (0.1)	0.99 (0.07)	0 (0)
Ut	19	985	0	31	140	0.28	71.55 (2)	0.96 (0.1)	0.88 (0.09)	0 (0)
Amf	7	1878	0	7	98	0.28	54.13 (0.88)	1.48 (0.12)	2.21 (0.13)	n.s.
Dt	1	20499	0	7	75	0.27	41.19 (0.16)	1.44 (0.03)	1.42 (0.04)	0 (0)

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Table J.1 – *Continued from previous page*

Case			***In/out range***			***Regression model coefficients***				
Station	Platform	n	min	med	max	$adj.R^2$	β_0 (SD)	β_1 (SD)	β_2 (SD)	β_3 (SD)
Ut	5	1633	0	26	138	0.27	82.23 (1.36)	0.89 (0.09)	0.93 (0.09)	0 (0)
Hfd	1	12640	0	5	62	0.27	38.72 (0.15)	1.4 (0.04)	0.99 (0.03)	0 (0)
Shl	5	5200	0	12	73	0.27	52.89 (0.55)	1.63 (0.06)	1.47 (0.04)	0 (0)
Bd	8	717	0	11	84	0.27	57.06 (1.4)	1.27 (0.18)	1.49 (0.16)	n.s.
Ledn	8B	1338	0	20	86	0.26	60.47 (1.51)	1 (0.09)	1.78 (0.13)	0 (0)
Gv	5AB	980	0	5	45	0.26	46.87 (0.93)	2.06 (0.22)	1.97 (0.21)	n.s.
Sdm	5AB	22648	0	4	36	0.26	37.21 (0.12)	1.86 (0.03)	1.69 (0.05)	0 (0)
Hvs	3e	4598	0	8	56	0.26	44.7 (0.46)	1.16 (0.1)	1.8 (0.05)	n.s.
Ass	4AB	3503	0	8	54	0.26	41.26 (0.43)	1.25 (0.05)	0.99 (0.09)	0 (0)
Rtb	3	7790	0	4	38	0.26	35.8 (0.2)	1.86 (0.05)	1.02 (0.04)	0 (0)
Htn	1	13814	0	3	33	0.26	36.88 (0.14)	1.58 (0.04)	1.75 (0.1)	0 (0)
Laa	5	4597	0	6	44	0.26	45.25 (0.43)	1.54 (0.14)	1.9 (0.08)	0 (0)
Ass	7AB	9000	0	5	44	0.26	42.46 (0.25)	0.85 (0.04)	2.89 (0.07)	0 (0)
Laa	6	6503	0	5	44	0.26	39.36 (0.34)	1.76 (0.09)	2.04 (0.15)	0 (0)
Hnk	2	1186	0	8	34	0.25	40.51 (0.54)	0.85 (0.04)	0.51 (0.09)	n.s.
Hfd	4A	2306	0	4	53	0.25	46.38 (0.49)	1.29 (0.1)	1.62 (0.12)	0 (0)
Hlm	3AmB	1297	0	11	61	0.25	52.45 (1.22)	0.97 (0.08)	1.01 (0.2)	0 (0)
Shl	3	2399	0	6	46	0.25	47.41 (0.7)	2.02 (0.09)	2.07 (0.19)	0 (0)
Asa	4	13775	0	6	61	0.25	38.33 (0.18)	1.17 (0.02)	1.08 (0.06)	0 (0)
Hwd	2	601	0	3	18	0.24	43.34 (0.67)	0.97 (0.4)	1.7 (0.13)	n.s.
Ypb	1	5874	0	2	16	0.24	44.63 (0.2)	3.48 (0.14)	1.72 (0.12)	0 (0)
Ass	5BA	6147	0	8	60	0.24	44.05 (0.31)	0.99 (0.06)	1.04 (0.03)	n.s.
Dt	2	21861	0	6	61	0.24	41.53 (0.15)	1.36 (0.05)	1.23 (0.03)	0 (0)
Tbu	1	3358	0	3	53	0.24	43.4 (0.29)	1.86 (0.09)	0.88 (0.06)	0 (0)
Shl	6	5262	0	12	72	0.24	53.59 (0.55)	1.32 (0.06)	1.48 (0.04)	0 (0)

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Table J.1 – *Continued from previous page*

Case			***In/out range***			***Regression model coefficients***				
Station	Platform	n	min	med	max	$adj.R^2$	β_0 (SD)	β_1 (SD)	β_2 (SD)	β_3 (SD)
Hlm	1A	2156	0	7	85	0.23	54.26 (0.65)	1.21 (0.13)	1.39 (0.17)	0 (0)
Shl	1	3153	0	10	53	0.23	52.71 (0.85)	2.1 (0.09)	1.9 (0.09)	n.s.
Apn	2	5713	0	8	47	0.23	53.63 (0.38)	1.26 (0.05)	1.58 (0.05)	0 (0)
Rtb	1	720	0	4	38	0.23	41.58 (0.73)	1.1 (0.18)	1.67 (0.18)	0 (0)
Ndb	2	6431	0	5	36	0.23	38.89 (0.23)	1.41 (0.05)	1.5 (0.09)	0 (0)
Ass	6BA	7230	0	8	54	0.23	44.22 (0.29)	0.99 (0.06)	1.1 (0.03)	0 (0)
Dvd	4	8272	0	4	45	0.23	41.49 (0.25)	0.57 (0.08)	2.02 (0.05)	0 (0)
Hlm	3Am	2159	0	9	75	0.23	57.83 (0.76)	1.41 (0.1)	1.47 (0.16)	0 (0)
Utln	1	6357	0	2	20	0.23	32.67 (0.21)	2.24 (0.11)	3.16 (0.11)	0 (0)
Wd	5	4726	0	5	40	0.23	41.88 (0.35)	1.73 (0.09)	1.26 (0.11)	0 (0)
Gv	6	3461	0	12	72	0.22	49.44 (0.81)	1.57 (0.1)	1.67 (0.12)	0 (0)
Aml	2B	1136	0	10	45	0.22	45.14 (0.84)	1 (0.08)	1.16 (0.11)	n.s.
Nm	3B	3079	0	10	104	0.22	57.98 (0.76)	1.64 (0.1)	1.25 (0.07)	n.s.
Zbm	2	4658	0	3	37	0.22	45.18 (0.26)	1.51 (0.07)	0.71 (0.08)	0 (0)
Rtd	9B	1164	0	13	79	0.22	63.59 (1.73)	2.18 (0.17)	0.48 (0.23)	0 (0)
Zd	5	8089	0	6	48	0.22	48.18 (0.3)	1.46 (0.06)	1.53 (0.08)	0 (0)
Wp	6	707	0	6	36	0.22	41.99 (1.19)	1.33 (0.26)	2.2 (0.31)	0 (0)
Ndb	3	907	0	4	31	0.21	39.67 (0.66)	1.17 (0.25)	1.2 (0.11)	0 (0)
Ut	7	1304	0	29	157	0.21	78.3 (1.77)	0.87 (0.08)	0.97 (0.12)	n.s.
Ah	3	636	0	12	70	0.21	67.37 (1.98)	1.3 (0.2)	0.72 (0.21)	0 (0)
Ledn	5B	1476	0	19	113	0.21	69.8 (1.75)	1.56 (0.22)	1.16 (0.11)	n.s.
Amf	7e	1394	0	9	51	0.21	60.89 (1.26)	1.18 (0.17)	2.62 (0.22)	n.s.
Ut	14	1156	0	15	90	0.20	63.97 (1.34)	1.67 (0.14)	0.42 (0.09)	0 (0)
Wp	2	596	0	7	43	0.20	43.74 (1.53)	1.87 (0.35)	1.21 (0.23)	0 (0)
Ed	4E	7320	0	7	41	0.20	54.93 (0.38)	1.48 (0.09)	1.79 (0.06)	n.s.

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Table J.1 – *Continued from previous page*

Case			***In/out range***			***Regression model coefficients***				
Station	Platform	n	min	med	max	$adj.R^2$	β_0 (SD)	β_1 (SD)	β_2 (SD)	β_3 (SD)
Uto	3	4111	0	2	54	0.20	36.17 (0.27)	1.91 (0.15)	1.73 (0.1)	0 (0)
Obd	1	621	0	2	10	0.20	41.82 (0.74)	1.54 (0.75)	4.2 (0.33)	n.s.
Bhv	1	12215	0	2	41	0.20	37.61 (0.15)	1.81 (0.06)	1.36 (0.06)	0 (0)
Gd	10	5441	0	6	42	0.20	43.77 (0.43)	0.89 (0.06)	2.81 (0.08)	0 (0)
Asa	1	12622	0	7	56	0.19	46.98 (0.23)	1.94 (0.08)	1.15 (0.03)	0 (0)
Ed	3	8521	0	8	43	0.19	51.97 (0.35)	1.32 (0.06)	1.82 (0.09)	0 (0)
Ztm	3	8257	0	3	33	0.19	32.87 (0.18)	1.77 (0.08)	0.71 (0.08)	0 (0)
Amf	1	2753	0	7	58	0.19	60.58 (0.96)	2.98 (0.15)	0.61 (0.13)	0 (0)
Amf	6AmB	1875	0	11	91	0.19	65.85 (0.99)	1.78 (0.1)	0.51 (0.1)	n.s.
Asb	3	1304	0	5	52	0.19	41.77 (0.78)	1.25 (0.13)	1.32 (0.1)	0 (0)
Ut	18	1540	0	28	128	0.19	69.85 (1.62)	0.96 (0.1)	0.77 (0.06)	n.s.
Amf	2B	966	0	12	71	0.18	70.46 (1.76)	0.67 (0.18)	2.01 (0.15)	n.s.
Cl	1	7936	0	3	48	0.18	47.67 (0.24)	1.19 (0.05)	1.91 (0.12)	0 (0)
Gv	4AB	1742	0	13	57	0.18	49.95 (1.04)	1.36 (0.17)	0.94 (0.13)	0 (0)
Hr	3	10422	0	4	36	0.18	50.62 (0.24)	2.31 (0.07)	1.12 (0.05)	n.s.
Ass	12	8095	0	8	76	0.18	43.89 (0.34)	2.02 (0.06)	0.75 (0.05)	0 (0)
Zd	4	6237	0	5	71	0.18	43.96 (0.38)	1.82 (0.07)	2.13 (0.14)	0 (0)
Amfs	3	14522	0	2	41	0.18	34.56 (0.11)	1.54 (0.09)	1.41 (0.04)	0 (0)
Ass	3AB	9403	0	8	96	0.18	43.58 (0.25)	0.73 (0.03)	0.98 (0.05)	0 (0)
Apd	1A	1920	0	8	44	0.17	47.38 (0.9)	2.36 (0.13)	n.s.	n.s.
Wad	1	1197	0	3	14	0.17	35.07 (0.54)	2.16 (0.16)	n.s.	0 (0)
Amfs	1	10774	0	2	39	0.17	37.56 (0.17)	1.37 (0.06)	2.28 (0.1)	0 (0)
Rm	1	1397	0	7	47	0.17	43.65 (0.63)	0.79 (0.1)	1.09 (0.1)	n.s.
Asdz	2	3566	0	8	68	0.16	47.18 (0.69)	1.25 (0.06)	1.7 (0.12)	0 (0)
Hd	2	4348	0	6	50	0.16	47.16 (0.38)	0.95 (0.07)	1.29 (0.09)	0 (0)

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Table J.1 – *Continued from previous page*

Case			***In/out range***			***Regression model coefficients***				
Station	Platform	n	min	med	max	$adj.R^2$	β_0 (SD)	β_1 (SD)	β_2 (SD)	β_3 (SD)
Ledn	4B	878	0	10	82	0.16	67.14 (1.84)	1.95 (0.25)	1.06 (0.21)	n.s.
Zd	1	8186	0	4	40	0.16	41.24 (0.27)	1.22 (0.1)	1.55 (0.06)	0 (0)
Db	2	887	0	3	23	0.16	39.23 (0.77)	1.17 (0.21)	2.88 (0.41)	n.s.
Asn	3e	2878	0	5	32	0.16	49.87 (0.54)	n.s.	3.03 (0.15)	0 (0)
Rai	2	4089	0	3	37	0.16	36.84 (0.37)	3.38 (0.15)	0.53 (0.11)	0 (0)
Ahpr	1	3063	0	1	30	0.16	43.25 (0.28)	1.28 (0.07)	1.77 (0.12)	0 (0)
Gd	5Am	526	0	7	43	0.15	44.3 (1.51)	1.55 (0.38)	1.24 (0.16)	0.04 (0.01)
Wp	1	691	0	6	42	0.15	43.38 (1.43)	2.42 (0.43)	0.87 (0.31)	0 (0)
Brd	3	4703	0	2	22	0.15	36.14 (0.22)	2.1 (0.25)	1.8 (0.08)	0 (0)
Mp	2B	1802	0	5	48	0.15	45.69 (0.92)	2.2 (0.17)	1.32 (0.2)	n.s.
Mp	3	6780	0	4	46	0.15	47.64 (0.3)	0.89 (0.07)	1.54 (0.05)	0 (0)
Zzs	2	8780	0	2	20	0.15	39.51 (0.21)	2.29 (0.06)	2.05 (0.54)	0 (0)
Assp	2	11832	0	2	25	0.15	35.4 (0.14)	1.57 (0.05)	2.55 (0.1)	0 (0)
Asdm	3	9060	0	4	26	0.15	43.6 (0.23)	1.42 (0.14)	1.56 (0.05)	0 (0)
Mp	2mB	1295	0	3	31	0.15	55.11 (0.64)	1.97 (0.19)	n.s.	n.s.
Kz	2	6865	0	2	14	0.14	50.37 (0.25)	2.6 (0.09)	1.82 (0.81)	0 (0)
Brn	2	7361	0	3	22	0.14	38.28 (0.24)	1.81 (0.07)	1.54 (0.11)	n.s.
Wp	5	858	0	7	34	0.14	42.66 (1.47)	1.75 (0.28)	1.15 (0.33)	0 (0)
Rta	1	17407	0	5	41	0.14	41 (0.2)	1.99 (0.04)	0.26 (0.05)	0 (0)
Sdm	3BA	12962	0	5	39	0.14	42.38 (0.26)	1.58 (0.11)	1.84 (0.06)	0 (0)
Tb	3	2587	0	10	60	0.14	60.03 (1.01)	1.08 (0.16)	1.76 (0.13)	0 (0)
Pmw	1	10106	0	1	18	0.14	29.79 (0.14)	2.14 (0.06)	1.75 (0.32)	0 (0)
Btl	502	4294	0	3	45	0.14	39.42 (0.3)	1.31 (0.08)	0.89 (0.13)	0 (0)
Rta	2	13844	0	5	39	0.14	42.68 (0.26)	0.95 (0.08)	2.04 (0.06)	n.s.
Htnc	1	13986	0	2	31	0.14	37.37 (0.14)	2.03 (0.06)	0.94 (0.07)	0 (0)

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Table J.1 – *Continued from previous page*

Case			***In/out range***			***Regression model coefficients***				
Station	Platform	n	min	med	max	$adj.R^2$	β_0 (SD)	β_1 (SD)	β_2 (SD)	β_3 (SD)
Bsk	1	907	0	1	15	0.14	27.53 (0.46)	2.31 (0.23)	1.58 (0.29)	n.s.
Hgv	2	970	0	3	40	0.14	51.39 (0.91)	0.99 (0.19)	0.82 (0.26)	0 (0)
Alm	1	3132	0	6	57	0.13	53.25 (0.77)	0.93 (0.14)	2.47 (0.14)	n.s.
Aml	4B	738	0	8	35	0.13	54.31 (1.32)	1.84 (0.26)	0.74 (0.16)	0 (0)
Esk	2	1553	0	2	34	0.13	38.05 (0.48)	5.52 (0.73)	1.3 (0.09)	n.s.
Rtd	6	786	0	10	74	0.13	62.49 (1.41)	1.7 (0.22)	0.64 (0.13)	0 (0)
Kz	1B	11071	0	2	19	0.13	38.77 (0.17)	n.s.	2.48 (0.06)	n.s.
Dvd	1	7513	0	5	61	0.13	44.3 (0.32)	1.54 (0.06)	0.81 (0.08)	0 (0)
Rtz	3	4378	0	1	13	0.13	35.47 (0.23)	3.06 (0.27)	2.63 (0.13)	0 (0)
Nkk	2	4923	0	4	32	0.13	43.03 (0.32)	0.57 (0.11)	1.49 (0.06)	0 (0)
Wd	2	4041	0	4	38	0.13	46.72 (0.41)	0.77 (0.11)	1.84 (0.11)	0 (0)
Hfd	4AB	741	0	5	33	0.13	41.8 (0.96)	0.86 (0.23)	1.52 (0.3)	0 (0)
Hmbv	1	8009	0	2	23	0.13	32.43 (0.19)	1.79 (0.06)	1.58 (0.4)	0 (0)
Zbm	1	7769	0	3	39	0.13	40.99 (0.27)	1.74 (0.08)	1.17 (0.06)	0 (0)
Dv	4AmB	1769	0	10	69	0.13	65.36 (0.98)	1.34 (0.14)	0.78 (0.14)	0 (0)
Hnk	1	1559	0	2	26	0.13	41.01 (0.42)	1.26 (0.08)	n.s.	n.s.
Sgn	1	806	0	3	30	0.13	41.99 (0.64)	1.08 (0.27)	0.99 (0.21)	n.s.
Ndb	1	531	0	4	21	0.12	40.2 (0.91)	2.29 (0.26)	n.s.	n.s.
Alm	4	5752	0	6	52	0.12	53 (0.58)	2.39 (0.12)	0.63 (0.1)	0 (0)
Apd	4	2194	0	9	60	0.12	53.98 (0.89)	0.72 (0.17)	1.47 (0.11)	n.s.
Bkl	3	3680	0	3	47	0.12	42.26 (0.33)	1.46 (0.09)	1.54 (0.1)	n.s.
Gd	3AmB	4583	0	6	36	0.12	50.34 (0.5)	1.65 (0.09)	1.26 (0.1)	n.s.
Uto	1	20318	0	3	36	0.12	38.36 (0.12)	1.26 (0.03)	1.11 (0.04)	0 (0)
Hlm	6BmA	2919	0	10	70	0.12	56.95 (0.74)	0.66 (0.14)	1.09 (0.06)	n.s.
Rtd	8	1132	0	10	48	0.12	60.73 (1.38)	1.91 (0.2)	n.s.	n.s.

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Table J.1 – *Continued from previous page*

Case			***In/out range***			***Regression model coefficients***				
Station	Platform	n	min	med	max	$adj.R^2$	β_0 (SD)	β_1 (SD)	β_2 (SD)	β_3 (SD)
Asdm	2	20354	0	4	27	0.12	39.31 (0.14)	1.12 (0.03)	0.84 (0.07)	0 (0)
Hlms	1	8243	0	1	18	0.12	36.51 (0.15)	2.2 (0.15)	1.33 (0.36)	0 (0)
Dr	2	623	0	2	11	0.12	41.48 (0.78)	1.97 (0.36)	3.93 (0.65)	n.s.
Rm	2f	1673	0	7	53	0.12	49.32 (0.68)	0.63 (0.1)	1.49 (0.16)	n.s.
Rsn	3	9720	0	4	30	0.12	42.62 (0.21)	1.37 (0.05)	1.06 (0.04)	n.s.
Rtd	7	853	0	11	52	0.12	61.87 (1.94)	1.68 (0.27)	1.03 (0.21)	n.s.
Db	1	7125	0	3	22	0.12	40.67 (0.21)	1.78 (0.15)	1.32 (0.07)	0 (0)
Hlm	8	1233	0	7	62	0.12	62.69 (1.05)	n.s.	1.47 (0.17)	0 (0)
Ah	7	908	0	10	69	0.11	70.58 (1.7)	0.79 (0.3)	1.43 (0.18)	n.s.
Bdg	1	884	0	3	17	0.11	50.35 (0.72)	1.33 (0.21)	2.11 (0.23)	n.s.
Ehv	5	651	0	15	112	0.11	74.49 (2.76)	0.7 (0.22)	1.56 (0.23)	n.s.
Ass	11	9056	0	6	61	0.11	44.69 (0.46)	1.57 (0.07)	1.62 (0.1)	0 (0)
Bdg	2	2417	0	3	21	0.11	49.73 (0.54)	1.84 (0.14)	1.89 (0.2)	0 (0)
Btl	506	1112	0	3	24	0.11	39.06 (0.59)	1.03 (0.19)	1.42 (0.18)	n.s.
Zd	2	7402	0	6	52	0.11	44.71 (0.37)	1.75 (0.11)	1.14 (0.06)	0 (0)
Dvc	1	8089	0	2	18	0.11	38.96 (0.19)	1.46 (0.05)	1.24 (0.13)	n.s.
Bv	5	7232	0	3	30	0.11	46.05 (0.24)	2.02 (0.17)	1.33 (0.08)	0 (0)
Rm	1e	2077	0	6	39	0.11	50.55 (0.58)	0.92 (0.11)	1.17 (0.11)	n.s.
Btl	507	777	0	2	29	0.11	35.16 (0.82)	1.3 (0.38)	1.75 (0.27)	n.s.
Utlr	1	7975	0	2	13	0.11	38.01 (0.18)	1.94 (0.1)	2.15 (0.21)	0 (0)
Asdl	2	15279	0	6	49	0.11	36.29 (0.26)	1.67 (0.08)	0.99 (0.04)	0 (0)
Bv	3	7011	0	4	50	0.11	49.89 (0.2)	0.48 (0.04)	1.69 (0.11)	0 (0)
Dron	1ef	4357	0	3	28	0.11	38.55 (0.28)	1.86 (0.11)	0.78 (0.06)	n.s.
Gvm	4	10540	0	1	20	0.11	33.55 (0.12)	2.27 (0.09)	0.91 (0.13)	0 (0)
Nm	4B	865	0	7	56	0.11	58.31 (1.19)	1.38 (0.22)	0.71 (0.11)	0 (0)

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Table J.1 – *Continued from previous page*

Case			***In/out range***			***Regression model coefficients***				
Station	Platform	n	min	med	max	$adj.R^2$	β_0 (SD)	β_1 (SD)	β_2 (SD)	β_3 (SD)
Pmo	2	7224	0	2	21	0.11	37.62 (0.15)	2.08 (0.17)	1.34 (0.07)	n.s.
Zwd	3	4459	0	2	23	0.11	40.31 (0.27)	1.54 (0.37)	1.84 (0.08)	n.s.
Rsw	3	5800	0	2	23	0.11	32.44 (0.28)	1.91 (0.23)	1.84 (0.18)	0 (0)
Dmn	2	5734	0	2	10	0.11	34.87 (0.3)	3.51 (0.18)	0.83 (0.33)	0 (0)
Wm	3	3276	0	2	16	0.11	36.65 (0.34)	1.96 (0.12)	n.s.	0 (0)
Dld	1	2720	0	1	13	0.10	41.51 (0.31)	3.41 (0.26)	2.87 (0.45)	n.s.
Est	1	6550	0	2	25	0.10	38.19 (0.24)	2 (0.09)	1.17 (0.16)	0 (0)
Bkg	2	1323	0	5	17	0.10	42.74 (0.72)	1.5 (0.12)	1.02 (0.13)	n.s.
Gd	8	6124	0	6	46	0.10	46.71 (0.43)	1.01 (0.07)	1.64 (0.09)	0 (0)
Rtz	2	7690	0	1	38	0.10	39.53 (0.18)	1.97 (0.15)	2.55 (0.14)	0 (0)
Laa	4	7122	0	2	19	0.10	36.9 (0.19)	1.96 (0.09)	0.74 (0.26)	0 (0)
Rlb	2B	13573	0	3	24	0.10	37.15 (0.15)	1.64 (0.08)	1.35 (0.14)	0 (0)
Vst	1	11917	0	1	22	0.10	36.8 (0.16)	1.99 (0.06)	1.31 (0.13)	0 (0)
Vtn	1	10794	0	3	50	0.10	36.49 (0.16)	1.26 (0.04)	0.91 (0.08)	0 (0)
Swk	2	7365	0	3	22	0.10	48.12 (0.32)	-1.09 (0.17)	1.77 (0.07)	n.s.
Mdb	2A	1777	0	5	26	0.10	40.55 (0.6)	1.22 (0.1)	1.64 (0.72)	n.s.
Bd	5	1346	0	8	81	0.10	50.44 (1.1)	1.51 (0.16)	0.62 (0.11)	n.s.
Gdm	3Am	744	0	3	30	0.10	47.39 (1.14)	2.42 (0.4)	2.49 (0.37)	n.s.
Gd	5AmB	2084	0	5	37	0.10	49.59 (0.87)	2.7 (0.21)	1.13 (0.14)	n.s.
Hwzb	1	5650	0	1	8	0.10	32.17 (0.21)	3.21 (0.21)	n.s.	0 (0)
Dvd	8A	10519	0	3	23	0.10	35.7 (0.17)	1.45 (0.06)	1.1 (0.08)	0 (0)
Akm	3	2717	0	1	17	0.09	43.93 (0.33)	2.2 (0.15)	0.73 (0.24)	0 (0)
Dv	3BmA	738	0	9	58	0.09	66.74 (1.66)	0.71 (0.28)	1.37 (0.26)	n.s.
Hgl	2Am	857	0	7	29	0.09	59.31 (1.47)	2.38 (0.27)	n.s.	n.s.
Hgl	3mA	1034	0	7	38	0.09	57.78 (1.16)	1.33 (0.21)	0.72 (0.2)	n.s.

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Table J.1 – *Continued from previous page*

Case			***In/out range***			***Regression model coefficients***				
Station	Platform	n	min	med	max	$adj.R^2$	β_0 (SD)	β_1 (SD)	β_2 (SD)	β_3 (SD)
Zp	3AmB	521	0	8	49	0.09	74.83 (1.87)	1.12 (0.24)	1.06 (0.34)	n.s.
Gd	3mB	503	0	6	28	0.09	45.72 (1.55)	2.56 (0.38)	0.4 (0.19)	n.s.
Ht	703AmB	1976	0	14	73	0.09	70.9 (1.37)	1.02 (0.12)	0.48 (0.18)	0 (0)
Hvsm	1	12064	0	2	32	0.09	35.8 (0.17)	1.54 (0.06)	1.07 (0.06)	0 (0)
Wdn	1	5781	0	2	27	0.09	41.33 (0.19)	1.64 (0.15)	0.89 (0.07)	n.s.
Zp	3BmA	711	0	8	35	0.09	73.98 (1.59)	0.55 (0.25)	1.5 (0.2)	n.s.
Bkl	2	1939	0	2	53	0.09	38.58 (0.52)	2.04 (0.2)	1.09 (0.14)	0 (0)
Pmw	2	7576	0	1	20	0.09	35.56 (0.16)	1.32 (0.31)	1.55 (0.06)	n.s.
Utt	1	11852	0	2	22	0.09	40.38 (0.19)	1.34 (0.05)	n.s.	0 (0)
Gdm	4B	627	0	3	31	0.09	44.2 (1.04)	1.49 (0.29)	1.23 (0.31)	0 (0)
Almp	1	12673	0	1	27	0.08	34.17 (0.13)	1.5 (0.05)	n.s.	0 (0)
Gz	4	6580	0	2	19	0.08	41.76 (0.28)	1.86 (0.1)	1.39 (0.13)	0 (0)
Htn	2	11990	0	4	36	0.08	39.51 (0.18)	2.13 (0.12)	0.72 (0.03)	0 (0)
Rsn	2	6109	0	4	38	0.08	38.42 (0.34)	0.88 (0.05)	1.42 (0.09)	n.s.
Vb	1	7486	0	1	14	0.08	34.69 (0.17)	1.95 (0.23)	1.66 (0.12)	0 (0)
Dmnz	2	10917	0	2	18	0.08	35.07 (0.17)	2.02 (0.11)	1.02 (0.14)	0 (0)
Htnc	2	6396	0	2	24	0.08	36.66 (0.22)	1.59 (0.1)	1.15 (0.08)	0 (0)
Rlb	1B	829	0	1	12	0.08	37.2 (0.48)	2.18 (0.35)	n.s.	0.01 (0)
Ass	9	777	0	7	43	0.08	49.78 (1.17)	0.6 (0.21)	0.78 (0.2)	0 (0)
Utln	1e	10860	0	2	16	0.08	35.18 (0.18)	1.56 (0.08)	2.57 (0.16)	0 (0)
Hvsm	2	19230	0	2	31	0.08	37.56 (0.11)	1.22 (0.05)	1.16 (0.04)	0 (0)
Almm	1	6354	0	2	19	0.08	33.81 (0.25)	1.7 (0.08)	0.52 (0.18)	0 (0)
Ht	704B	618	0	14	58	0.08	77.23 (2.74)	1.19 (0.31)	0.59 (0.28)	0 (0)
Rlb	3B	9032	0	2	20	0.08	32.64 (0.16)	2.17 (0.18)	0.94 (0.08)	0 (0)
Hlo	1	12266	0	2	23	0.08	52.25 (0.14)	1.84 (0.2)	1.44 (0.05)	0 (0)

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Table J.1 – *Continued from previous page*

Case			***In/out range***			***Regression model coefficients***				
Station	Platform	n	min	med	max	$adj.R^2$	β_0 (SD)	β_1 (SD)	β_2 (SD)	β_3 (SD)
Ashd	2	9367	0	2	22	0.08	35.58 (0.17)	1.35 (0.09)	1.73 (0.08)	0 (0)
Ehv	2	704	0	18	85	0.08	76.51 (2.41)	1.07 (0.16)	n.s.	n.s.
Vtn	4	5603	0	2	32	0.08	38.29 (0.21)	1.44 (0.1)	0.85 (0.05)	n.s.
Ztmo	2	8769	0	2	19	0.08	40.77 (0.22)	1.55 (0.11)	1.62 (0.14)	0 (0)
Nwk	2	6324	0	2	17	0.08	38.34 (0.2)	1.18 (0.07)	0.73 (0.09)	0 (0)
Vss	2	8102	0	1	12	0.08	29.37 (0.23)	3.44 (0.13)	7.24 (2.04)	n.s.
Cas	2	13613	0	2	37	0.07	42.57 (0.22)	1.62 (0.07)	4.03 (0.32)	0 (0)
Dtz	2	9263	0	2	24	0.07	36.65 (0.16)	1.47 (0.11)	1.82 (0.14)	0 (0)
Utln	2e	11694	0	2	26	0.07	37.64 (0.16)	4.91 (0.19)	0.8 (0.07)	0 (0)
Utvr	3	12143	0	2	23	0.07	40.02 (0.24)	1.56 (0.11)	2.08 (0.12)	0 (0)
Bnk	2	5498	0	2	13	0.07	39.73 (0.2)	1.84 (0.19)	1.21 (0.09)	n.s.
Had	2	19952	0	1	23	0.07	35.97 (0.13)	2.04 (0.09)	1.81 (0.06)	0 (0)
Ashd	5	8343	0	2	23	0.07	35.45 (0.18)	1.4 (0.08)	0.99 (0.07)	0 (0)
Dvd	5A	8470	0	3	32	0.07	36.95 (0.19)	1 (0.07)	1.24 (0.08)	0 (0)
Zwd	2	6832	0	2	23	0.07	39.31 (0.21)	1.34 (0.06)	1.46 (0.27)	n.s.
Cl	2	8456	0	3	49	0.07	39.38 (0.29)	1.57 (0.14)	1.1 (0.06)	0 (0)
Bdpb	2	7190	0	1	14	0.07	45.22 (0.2)	1.8 (0.13)	2.24 (0.15)	n.s.
Ampo	1	28767	0	2	33	0.07	35.7 (0.09)	1.3 (0.05)	0.88 (0.05)	0 (0)
Asn	3	2004	0	5	71	0.07	50.84 (0.98)	0.8 (0.23)	1.98 (0.22)	n.s.
Pmr	1	6732	0	2	18	0.07	38.91 (0.22)	1.6 (0.11)	2.05 (0.35)	n.s.
Aml	2Bm	964	0	5	23	0.07	58.88 (1.17)	1.23 (0.2)	1.38 (0.29)	n.s.
Assp	1	15470	0	2	40	0.07	36.07 (0.14)	2.05 (0.13)	0.81 (0.04)	0 (0)
Brd	2	5535	0	2	20	0.07	41.97 (0.31)	1.75 (0.09)	1.03 (0.36)	n.s.
Ddr	5	1178	0	8	61	0.07	60.76 (1.09)	1.91 (0.57)	0.76 (0.11)	n.s.
Rlb	4B	682	0	2	16	0.07	34.13 (0.57)	2.99 (0.68)	n.s.	0 (0)

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Table J.1 – *Continued from previous page*

Case			***In/out range***			***Regression model coefficients***				
Station	Platform	n	min	med	max	$adj.R^2$	β_0 (SD)	β_1 (SD)	β_2 (SD)	β_3 (SD)
Vg	1	920	0	2	10	0.07	38.63 (0.5)	1.66 (0.23)	1.84 (0.41)	n.s.
Bet	4	11715	0	3	27	0.07	37.91 (0.21)	1.52 (0.07)	0.9 (0.07)	0 (0)
Btl	503	4202	0	3	38	0.07	41.93 (0.33)	1.24 (0.14)	0.85 (0.1)	n.s.
Hk	2	2769	0	1	17	0.07	46.11 (0.35)	1.55 (0.14)	1.57 (0.27)	0 (0)
Laa	3	11569	0	2	23	0.07	38.44 (0.14)	1.19 (0.24)	1.2 (0.05)	0 (0)
Wt	3B	5606	0	4	33	0.07	44.55 (0.39)	0.27 (0.12)	1.03 (0.08)	0 (0)
Bnk	1	7264	0	2	17	0.07	35.53 (0.2)	1.04 (0.08)	1.59 (0.18)	0 (0)
Utg	4B	1661	0	1	15	0.07	48.66 (0.5)	1.92 (0.26)	1.49 (0.36)	0 (0)
Avat	3	8361	0	2	18	0.06	40.47 (0.2)	0.67 (0.15)	1.14 (0.07)	0 (0)
Dv	4mB	1566	0	11	53	0.06	59.55 (1.19)	0.51 (0.14)	0.88 (0.13)	0 (0)
Gp	1	1632	0	2	13	0.06	38.15 (0.56)	2.14 (0.21)	n.s.	n.s.
Mas	802	2527	0	3	28	0.06	35.82 (0.37)	0.6 (0.13)	1.04 (0.1)	0 (0)
Bet	3	589	0	3	18	0.06	38.13 (0.95)	0.95 (0.33)	1.53 (0.31)	n.s.
Dr	1	648	0	2	17	0.06	42.13 (0.7)	2.14 (0.57)	0.87 (0.27)	0 (0)
Lls	1	3322	0	6	34	0.06	60.47 (0.73)	1.35 (0.11)	0.72 (0.32)	0 (0)
Bhv	2	13735	0	3	26	0.06	42.78 (0.18)	1.14 (0.07)	1.16 (0.06)	0 (0)
Kma	2	11352	0	3	30	0.06	45.71 (0.19)	1.05 (0.04)	n.s.	0 (0)
Br	2	4975	0	1	16	0.06	34.96 (0.31)	0.8 (0.11)	21.56 (1.3)	n.s.
Gvmw	3	4718	0	1	12	0.06	39.8 (0.28)	2.26 (0.3)	2.53 (0.17)	0 (0)
Hmbv	2	2826	0	1	12	0.06	37.53 (0.36)	2.26 (0.9)	1.78 (0.14)	0.05 (0.02)
Std	2B	1865	0	6	37	0.06	60.21 (0.84)	1.19 (0.17)	0.81 (0.2)	n.s.
Ypb	2AB	7926	0	1	13	0.06	38.15 (0.15)	1.4 (0.1)	1.44 (0.13)	0 (0)
Ac	2	8170	0	1	13	0.06	36.49 (0.22)	2.48 (0.13)	n.s.	0 (0)
Ass	7B	1088	0	5	35	0.06	41.24 (1.28)	1.38 (0.25)	n.s.	0 (0)
Wv	3	2576	0	2	15	0.06	42.63 (0.4)	1.15 (0.13)	1.27 (0.15)	n.s.

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Table J.1 – *Continued from previous page*

Case			***In/out range***			***Regression model coefficients***				
Station	Platform	n	min	med	max	$adj.R^2$	β_0 (SD)	β_1 (SD)	β_2 (SD)	β_3 (SD)
Asdm	8	7852	0	4	32	0.06	42.97 (0.27)	0.96 (0.11)	1.02 (0.06)	n.s.
Utt	4	12938	0	2	21	0.06	37.48 (0.16)	1.03 (0.12)	1.04 (0.04)	0 (0)
Gw	2	3053	0	2	19	0.06	43.88 (0.38)	0.65 (0.24)	2.18 (0.18)	0.12 (0.06)
Had	1	12011	0	1	25	0.06	41.89 (0.18)	1.91 (0.09)	1.35 (0.12)	0 (0)
Dron	4fe	1507	0	3	34	0.05	40.96 (0.59)	0.98 (0.12)	0.67 (0.18)	n.s.
Gdg	1	3116	0	1	11	0.05	40.75 (0.32)	1.11 (0.26)	2.64 (0.22)	0 (0)
Gvm	1	8872	0	1	22	0.05	37.64 (0.15)	1.03 (0.17)	1.23 (0.11)	0 (0)
Hlms	2	5459	0	1	15	0.05	47.17 (0.26)	1.15 (0.49)	2.46 (0.21)	0 (0)
Ddr	1AmB	562	0	10	68	0.05	54.87 (1.72)	0.45 (0.2)	3.69 (1.51)	n.s.
Pmr	2	6008	0	2	23	0.05	41.85 (0.27)	1.64 (0.34)	1.18 (0.11)	n.s.
Vst	4	5236	0	2	27	0.05	46.27 (0.32)	n.s.	2.1 (0.13)	n.s.
Zdk	2	7361	0	1	11	0.05	34.77 (0.25)	5.2 (0.29)	n.s.	0 (0)
Ehs	4	15810	0	1	41	0.05	39.32 (0.16)	1.84 (0.11)	1.75 (0.08)	0 (0)
Asb	1	1327	0	2	59	0.05	42.39 (1.15)	1.09 (0.14)	n.s.	n.s.
Est	2	7613	0	2	25	0.05	54.23 (0.27)	1.55 (0.15)	1.68 (0.12)	n.s.
Gdg	4	693	0	1	14	0.05	35.1 (0.73)	2.27 (0.61)	4.5 (1.03)	n.s.
Gdm	3AmB	720	0	3	19	0.05	44.38 (1.24)	2.01 (0.42)	2.54 (0.52)	n.s.
Hdrz	1	2527	0	1	15	0.05	35.84 (0.32)	n.s.	1.29 (0.11)	n.s.
Kpnz	GT	2620	0	2	17	0.05	37.45 (0.43)	1.81 (0.16)	n.s.	n.s.
Std	3Am	504	0	9	37	0.05	61.24 (1.61)	0.65 (0.28)	0.84 (0.22)	n.s.
Utvr	4	12519	0	3	17	0.05	35.08 (0.24)	3.5 (0.17)	0.61 (0.08)	0 (0)
Hgl	2AmB	710	0	4	21	0.05	70.31 (1.39)	1.12 (0.33)	2.09 (0.56)	n.s.
Rtn	1	10829	0	2	15	0.05	35.89 (0.18)	1.53 (0.07)	0.98 (0.19)	0 (0)
Rtn	2	9155	0	2	12	0.05	40.99 (0.2)	2.28 (0.23)	1.61 (0.1)	0 (0)
Bsmz	1	6629	0	3	17	0.05	43.16 (0.3)	1.39 (0.13)	1.01 (0.1)	0 (0)

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Table J.1 – *Continued from previous page*

Case			***In/out range***			***Regression model coefficients***				
Station	Platform	n	min	med	max	$adj.R^2$	β_0 (SD)	β_1 (SD)	β_2 (SD)	β_3 (SD)
Gerp	3	6241	0	1	18	0.05	38.79 (0.19)	1.18 (0.07)	0.7 (0.26)	0 (0)
Std	2A	1193	0	5	31	0.05	58.23 (0.83)	0.61 (0.22)	1.23 (0.2)	n.s.
Hze	1	2833	0	2	21	0.05	48.67 (0.39)	1.42 (0.12)	n.s.	n.s.
Rlb	3BA	784	0	2	9	0.05	40.05 (0.63)	n.s.	1.4 (0.41)	0.04 (0.01)
Utvr	1	5915	0	3	25	0.05	39.18 (0.31)	1.02 (0.14)	1.07 (0.16)	0 (0)
Wadt	1	23196	0	1	9	0.05	24.61 (0.08)	2.69 (0.09)	0.65 (0.1)	0 (0)
Ahp	2	6536	0	2	20	0.04	41.15 (0.2)	1.25 (0.12)	1.19 (0.16)	0 (0)
Hmh	1	9927	0	2	18	0.04	34.08 (0.18)	1.49 (0.08)	1.81 (0.39)	0 (0)
Hrt	2	888	0	1	19	0.04	43.31 (0.69)	1.88 (0.5)	1.13 (0.25)	n.s.
Ldl	1	8028	0	4	25	0.04	60.15 (0.32)	n.s.	1.39 (0.08)	0 (0)
Wm	2	6239	0	2	16	0.04	38.21 (0.23)	2.33 (0.47)	0.95 (0.06)	n.s.
Mas	803	7566	0	3	23	0.04	35.89 (0.25)	0.91 (0.06)	0.86 (0.13)	0 (0)
Dtz	1	8570	0	2	25	0.04	38.96 (0.22)	1.98 (0.22)	1.15 (0.16)	0 (0)
Nwk	1	4968	0	2	19	0.04	38.96 (0.4)	1.81 (0.13)	0.67 (0.16)	0 (0)
Amrn	2	10619	0	2	23	0.04	39.22 (0.16)	0.73 (0.18)	0.89 (0.04)	n.s.
Bll	2A	3365	0	1	14	0.04	32.57 (0.27)	2.52 (0.39)	1.81 (0.24)	0 (0)
Cas	1	15118	0	2	27	0.04	53.88 (0.25)	0.91 (0.22)	1.52 (0.06)	n.s.
Tbr	2	7328	0	3	29	0.04	39.1 (0.38)	1.52 (0.11)	0.59 (0.17)	0 (0)
Wf	1	5294	0	1	7	0.04	33.73 (0.29)	3.12 (0.26)	1.88 (0.28)	n.s.
Almb	2	10024	0	3	24	0.04	37.03 (0.2)	2.36 (0.23)	0.79 (0.05)	n.s.
Bl	1	4184	0	3	16	0.04	48.26 (0.38)	1.11 (0.16)	1.15 (0.11)	n.s.
Ehv	1	558	0	16	69	0.04	71.11 (2.81)	0.91 (0.28)	0.44 (0.19)	n.s.
Ht	706A	688	0	12	71	0.04	78.83 (2.98)	1.03 (0.28)	0.98 (0.27)	n.s.
Kma	1	6989	0	3	25	0.04	39.33 (0.26)	n.s.	0.87 (0.05)	n.s.
Dmnz	1	8985	0	2	14	0.04	37.93 (0.21)	1.74 (0.17)	0.62 (0.14)	0 (0)

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Table J.1 – *Continued from previous page*

Case			***In/out range***			***Regression model coefficients***				
Station	Platform	n	min	med	max	$adj.R^2$	β_0 (SD)	β_1 (SD)	β_2 (SD)	β_3 (SD)
Hwzb	2	579	0	1	6	0.04	44.48 (0.75)	4.41 (1.54)	2.03 (0.84)	n.s.
Std	3A	765	0	9	49	0.04	62.62 (1.52)	n.s.	1.09 (0.2)	n.s.
Bll	1	9756	0	1	12	0.04	45.24 (0.17)	1.65 (0.17)	1.77 (0.22)	0 (0)
Cps	2	8506	0	2	14	0.04	34.02 (0.24)	1.29 (0.1)	0.8 (0.2)	0 (0)
Utg	1A	3733	0	1	22	0.04	48.57 (0.33)	1.43 (0.19)	1.34 (0.23)	n.s.
Bgn	2	2448	0	6	45	0.04	38.49 (1.34)	1.47 (0.43)	1.21 (0.16)	n.s.
Tpsw	1	12842	0	1	26	0.04	47.69 (0.11)	0.57 (0.04)	1.13 (0.06)	0 (0)
Drh	2	6101	0	1	9	0.04	39.07 (0.2)	2.76 (0.25)	1.8 (0.43)	0 (0)
Ot	1e	9609	0	3	27	0.04	43.82 (0.26)	1.85 (0.13)	0.74 (0.1)	0 (0)
Tbu	2	6870	0	3	42	0.04	47.78 (0.47)	0.98 (0.14)	1.22 (0.13)	0 (0)
Amr	1	760	0	6	36	0.03	63.22 (1.58)	0.52 (0.26)	1.4 (0.28)	n.s.
Ehs	1	10326	0	1	36	0.03	38.1 (0.25)	1.83 (0.12)	1.38 (0.14)	0 (0)
Hto	1	9189	0	1	11	0.03	43.31 (0.29)	3.66 (0.28)	3.02 (0.4)	n.s.
Bet	1	7106	0	3	51	0.03	36.23 (0.32)	1.27 (0.12)	0.97 (0.09)	n.s.
Utlr	4	5657	0	1	18	0.03	38.88 (0.27)	2.31 (0.36)	0.96 (0.13)	0 (0)
Dmn	1	15977	0	1	10	0.03	37.35 (0.16)	0.63 (0.15)	1.79 (0.1)	0 (0)
Hlo	2	8335	0	2	18	0.03	41.98 (0.18)	0.74 (0.05)	n.s.	0 (0)
Rsw	1	12658	0	2	29	0.03	40.15 (0.3)	2.08 (0.17)	0.94 (0.22)	n.s.
Dld	2	4657	0	1	12	0.03	38.19 (0.28)	n.s.	1.83 (0.18)	0 (0)
Hde	2	4138	0	2	17	0.03	32.88 (0.35)	1.82 (0.17)	n.s.	n.s.
Hrn	2	4466	0	2	10	0.03	38.11 (0.3)	1.02 (0.23)	1.81 (0.17)	n.s.
Otb	2	5054	0	1	24	0.03	35.72 (0.3)	2.99 (0.32)	1.87 (0.23)	n.s.
Gvmw	1	17819	0	1	16	0.03	37.16 (0.15)	1.74 (0.09)	2.47 (0.2)	0 (0)
Wt	2	4400	0	4	31	0.03	47.71 (0.59)	1.17 (0.12)	n.s.	0 (0)
Arn	1	2498	0	0	5	0.03	51.9 (0.52)	4.24 (0.49)	n.s.	n.s.

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Table J.1 – *Continued from previous page*

Case			***In/out range***			***Regression model coefficients***				
Station	Platform	n	min	med	max	$adj.R^2$	β_0 (SD)	β_1 (SD)	β_2 (SD)	β_3 (SD)
Ddr	1mB	1260	0	7	42	0.03	61.34 (1.36)	0.79 (0.18)	n.s.	n.s.
Ana	2A	1748	0	1	13	0.03	39.36 (0.46)	n.s.	1.27 (0.18)	n.s.
Wadn	1	10575	0	1	11	0.03	26.02 (0.14)	1.26 (0.09)	1.05 (0.1)	0 (0)
Zvb	2A	4114	0	2	22	0.03	41.57 (0.36)	0.65 (0.12)	1.32 (0.15)	n.s.
Utzl	2	3407	0	1	22	0.03	36.79 (0.25)	1.06 (0.14)	0.55 (0.15)	n.s.
Vndw	1	9825	0	1	14	0.02	40.73 (0.18)	1.16 (0.08)	2.26 (0.85)	0 (0)
Hto	2	10571	0	1	17	0.02	44.68 (0.19)	1.96 (0.24)	1.93 (0.17)	n.s.
Lls	4	2120	0	6	44	0.02	63.99 (1.11)	0.84 (0.29)	0.75 (0.14)	0 (0)
Ost	2	2181	0	1	8	0.02	48.5 (0.59)	2.92 (0.46)	2.19 (0.61)	n.s.
Rvs	1	4006	0	1	15	0.02	43.3 (0.43)	2.05 (0.23)	n.s.	n.s.
Vb	2	7518	0	1	10	0.02	40.8 (0.26)	1.56 (0.23)	1.11 (0.38)	0 (0)
Almp	2	21795	0	1	19	0.02	36.23 (0.1)	0.97 (0.16)	0.94 (0.04)	n.s.
Ddzd	1	17667	0	1	8	0.02	39.69 (0.13)	3.72 (0.19)	0.56 (0.13)	n.s.
Dv	3mA	1774	0	9	37	0.02	61.92 (1.04)	0.71 (0.15)	0.38 (0.13)	n.s.
Zdk	1	9507	0	1	13	0.02	42.42 (0.31)	2.03 (0.22)	2.24 (0.42)	0 (0)
Zlw	4	3405	0	1	10	0.02	36.31 (0.34)	3.56 (0.46)	1.45 (0.44)	0.03 (0.01)
Almm	2	13722	0	2	24	0.02	35.06 (0.23)	1.02 (0.17)	1.05 (0.07)	0 (0)
Bsks	1	5683	0	1	6	0.02	27.34 (0.17)	1.82 (0.17)	0.67 (0.18)	n.s.
Dv	1	939	0	10	58	0.02	86 (2.42)	n.s.	1.23 (0.27)	n.s.
Hmbh	2	7545	0	2	13	0.02	40.82 (0.3)	3.22 (0.71)	1.3 (0.13)	n.s.
Utvr	2	9010	0	2	25	0.02	35.75 (0.29)	1.96 (0.23)	0.75 (0.11)	n.s.
Zlw	3	3034	0	0	6	0.02	50.74 (0.29)	2.2 (0.41)	2.57 (0.5)	0 (0)
Bdpb	1	5459	0	1	25	0.02	36.17 (0.49)	3.34 (0.33)	n.s.	n.s.
Sptn	1	6449	0	1	7	0.02	33.45 (0.18)	1.97 (0.74)	2.26 (0.21)	n.s.
Ahp	1	3356	0	2	17	0.02	50.34 (0.4)	1.69 (0.31)	n.s.	n.s.

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Table J.1 – *Continued from previous page*

Case			***In/out range***			***Regression model coefficients***				
Station	Platform	n	min	med	max	$adj.R^2$	β_0 (SD)	β_1 (SD)	β_2 (SD)	β_3 (SD)
Ampo	2	17814	0	2	32	0.02	36.1 (0.2)	1.16 (0.12)	0.99 (0.09)	0 (0)
Nmgo	2	11568	0	1	42	0.02	45.04 (0.2)	2.37 (0.18)	1.02 (0.17)	n.s.
Nvp	2	8191	0	2	18	0.02	34.27 (0.37)	1.82 (0.22)	1.12 (0.15)	0 (0)
Ns	1	4193	0	3	24	0.02	45.36 (0.41)	0.94 (0.12)	0.25 (0.12)	0 (0)
Ac	3	4948	0	1	9	0.02	35.53 (0.28)	0.99 (0.51)	1.4 (0.18)	0 (0)
Nmgo	1	5842	0	1	20	0.02	33.56 (0.2)	1.21 (0.23)	1.4 (0.17)	n.s.
Rb	2	7074	0	0	5	0.02	31.33 (0.18)	2.46 (0.26)	2.4 (0.35)	n.s.
Almb	1	7838	0	3	33	0.02	44.04 (0.45)	1.31 (0.12)	n.s.	0 (0)
Bkf	1	6531	0	1	7	0.02	38.07 (0.19)	4.11 (0.82)	1.33 (0.15)	n.s.
Mrn	2	8206	0	1	13	0.02	44.07 (0.18)	n.s.	0.96 (0.09)	n.s.
Amrn	1	8397	0	1	24	0.01	47.14 (0.18)	0.42 (0.06)	1.05 (0.2)	0 (0)
Hil	1	3537	0	2	18	0.01	48.71 (0.36)	0.99 (0.18)	0.99 (0.18)	n.s.
Hks	2	1475	0	1	17	0.01	42.8 (0.52)	0.97 (0.35)	0.76 (0.17)	n.s.
Stz	1	3334	0	2	19	0.01	52.89 (0.3)	1.24 (0.29)	0.61 (0.09)	n.s.
Hgl	3BmA	594	0	5	23	0.01	62.97 (1.69)	n.s.	1.04 (0.38)	n.s.
Mrn	1	5095	0	1	15	0.01	47.03 (0.3)	0.76 (0.12)	n.s.	0 (0)
Zzs	1	6452	0	2	34	0.01	63.83 (0.22)	-1.94 (0.71)	0.66 (0.07)	n.s.
Kbd	2	3106	0	1	10	0.01	59.26 (0.89)	3.69 (0.6)	n.s.	n.s.
Otb	1	8786	0	1	20	0.01	31.43 (0.37)	2.46 (0.36)	2.8 (0.35)	n.s.
Cps	1	3982	0	2	10	0.01	38.02 (0.3)	n.s.	n.s.	0 (0)
Gdg	3	7296	0	1	10	0.01	39.34 (0.24)	1.25 (0.19)	1.31 (0.17)	n.s.
Nml	1	17753	0	1	13	0.01	31.96 (0.14)	1.94 (0.14)	n.s.	n.s.
Ot	2	7283	0	3	24	0.01	58.16 (0.26)	0.49 (0.09)	0.56 (0.11)	0 (0)
Hrn	1	11018	0	2	10	0.01	47.35 (0.3)	1.97 (0.18)	n.s.	n.s.
Nml	2	10795	0	1	8	0.01	36.91 (0.23)	2.81 (0.39)	1.86 (0.23)	0 (0)

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Table J.1 – *Continued from previous page*

Case			***In/out range***			***Regression model coefficients***				
Station	Platform	n	min	med	max	$adj.R^2$	β_0 (SD)	β_1 (SD)	β_2 (SD)	β_3 (SD)
Hmbh	1	5090	0	2	21	0.01	47.95 (0.48)	0.97 (0.16)	n.s.	n.s.
Mz	2	5926	0	1	14	0.01	49.03 (0.26)	1.04 (0.4)	0.77 (0.1)	n.s.
Tbr	1	3408	0	3	16	0.01	43.64 (0.73)	1.12 (0.29)	1.13 (0.23)	n.s.
Dvc	2	5219	0	3	57	0.01	61.09 (0.23)	n.s.	0.41 (0.06)	n.s.
Hil	2	7505	0	2	20	0.01	46.05 (0.16)	0.49 (0.08)	0.52 (0.09)	n.s.
Hk	1	10014	0	1	17	0.01	52.75 (0.24)	0.51 (0.15)	1.09 (0.12)	0.01 (0)
Sptz	2	10019	0	0	6	0.01	39.82 (0.2)	n.s.	2.24 (0.23)	n.s.
Amri	1	1518	0	2	9	0.01	37.88 (0.68)	n.s.	1 (0.32)	n.s.
Utzl	3	6532	0	1	24	0.01	36.48 (0.55)	0.85 (0.31)	2.95 (0.44)	n.s.
Kpnz	GG	9277	0	2	32	0.01	42.54 (0.22)	1.08 (0.13)	n.s.	n.s.
Rb	1	3577	0	0	9	0.01	39.83 (0.43)	2.3 (0.45)	1.86 (0.84)	n.s.
Rvs	2	3710	0	1	12	0.01	55.48 (0.52)	1.53 (0.35)	1.14 (0.33)	n.s.
Gp	2	6401	0	2	12	0.01	42.32 (0.31)	n.s.	0.7 (0.12)	n.s.
Drh	1	7703	0	1	7	0.00	46.91 (0.21)	n.s.	1.74 (0.29)	n.s.
Nmd	1	3965	0	1	12	0.00	43.24 (0.46)	n.s.	1.28 (0.28)	n.s.
Eml	2	5652	0	4	28	0.00	59.01 (0.57)	n.s.	-0.52 (0.26)	0 (0)
Hmh	2	2365	0	1	10	0.00	59.77 (0.61)	n.s.	0.91 (0.35)	n.s.
Sptz	1	3823	0	1	6	0.00	48.67 (0.74)	2.74 (0.78)	n.s.	n.s.
Arn	2	5456	0	0	4	0.00	32.25 (0.28)	2.31 (0.61)	n.s.	n.s.
Ddzd	2	9876	0	1	10	0.00	42.06 (0.27)	1.27 (0.35)	1.26 (0.39)	0.03 (0.01)
Zlw	2	536	0	1	7	0.00	35.76 (0.97)	n.s.	n.s.	n.s.
Asdm	9	10155	0	4	23	0.00	52.06 (0.69)	0.84 (0.19)	n.s.	n.s.
Dvnk	4	8179	0	2	19	0.00	43.85 (0.59)	n.s.	1.01 (0.25)	n.s.
Nmd	2	6974	0	1	14	0.00	43.38 (0.51)	0.73 (0.33)	n.s.	0 (0)
Dn	2	6229	0	2	25	0.00	62.98 (0.72)	n.s.	0.47 (0.18)	n.s.

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Table J.1 – *Continued from previous page*

Case			***In/out range***			***Regression model coefficients***				
Station	Platform	n	min	med	max	$adj.R^2$	β_0 (SD)	β_1 (SD)	β_2 (SD)	β_3 (SD)
Kbd	1	7776	0	0	6	0.00	41.87 (0.2)	n.s.	0.66 (0.22)	3.41 (1.5)
Ow	1	2334	0	1	16	0.00	61.84 (2.31)	n.s.	n.s.	n.s.
Rai	3	6508	0	3	56	0.00	42.75 (2.55)	n.s.	n.s.	n.s.
Dvnk	1	9574	0	1	16	-0.00	36.22 (2.12)	n.s.	n.s.	n.s.
Eml	1	6439	0	4	26	0.00	50.37 (0.48)	n.s.	n.s.	n.s.
Nvp	1	15806	0	2	18	0.00	37.95 (0.89)	1.28 (0.42)	n.s.	n.s.
Ow	2	6047	0	2	10	-0.00	84.41 (0.63)	n.s.	n.s.	n.s.
Vg	2	8777	0	2	14	0.00	51.5 (0.41)	0.52 (0.25)	n.s.	n.s.
Bll	2AB	1310	0	1	6	-0.00	47.12 (0.55)	n.s.	n.s.	n.s.
Br	1	2174	0	1	15	-0.00	57.84 (0.55)	n.s.	n.s.	n.s.

Table J.1: Regression coefficients for all station/platform combinations with 500 or more observations (n.s. = not significant)

J.2 Influence of weather conditions

Scenario					***Sample***		***Tests***				***Rain sample***		
Station	Platform	Time	Stock	Length	Rain	No rain	p_{WMW}	H_{WMW}	p_{KS}	H_{KS}	Mth	Days	Train Nos
Ahpr	2	DAL	SGMM	3	12	157	0.36	H_0	0.43	H_0	2	2	10
Almp	1	DAL	SLT	6	34	430	0.45	H_0	0.57	H_0	4	4	21
Almp	2	DAL	SLT	10	16	209	0.34	H_0	0.33	H_0	3	5	13
Almp	2	DAL	SLT	4	13	246	0.67	H_0	0.26	H_0	4	4	10
Almp	2	DAL	SLT	6	36	501	0.18	H_0	0.23	H_0	3	3	25
Ampo	1	DAL	SLT	4	24	673	0.82	H_0	0.80	H_0	5	5	13
Ampo	1	DAL	SLT	6	33	807	0.93	H_0	0.69	H_0	5	5	20
Ampo	2	DAL	SLT	6	16	253	0.41	H_0	0.37	H_0	2	3	14
Assp	1	DAL	SLT	4	11	378	0.46	H_0	0.51	H_0	4	5	9
Assp	1	DAL	SLT	6	15	484	0.63	H_0	0.58	H_0	5	5	12
Assp	2	DAL	SLT	6	19	537	0.03	H_1	0.08	H_0	4	4	14
Bet	4	DAL	FLIRT	4	11	150	0.50	H_0	0.14	H_0	5	3	7
Cas	1	DAL	SGMM	5	10	130	0.14	H_0	0.06	H_0	4	3	8
Cas	2	DAL	SGMM	3	11	170	0.36	H_0	0.12	H_0	4	4	9
Cas	2	DAL	SGMM	5	16	323	0.95	H_0	0.58	H_0	5	3	9
Ddzd	1	DAL	FLIRT	3	60	1986	0.09	H_0	0.08	H_0	5	3	34
Ddzd	1	DAL	FLIRT	4	33	989	0.84	H_0	0.53	H_0	6	4	24
Ddzd	1	DAL	FLIRT	7	32	634	0.21	H_0	0.19	H_0	6	4	18
Ddzd	2	DAL	FLIRT	3	36	951	0.01	H_1	0.00	H_1	6	4	22
Ddzd	2	DAL	FLIRT	4	13	524	0.65	H_0	0.23	H_0	6	4	13
Ddzd	2	DAL	FLIRT	7	20	267	0.21	H_0	0.09	H_0	5	3	16
Dmn	1	DAL	SLT	6	14	346	1.00	H_0	0.99	H_0	3	4	11
Dmnz	2	DAL	SLT	6	11	211	0.71	H_0	0.91	H_0	5	5	8
Dvc	1	DAL	DD-AR	3	12	299	0.86	H_0	0.49	H_0	3	4	10
Dvc	1	DAL	SGMM	3	12	78	0.91	H_0	0.89	H_0	3	5	7
Ehs	1	DAL	FLIRT	4	14	311	0.55	H_0	0.15	H_0	4	4	11

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Table J.2 – *Continued from previous page*

Scenario					***Sample***		***Tests***				***Rain sample***		
Station	Platform	Time	Stock	Length	Rain	No rain	p_{WMW}	H_{WMW}	p_{KS}	H_{KS}	Mth	Days	Train Nos
Ehs	1	DAL	FLIRT	7	12	322	0.15	H_0	0.03	H_1	5	3	8
Ehs	4	DAL	FLIRT	3	13	248	0.82	H_0	0.62	H_0	5	4	10
Ehs	4	DAL	FLIRT	4	18	555	0.41	H_0	0.42	H_0	4	4	14
Gerp	3	DAL	ICM	3	18	424	0.00	H_1	0.00	H_1	3	5	14
Hde	2	DAL	DD-AR	3	11	222	0.97	H_0	0.82	H_0	3	5	7
Hk	1	DAL	SGMM	5	14	127	0.97	H_0	0.85	H_0	3	3	11
Hlms	1	DAL	SGMM	5	14	276	0.59	H_0	0.36	H_0	4	4	9
Hlo	1	DAL	SGMM	5	11	169	0.52	H_0	0.44	H_0	5	4	8
Hmh	1	DAL	FLIRT	4	11	244	0.16	H_0	0.24	H_0	4	3	8
Htn	2	DAL	SLT	10	10	38	0.77	H_0	0.35	H_0	5	4	5
Htnc	1	DAL	SLT	4	19	340	0.86	H_0	0.58	H_0	5	5	12
Htnc	1	DAL	SLT	6	14	398	0.71	H_0	0.44	H_0	3	4	13
Htnc	2	DAL	SLT	10	13	24	0.21	H_0	0.09	H_0	4	3	12
Hto	1	DAL	FLIRT	4	13	495	0.28	H_0	0.12	H_0	3	4	11
Hto	1	DAL	FLIRT	7	10	369	0.16	H_0	0.25	H_0	3	4	5
Hto	2	DAL	FLIRT	4	11	501	0.94	H_0	0.58	H_0	2	3	9
Kpnz	GG	DAL	SLT	6	14	254	0.73	H_0	0.37	H_0	3	3	11
Nmgo	2	DAL	FLIRT	7	10	425	0.29	H_0	0.29	H_0	4	4	5
Nml	1	DAL	FLIRT	3	36	495	0.89	H_0	0.65	H_0	5	4	24
Nml	1	DAL	FLIRT	4	23	392	0.78	H_0	0.45	H_0	6	5	16
Nml	1	DAL	FLIRT	6	17	221	0.87	H_0	0.67	H_0	5	4	11
Nml	1	DAL	FLIRT	7	18	502	0.33	H_0	0.24	H_0	5	5	9
Nml	1	DAL	SGMM	3	30	489	0.84	H_0	0.47	H_0	4	4	20
Nml	1	DAL	SGMM	5	19	442	0.33	H_0	0.15	H_0	6	5	13
Nml	2	DAL	FLIRT	3	14	173	0.68	H_0	0.53	H_0	5	4	9

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Table J.2 – *Continued from previous page*

Scenario					***Sample***		***Tests***				***Rain sample***		
Station	Platform	Time	Stock	Length	Rain	No rain	p_{WMW}	H_{WMW}	p_{KS}	H_{KS}	Mth	Days	Train Nos
Nml	2	DAL	FLIRT	4	18	332	0.67	H_0	0.88	H_0	3	3	14
Nml	2	DAL	FLIRT	7	21	576	0.44	H_0	0.40	H_0	6	5	11
Nml	2	DAL	SGMM	3	16	160	0.13	H_0	0.10	H_0	4	3	12
Nvp	1	DAL	SLT	4	15	252	0.88	H_0	0.95	H_0	2	3	13
Nvp	1	DAL	SLT	6	11	223	0.37	H_0	0.43	H_0	3	3	10
Otb	1	DAL	FLIRT	3	47	1778	0.03	H_1	0.00	H_1	5	5	23
Otb	1	DAL	FLIRT	4	11	166	0.00	H_1	0.00	H_1	2	2	11
Otb	2	DAL	FLIRT	3	32	862	0.00	H_1	0.00	H_1	5	5	17
Otb	2	DAL	FLIRT	4	11	80	0.06	H_0	0.00	H_1	2	2	11
Pmr	1	DAL	SLT	4	11	161	1.00	H_0	0.90	H_0	4	4	7
Pmw	1	DAL	SLT	4	21	365	1.00	H_0	0.98	H_0	4	5	13
Pmw	2	DAL	SLT	4	16	213	0.94	H_0	0.49	H_0	3	3	14
Rsn	3	DAL	DD-AR	3	10	164	0.78	H_0	0.27	H_0	1	2	9
Tpsw	1	DAL	SLT	4	18	277	0.88	H_0	0.58	H_0	3	3	14
Utt	1	DAL	SLT	4	10	118	0.67	H_0	0.21	H_0	4	5	8
Utt	1	DAL	SLT	6	10	239	0.97	H_0	0.47	H_0	5	5	5
Utt	4	DAL	SLT	10	10	183	0.66	H_0	0.97	H_0	5	5	7
Utt	4	DAL	SLT	6	10	160	1.00	H_0	0.76	H_0	4	5	8
Wadn	1	DAL	FLIRT	2	77	1149	0.71	H_0	0.78	H_0	6	4	47
Wadn	1	DAL	FLIRT	4	11	307	0.99	H_0	0.67	H_0	4	3	7
Wadn	1	OS	FLIRT	2	11	86	0.50	H_0	0.33	H_0	4	3	8
Wf	1	DAL	FLIRT	3	21	658	0.04	H_1	0.09	H_0	5	5	11
Zdk	1	DAL	SLT	4	11	219	0.45	H_0	0.91	H_0	4	4	10
Zlw	3	DAL	FLIRT	7	12	354	0.70	H_0	0.28	H_0	5	5	10
Zlw	4	DAL	FLIRT	7	17	191	0.54	H_0	0.94	H_0	4	5	13

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Table J.2 – *Continued from previous page*

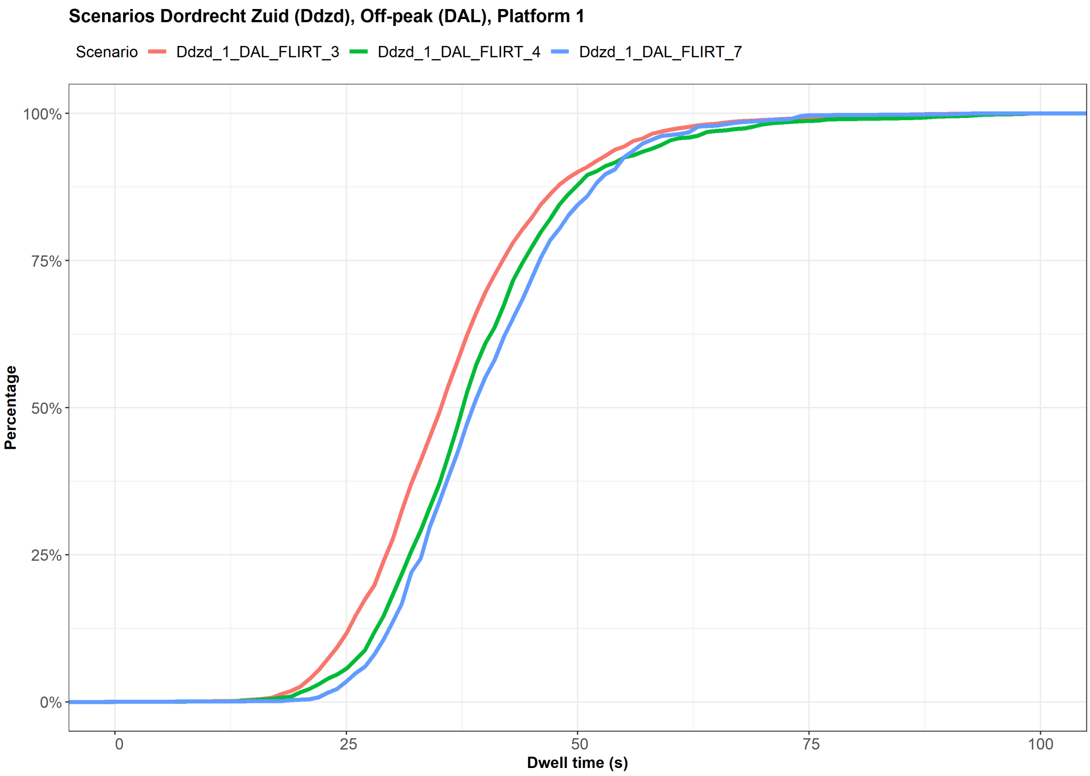
Scenario					***Sample***		***Tests***				***Rain sample***		
Station	Platform	Time	Stock	Length	Rain	No rain	p_{WMW}	H_{WMW}	p_{KS}	H_{KS}	Mth	Days	Train Nos

Table J.2: Results of Kolmogorov-Smirnov (KS) and Wilcoxon-Mann-Whitney (WMW) tests on effects of weather, with no boarders/alighters

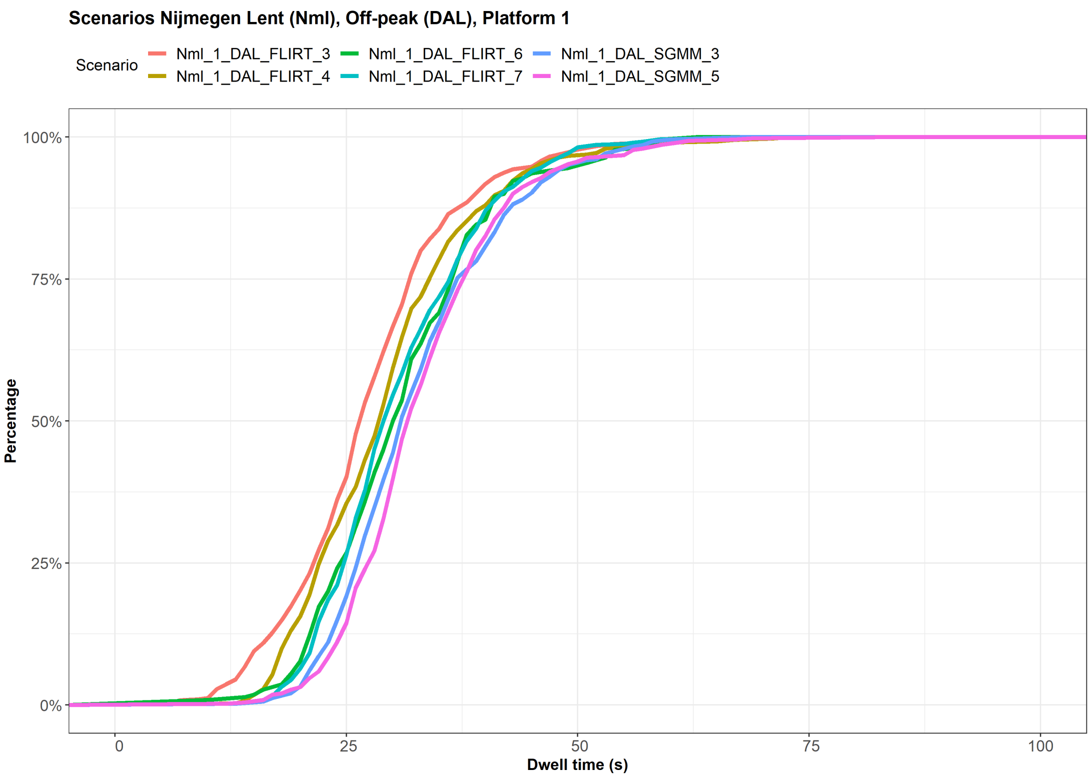
Scenario						***Sample***		***Tests***			
Station	Platform	Time	Stock	Length	No. alighters/boarders	Rain	No rain	p_{KS}	H_{KS}	p_{WMW}	H_{WMW}
Almp	1	DAL	SLT	6	8	11	129	0.62	H_0	0.30	H_0
Almp	2	DAL	SLT	10	8	11	81	0.54	H_0	0.61	H_0
Almp	2	DAL	SLT	6	7;9;11;17;12;15;19	86	1748	0.15	H_0	0.16	H_0
Ampo	1	DAL	SLT	6	9;10;6;7	47	948	0.24	H_0	0.11	H_0
Dmn	1	DAL	SLT	6	15	12	227	0.65	H_0	0.48	H_0
Otb	1	DAL	FLIRT	3	7	17	285	0.01	H_1	0.00	H_1
Wadn	1	DAL	FLIRT	2	7;8	22	397	0.85	H_0	0.83	H_0

Table J.3: Results of Kolmogorov-Smirnov (KS) and Wilcoxon-Mann-Whitney (WMW) tests on effects of weather, with alighters/boarders

J.3 Influence of operating characteristics



(a) Dordrecht Zuid, Platform 1



(b) Nijmegen Lent, Platform 1

Figure J.1: Frequency distributions for dwell times

Station & Platform		***Scenario A***			***Scenario B***			***Tests***			
Station	Platform	Stock	Length	n	Stock	Length	n	p_{WMW}	H_{WMW}	p_{KS}	H_{KS}
Almp	2	SLT	4	246	SLT	6	501	0.01	H_1	0.00	H_1
Almp	2	SLT	4	246	SLT	10	209	0.00	H_1	0.00	H_1
Almp	2	SLT	6	501	SLT	4	246	0.01	H_1	0.00	H_1
Almp	2	SLT	6	501	SLT	10	209	0.00	H_1	0.00	H_1
Almp	2	SLT	10	209	SLT	4	246	0.00	H_1	0.00	H_1
Almp	2	SLT	10	209	SLT	6	501	0.00	H_1	0.00	H_1
Ddzd	1	FLIRT	4	989	FLIRT	3	1986	0.00	H_1	0.00	H_1
Ddzd	1	FLIRT	4	989	FLIRT	7	634	0.08	H_0	0.01	H_1
Ddzd	1	FLIRT	3	1986	FLIRT	4	989	0.00	H_1	0.00	H_1
Ddzd	1	FLIRT	3	1986	FLIRT	7	634	0.00	H_1	0.00	H_1
Ddzd	1	FLIRT	7	634	FLIRT	4	989	0.08	H_0	0.01	H_1
Ddzd	1	FLIRT	7	634	FLIRT	3	1986	0.00	H_1	0.00	H_1
Nml	1	FLIRT	6	221	FLIRT	4	392	0.06	H_0	0.01	H_1
Nml	1	FLIRT	6	221	FLIRT	3	495	0.00	H_1	0.00	H_1
Nml	1	FLIRT	6	221	FLIRT	7	502	0.80	H_0	0.60	H_0
Nml	1	FLIRT	6	221	SGMM	5	442	0.01	H_1	0.00	H_1
Nml	1	FLIRT	6	221	SGMM	3	489	0.16	H_0	0.05	H_0
Nml	1	FLIRT	4	392	FLIRT	6	221	0.06	H_0	0.01	H_1
Nml	1	FLIRT	4	392	FLIRT	3	495	0.01	H_1	0.00	H_1
Nml	1	FLIRT	4	392	FLIRT	7	502	0.02	H_1	0.01	H_1
Nml	1	FLIRT	4	392	SGMM	5	442	0.00	H_1	0.00	H_1
Nml	1	FLIRT	4	392	SGMM	3	489	0.00	H_1	0.00	H_1
Nml	1	FLIRT	3	495	FLIRT	6	221	0.00	H_1	0.00	H_1
Nml	1	FLIRT	3	495	FLIRT	4	392	0.01	H_1	0.00	H_1
Nml	1	FLIRT	3	495	FLIRT	7	502	0.00	H_1	0.00	H_1
Nml	1	FLIRT	3	495	SGMM	5	442	0.00	H_1	0.00	H_1

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Table J.4 – *Continued from previous page*

Station & Platform		***Scenario A***			***Scenario B***			***Tests***			
Station	Platform	Stock	Length	n	Stock	Length	n	p_{WMW}	H_{WMW}	p_{KS}	H_{KS}
Nml	1	FLIRT	3	495	SGMM	3	489	0.00	H_1	0.00	H_1
Nml	1	FLIRT	7	502	FLIRT	6	221	0.80	H_0	0.60	H_0
Nml	1	FLIRT	7	502	FLIRT	4	392	0.02	H_1	0.01	H_1
Nml	1	FLIRT	7	502	FLIRT	3	495	0.00	H_1	0.00	H_1
Nml	1	FLIRT	7	502	SGMM	5	442	0.00	H_1	0.00	H_1
Nml	1	FLIRT	7	502	SGMM	3	489	0.01	H_1	0.00	H_1
Nml	1	SGMM	5	442	FLIRT	6	221	0.01	H_1	0.00	H_1
Nml	1	SGMM	5	442	FLIRT	4	392	0.00	H_1	0.00	H_1
Nml	1	SGMM	5	442	FLIRT	3	495	0.00	H_1	0.00	H_1
Nml	1	SGMM	5	442	FLIRT	7	502	0.00	H_1	0.00	H_1
Nml	1	SGMM	5	442	SGMM	3	489	0.14	H_0	0.18	H_0
Nml	1	SGMM	3	489	FLIRT	6	221	0.16	H_0	0.05	H_0
Nml	1	SGMM	3	489	FLIRT	4	392	0.00	H_1	0.00	H_1
Nml	1	SGMM	3	489	FLIRT	3	495	0.00	H_1	0.00	H_1
Nml	1	SGMM	3	489	FLIRT	7	502	0.01	H_1	0.00	H_1
Nml	1	SGMM	3	489	SGMM	5	442	0.14	H_0	0.18	H_0
Nml	2	FLIRT	4	332	FLIRT	3	173	0.67	H_0	0.61	H_0
Nml	2	FLIRT	4	332	FLIRT	7	576	0.75	H_0	0.88	H_0
Nml	2	FLIRT	4	332	SGMM	3	160	0.02	H_1	0.04	H_0
Nml	2	FLIRT	3	173	FLIRT	4	332	0.67	H_0	0.61	H_0
Nml	2	FLIRT	3	173	FLIRT	7	576	0.92	H_0	0.78	H_0
Nml	2	FLIRT	3	173	SGMM	3	160	0.09	H_0	0.05	H_0
Nml	2	FLIRT	7	576	FLIRT	4	332	0.75	H_0	0.88	H_0
Nml	2	FLIRT	7	576	FLIRT	3	173	0.92	H_0	0.78	H_0
Nml	2	FLIRT	7	576	SGMM	3	160	0.14	H_0	0.03	H_0

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Table J.4 – *Continued from previous page*

Station & Platform		***Scenario A***			***Scenario B***			***Tests***			
Station	Platform	Stock	Length	n	Stock	Length	n	p_{WMW}	H_{WMW}	p_{KS}	H_{KS}
Nml	2	SGMM	3	160	FLIRT	4	332	0.02	H_1	0.04	H_0
Nml	2	SGMM	3	160	FLIRT	3	173	0.09	H_0	0.05	H_0
Nml	2	SGMM	3	160	FLIRT	7	576	0.14	H_0	0.03	H_0

Table J.4: Results of Kolmogorov-Smirnov (KS) and Wilcoxon-Mann-Whitney (WMW) tests on operating characteristics

J.4 Influence of passenger behaviour

Scenario					***Sample***		***Tests***			
Station	Platform	Stock	Length	No. of alighters and boarders	Peak	Off-peak	p_{KS}	H_{KS}	p_{WMW}	H_{WMW}
Almm	2	SLT	6	55	12	12	0.85	H_0	1.00	H_0
Ampo	1	SLT	6	50	11	20	0.99	H_0	0.88	H_0
Ampo	1	SLT	6	53	11	14	0.02	H_1	0.00	H_1
Ampo	1	SLT	6	55	14	13	0.78	H_0	0.77	H_0
Ampo	1	SLT	6	50;53;55	36	47	0.31	H_0	0.07	H_0
Ampo	2	SLT	6	53	11	11	0.21	H_0	0.25	H_0
Asdm	2	SLT	6	75	11	21	0.14	H_0	0.10	H_0
Asdm	2	SLT	6	77	13	21	0.58	H_0	0.70	H_0
Asdm	2	SLT	6	89	12	11	0.93	H_0	0.64	H_0
Gz	4	FLIRT-FFF	7	52	11	11	0.99	H_0	0.51	H_0
Rlb	2B	SGMM	5	50	13	40	0.52	H_0	0.38	H_0
Rlb	2B	SGMM	5	51	18	38	0.45	H_0	0.48	H_0
Rlb	2B	SGMM	5	52	14	29	0.94	H_0	0.88	H_0
Rlb	2B	SGMM	5	54	12	25	0.92	H_0	0.67	H_0
Rlb	2B	SGMM	5	55	11	22	0.65	H_0	0.53	H_0
Rlb	2B	SGMM	5	56	12	25	0.49	H_0	0.30	H_0
Rlb	2B	SGMM	5	58	14	15	0.31	H_0	0.04	H_0
Rlb	2B	SGMM	5	60	14	14	0.62	H_0	0.91	H_0
Rlb	2B	SGMM	5	62	14	15	0.96	H_0	0.74	H_0
Rlb	2B	SGMM	5	63	11	13	0.68	H_0	0.56	H_0
Rlb	2B	SGMM	5	64	12	11	0.31	H_0	0.16	H_0
Rlb	2B	SGMM	5	65	16	12	0.02	H_1	0.02	H_1
Rlb	2B	SGMM	5	66	17	14	0.64	H_0	0.41	H_0
Rlb	2B	SGMM	5	68	16	11	0.98	H_0	0.96	H_0
Rlb	2B	SGMM	5	71	12	11	0.55	H_0	0.56	H_0
Rlb	2B	SGMM	5	64;66;65	45	37	0.12	H_0	0.25	H_0

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Table J.5 – *Continued from previous page*

Scenario					***Sample***		***Tests***			
Sstation	Platform	Stock	Length	No. of alighters and boarders	Peak	Off-peak	p_{KS}	H_{KS}	p_{WMW}	H_{WMW}
Rsn	3	DD-AR	3	54	11	14	0.70	H_0	0.41	H_0
Rsn	3	DD-AR	3	58	13	13	0.29	H_0	0.12	H_0
Rsn	3	DD-AR	3	65	13	11	0.60	H_0	0.47	H_0
Sdm	5AB	SGMM	5	55	14	44	0.41	H_0	0.11	H_0
Sdm	5AB	SGMM	5	59	14	40	0.40	H_0	0.17	H_0
Sdm	5AB	SGMM	5	98	13	12	0.89	H_0	0.34	H_0

Table J.5: Results of Kolmogorov-Smirnov (KS) and Wilcoxon-Mann-Whitney (WMW) tests on passenger behaviour

J.5 Results of regression analyses

Hennige model scenarios

No.	Station	Platform	Stock	Len.	n	$Adj.R^2$	β_0 (SD)	β_1 (SD)	%PST	%laat	%lang
1	Apn	2	ICM	3	65	0.57	46.81 (2.99)	0.35 (0.04)	0.30	0.82	0.81
2	Asb	2	VIRM	6	693	0.43	37.82 (0.8)	0.13 (0.01)	0.20	0.68	0.56
3	Asb	2	VIRM	8	153	0.42	43.03 (1.63)	0.08 (0.01)	0.16	0.70	0.67
4	Asb	3	SLT	12	56	0.53	37.9 (2.42)	0.1 (0.01)	0.24	0.79	0.91
5	Asb	6	SGMM	5	83	0.40	31 (1.89)	0.11 (0.01)	0.26	0.66	0.47
6	Asb	7	VIRM	6	461	0.44	37.87 (1.07)	0.14 (0.01)	0.23	0.82	0.59
7	Asb	8	VIRM	4	147	0.50	36.05 (1.64)	0.2 (0.02)	0.16	0.91	0.49
8	Asb	8	VIRM	6	124	0.70	38.78 (1.72)	0.14 (0.01)	0.18	0.92	0.62
9	Asdl	1	SLT	8	677	0.41	36.9 (0.81)	0.14 (0.01)	0.23	0.75	0.78
10	Asdz	1	DDZ	8	69	0.51	45.61 (3.72)	0.1 (0.01)	0.32	0.67	0.90
11	Asdz	1	ICM	4	51	0.48	36.24 (5.76)	0.26 (0.04)	0.45	0.67	0.87
12	Asdz	1	ICM	7	109	0.42	51.69 (3.36)	0.11 (0.01)	0.28	0.61	0.93
13	Asdz	1	VIRM	10	344	0.42	41.02 (1.65)	0.06 (0)	0.35	0.62	0.65
14	Asdz	3	ICM	3	108	0.63	37.01 (1.63)	0.31 (0.02)	0.27	0.61	0.41
15	Asdz	3	ICM	6	108	0.44	41.99 (2.91)	0.16 (0.02)	0.30	0.87	0.42
16	Asdz	3	ICM	8	66	0.44	42.67 (2.7)	0.13 (0.02)	0.23	0.92	0.37
17	Asdz	3	SLT	4	501	0.60	38.28 (0.93)	0.3 (0.01)	0.26	0.71	0.50
18	Asdz	3	SLT	6	537	0.52	35.9 (1.14)	0.23 (0.01)	0.28	0.70	0.50
19	Asdz	4	DDZ	4	266	0.49	39.09 (1.99)	0.18 (0.01)	0.39	0.90	0.74
20	Asdz	4	ICM	10	55	0.44	63.08 (4.53)	0.06 (0.01)	0.25	0.99	0.90
21	Asdz	4	ICM	3	86	0.49	44.31 (2.65)	0.22 (0.02)	0.28	0.86	0.62
22	Asdz	4	ICM	4	98	0.43	40.55 (3.43)	0.24 (0.03)	0.39	0.91	0.74
23	Asdz	4	VIRM	8	74	0.47	37.88 (3.67)	0.1 (0.01)	0.34	0.89	0.51
24	Ass	4AB	SGMM	3	88	0.44	34.62 (1.86)	0.18 (0.02)	0.25	0.75	0.82
25	Ass	4AB	SLT	6	86	0.51	28.85 (2.95)	0.27 (0.03)	0.44	0.79	0.82

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Table J.6 – *Continued from previous page*

Hennige model scenarios											
No.	Station	Platform	Stock	Len.	n	$Adj.R^2$	β_0 (SD)	β_1 (SD)	%PST	%laat	%lang
26	Ass	5BA	SLT	12	94	0.71	36.82 (1.47)	0.1 (0.01)	0.26	0.96	0.84
27	Ass	6BA	SLT	12	91	0.52	41.32 (1.71)	0.07 (0.01)	0.21	0.83	0.89
28	Bhv	1	SGMM	8	51	0.57	29.84 (2.81)	0.13 (0.02)	0.40	0.94	0.60
29	Brd	4	SGMM	3	66	0.41	36.92 (1.4)	0.24 (0.04)	0.11	0.69	0.55
30	Dron	1e	SLT	4	178	0.40	33.54 (0.97)	0.22 (0.02)	0.15	0.90	0.50
31	Dv	1	ICM	3	63	0.45	49.35 (6.17)	0.33 (0.05)	0.36	0.83	0.47
32	Dv	3BmA	ICM	6	67	0.40	58.2 (4.26)	0.14 (0.02)	0.25	0.84	0.78
33	Dvd	4	VIRM	8	57	0.47	39.11 (2.45)	0.09 (0.01)	0.26	0.80	0.89
34	Ed	4E	VIRM	10	609	0.40	48.9 (1.1)	0.11 (0.01)	0.26	0.94	0.93
35	Gd	3Am	SLT	4	74	0.47	31.03 (2.42)	0.25 (0.03)	0.34	0.81	0.62
36	Gd	5AmB	ICM	8	65	0.59	43.33 (2.38)	0.19 (0.02)	0.24	0.86	0.90
37	Gv	5AB	VIRM	6	57	0.50	43.07 (3.38)	0.17 (0.02)	0.29	0.86	0.45
38	Hfd	4A	SLT	6	206	0.43	35.48 (1.3)	0.17 (0.01)	0.20	0.73	0.26
39	Hlms	1	SLT	6	82	0.53	29.75 (1.69)	0.51 (0.05)	0.18	0.99	0.36
40	Hmbv	1	FLIRT	8	318	0.40	33.35 (0.66)	0.16 (0.01)	0.09	0.99	0.35
41	Hwzb	1	SLT	6	53	0.51	27.05 (2.04)	0.6 (0.08)	0.21	0.72	0.38
42	Nm	3B	ICM	3	85	0.48	53.51 (4.95)	0.29 (0.03)	0.36	0.80	0.46
43	Rai	2	VIRM	4	89	0.63	31.59 (2.84)	0.72 (0.06)	0.36	0.84	0.33
44	Rai	2	VIRM	6	130	0.50	26.51 (2.43)	0.71 (0.06)	0.39	0.85	0.27
45	Rai	3	VIRM	4	75	0.55	22.92 (3.87)	0.81 (0.08)	0.50	0.86	0.29
46	Rai	3	VIRM	6	108	0.41	34.74 (2.73)	0.44 (0.05)	0.30	0.88	0.33
47	Rta	1	ICM	12	107	0.42	50.14 (2.29)	0.09 (0.01)	0.27	1.00	0.95
48	Rta	1	SLT	4	503	0.40	31.85 (0.66)	0.21 (0.01)	0.22	0.77	0.60
49	Rta	2	SLT	4	952	0.46	36.56 (0.58)	0.27 (0.01)	0.25	0.95	0.75

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Table J.6 – *Continued from previous page*

Hennige model scenarios											
No.	Station	Platform	Stock	Len.	n	$Adj.R^2$	β_0 (SD)	β_1 (SD)	%PST	%laat	%lang
50	Rta	2	SLT	6	1061	0.44	37.79 (0.49)	0.21 (0.01)	0.19	0.94	0.71
51	Rtb	2	SGMM	8	65	0.42	42.15 (1.77)	0.1 (0.01)	0.15	0.91	0.80
52	Rtd	9B	VIRM	4	115	0.40	54.62 (5.05)	0.25 (0.03)	0.40	0.93	0.62
53	Sdm	5AB	SLT	6	65	0.71	33.91 (1.32)	0.22 (0.02)	0.26	1.00	0.57
54	Shl	1	DDZ	4	53	0.44	46.95 (7.72)	0.32 (0.05)	0.49	0.95	0.53
55	Shl	1	ICM	7	59	0.42	51.79 (7.81)	0.27 (0.04)	0.46	0.89	0.49
56	Shl	1	SLT	4	142	0.40	51.23 (2.93)	0.28 (0.03)	0.31	0.82	0.70
57	Shl	2	DDZ	6	74	0.42	45.42 (5.81)	0.23 (0.03)	0.43	0.96	0.40
58	Shl	2	SLT	4	225	0.46	45.13 (2.71)	0.36 (0.03)	0.38	0.84	0.72
59	Shl	2	SLT	6	363	0.40	45.07 (2.25)	0.26 (0.02)	0.37	0.86	0.70
60	Shl	6	ICM	4	50	0.56	59.97 (3.78)	0.28 (0.04)	0.30	0.90	0.42
61	Tb	1e	DDZ	6	119	0.47	51.96 (2.89)	0.12 (0.01)	0.26	0.49	0.90
62	Tb	1e	ICM	3	83	0.56	45.09 (4.04)	0.33 (0.03)	0.42	0.52	0.94
63	Tb	1e	ICM	4	78	0.52	52.16 (3.54)	0.23 (0.02)	0.32	0.50	0.95
64	Tb	1e	ICM	7	240	0.40	46.04 (2.51)	0.13 (0.01)	0.32	0.43	0.90
65	Tb	3	FLIRT	6	72	0.44	44.85 (3.56)	0.16 (0.02)	0.33	0.86	0.88
66	Ut	18	VIRM	4	259	0.42	49.72 (3.35)	0.15 (0.01)	0.43	0.69	0.71
67	Ut	19	VIRM	4	137	0.46	52.84 (5.5)	0.16 (0.02)	0.48	0.70	0.80
68	Wd	5	ICM	3	51	0.69	33.69 (1.4)	0.28 (0.03)	0.18	0.68	0.53
69	Wd	5	ICM	6	144	0.42	37.34 (2.05)	0.21 (0.02)	0.30	0.86	0.60
70	Wp	5	SLT	4	95	0.40	30.68 (3.9)	0.46 (0.06)	0.44	0.66	0.65
71	Wp	6	SLT	4	60	0.46	35.21 (2.75)	0.32 (0.04)	0.25	0.61	0.88
72	Zd	1	VIRM	4	146	0.46	43.21 (1.57)	0.24 (0.02)	0.02	0.93	0.57
73	Zd	4	SLT	4	60	0.64	30.15 (3.08)	0.49 (0.05)	0.39	0.80	0.72

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Table J.6 – *Continued from previous page*

No.	Station	Platform	Stock	Len.	n	$Adj.R^2$	β_0 (SD)	β_1 (SD)	%PST	%laat	%lang
Hennige model scenarios											
74	Zd	4	SLT	6	181	0.46	35.27 (1.7)	0.25 (0.02)	0.32	0.85	0.75

Table J.6: Overview of results obtained using the Hennige regression model

Lam-Puong model scenarios

No.	Station	Platform	Stock	Len.	n	$Adj.R^2$	β_0 (SD)	β_1 (SD)	β_2 (SD)	%PST	%laat	%lang
1	Alm	4	DDZ	4	108	0.43	38.12 (4.57)	0.48 (0.07)	n.s.	0.42	0.74	0.57
2	Almp	1	SLT	12	161	0.41	33.01 (1.05)	0.14 (0.02)	0.51 (0.15)	0.22	0.99	0.42
3	Apn	2	ICM	3	65	0.59	48.11 (3.01)	0.43 (0.06)	0.24 (0.06)	0.26	0.82	0.81
4	Asb	2	VIRM	6	693	0.43	38.24 (0.83)	0.14 (0.01)	0.12 (0.01)	0.19	0.68	0.56
5	Asb	2	VIRM	8	153	0.56	41.74 (1.43)	0.14 (0.01)	0.04 (0.01)	0.15	0.70	0.67
6	Asb	3	SLT	12	56	0.55	37.66 (2.38)	0.12 (0.02)	0.09 (0.01)	0.26	0.79	0.91
7	Asb	6	SGMM	3	77	0.42	29.14 (2.3)	0.3 (0.06)	0.16 (0.03)	0.31	0.63	0.42
8	Asb	6	SGMM	5	83	0.41	30.7 (1.88)	0.14 (0.02)	0.1 (0.02)	0.27	0.66	0.47
9	Asb	6	SGMM	6	55	0.43	32.42 (2.46)	0.22 (0.04)	0.08 (0.02)	0.29	0.70	0.41
10	Asb	7	VIRM	6	461	0.47	39.11 (1.06)	0.17 (0.01)	0.08 (0.01)	0.21	0.82	0.59
11	Asb	8	VIRM	4	147	0.50	35.39 (1.82)	0.2 (0.02)	0.27 (0.08)	0.17	0.91	0.49
12	Asb	8	VIRM	6	124	0.70	37.62 (2.04)	0.14 (0.01)	0.21 (0.07)	0.20	0.92	0.62
13	Asdl	1	SLT	8	677	0.44	37.5 (0.8)	0.21 (0.01)	n.s.	0.23	0.75	0.78
14	Asdz	1	DDZ	8	69	0.54	46.39 (3.62)	0.06 (0.02)	0.12 (0.02)	0.33	0.67	0.90
15	Asdz	1	ICM	4	51	0.57	37.24 (5.28)	0.5 (0.08)	n.s.	0.44	0.67	0.87
16	Asdz	1	ICM	7	109	0.45	45.43 (4.28)	0.22 (0.05)	0.1 (0.01)	0.38	0.61	0.93
17	Asdz	1	VIRM	10	344	0.42	41.21 (1.73)	0.06 (0.01)	0.06 (0)	0.34	0.62	0.65
18	Asdz	3	ICM	3	108	0.63	37.43 (1.68)	0.39 (0.08)	0.27 (0.04)	0.25	0.61	0.41
19	Asdz	3	ICM	6	108	0.51	43.58 (2.77)	0.32 (0.05)	0.1 (0.02)	0.26	0.87	0.42
20	Asdz	3	ICM	8	66	0.44	42.77 (2.72)	0.16 (0.05)	0.12 (0.03)	0.24	0.92	0.37
21	Asdz	3	SLT	4	501	0.61	37.89 (0.93)	0.4 (0.03)	0.23 (0.02)	0.27	0.71	0.50
22	Asdz	3	SLT	6	537	0.52	36.11 (1.15)	0.2 (0.02)	0.24 (0.02)	0.28	0.70	0.50
23	Asdz	3	VIRM	12	117	0.41	62.08 (3.02)	0.35 (0.08)	0.02 (0.01)	0.28	0.98	0.19
24	Asdz	4	DDZ	4	266	0.49	39 (2.01)	0.18 (0.02)	0.17 (0.02)	0.39	0.90	0.74
25	Asdz	4	ICM	10	55	0.57	59.48 (4.07)	0.04 (0.01)	0.13 (0.02)	0.30	0.99	0.90
26	Asdz	4	ICM	3	86	0.49	44.11 (2.66)	0.2 (0.04)	0.27 (0.06)	0.28	0.86	0.62

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Table J.7 – *Continued from previous page*

No.	Station	Platform	Stock	Len.	n	$Adj.R^2$	β_0 (SD)	β_1 (SD)	β_2 (SD)	%PST	%laat	%lang
Lam-Puong model scenarios												
27	Asdz	4	ICM	4	98	0.43	41.65 (3.68)	0.26 (0.04)	0.18 (0.08)	0.38	0.91	0.74
28	Asdz	4	ICM	7	262	0.42	45.31 (1.94)	0.07 (0.01)	0.19 (0.02)	0.33	0.95	0.78
29	Asdz	4	VIRM	8	74	0.46	37.92 (3.7)	0.1 (0.02)	0.09 (0.02)	0.34	0.89	0.51
30	Ass	3AB	SLT	4	97	0.43	34.56 (2.71)	0.4 (0.05)	n.s.	0.33	0.70	0.92
31	Ass	4AB	SGMM	3	88	0.44	34.94 (1.9)	0.19 (0.03)	0.14 (0.05)	0.24	0.75	0.82
32	Ass	4AB	SLT	6	86	0.57	33.22 (3.06)	0.33 (0.03)	n.s.	0.30	0.79	0.82
33	Ass	5BA	SLT	12	94	0.71	36.5 (2.23)	0.1 (0.04)	0.1 (0.01)	0.27	0.96	0.84
34	Ass	6BA	SLT	12	91	0.54	43.62 (1.97)	n.s.	0.08 (0.01)	0.13	0.83	0.89
35	Ass	7AB	VIRM	8	515	0.43	42.84 (1.05)	0.04 (0.01)	0.23 (0.01)	0.20	0.77	0.71
36	Bd	5	FLIRT	4	124	0.45	42.7 (2.73)	0.46 (0.05)	0.07 (0.03)	0.24	0.76	0.48
37	Bhv	1	SGMM	8	51	0.57	33.33 (4.3)	n.s.	0.13 (0.02)	0.29	0.94	0.60
38	Brd	4	SGMM	3	66	0.41	36.61 (1.51)	n.s.	0.22 (0.05)	0.08	0.69	0.55
39	Dv	1	ICM	3	63	0.47	48.01 (6.14)	n.s.	0.45 (0.08)	0.36	0.83	0.47
40	Dvd	4	VIRM	8	57	0.58	42 (2.31)	n.s.	0.11 (0.01)	0.12	0.80	0.89
41	Ed	4E	VIRM	10	609	0.40	48.91 (1.12)	0.11 (0.02)	0.11 (0.01)	0.26	0.94	0.93
42	Gd	3Am	SLT	4	74	0.49	32.59 (2.46)	0.33 (0.05)	0.2 (0.04)	0.30	0.81	0.62
43	Gd	3AmB	ICM	4	50	0.48	45.33 (7.28)	0.71 (0.1)	n.s.	0.28	0.95	0.80
44	Gd	5AmB	ICM	8	65	0.61	44 (2.37)	0.22 (0.02)	0.14 (0.03)	0.23	0.86	0.90
45	Gv	5AB	VIRM	6	57	0.52	44.84 (3.49)	0.22 (0.04)	n.s.	0.22	0.86	0.45
46	Hfd	4A	SLT	6	206	0.43	35.48 (1.3)	0.21 (0.03)	0.12 (0.03)	0.20	0.73	0.26
47	Hlms	1	SLT	6	82	0.54	30.01 (1.69)	0.69 (0.14)	n.s.	0.17	0.99	0.36
48	Hmbv	1	FLIRT	8	318	0.41	32.84 (0.76)	0.16 (0.01)	0.42 (0.19)	0.12	0.99	0.35
49	Hwzb	1	SLT	6	53	0.50	27.12 (2.05)	0.54 (0.13)	0.82 (0.35)	0.21	0.72	0.38
50	Nm	3B	ICM	3	85	0.48	53.55 (4.99)	0.3 (0.09)	0.29 (0.07)	0.36	0.80	0.46
51	Rai	2	VIRM	4	89	0.64	34.62 (3.13)	0.76 (0.06)	n.s.	0.21	0.84	0.33

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Table J.7 – *Continued from previous page*

No.	Station	Platform	Stock	Len.	n	$Adj.R^2$	β_0 (SD)	β_1 (SD)	β_2 (SD)	%PST	%laat	%lang
Lam-Puong model scenarios												
52	Rai	2	VIRM	6	130	0.52	28.21 (2.48)	0.76 (0.06)	0.37 (0.15)	0.33	0.85	0.27
53	Rai	3	VIRM	4	75	0.55	23.68 (4.06)	0.63 (0.28)	0.83 (0.09)	0.49	0.86	0.29
54	Rai	3	VIRM	6	108	0.41	35.29 (2.79)	0.33 (0.13)	0.46 (0.05)	0.29	0.88	0.33
55	Rta	1	ICM	12	107	0.42	50.28 (2.56)	0.09 (0.02)	0.09 (0.03)	0.27	1.00	0.95
56	Rta	1	SLT	4	503	0.42	30.99 (0.7)	0.28 (0.03)	0.18 (0.01)	0.24	0.77	0.60
57	Rta	2	ICM	10	100	0.42	51.69 (2.14)	0.23 (0.05)	0.09 (0.02)	0.22	0.96	0.94
58	Rta	2	SLT	4	952	0.46	36.6 (0.59)	0.26 (0.02)	0.27 (0.02)	0.25	0.95	0.75
59	Rta	2	SLT	6	1061	0.44	37.66 (0.5)	0.23 (0.02)	0.2 (0.01)	0.19	0.94	0.71
60	Rtb	2	SGMM	8	65	0.41	42.08 (1.8)	0.11 (0.04)	0.09 (0.03)	0.16	0.91	0.80
61	Rtb	4	SGMM	5	65	0.41	30.75 (1.66)	0.33 (0.08)	n.s.	0.11	0.83	0.38
62	Rtd	9B	VIRM	4	115	0.40	54.23 (5.1)	0.27 (0.05)	0.21 (0.06)	0.40	0.93	0.62
63	Sdm	5AB	SLT	6	65	0.72	33.3 (1.36)	0.17 (0.03)	0.32 (0.06)	0.26	1.00	0.57
64	Shl	1	DDZ	4	53	0.43	48.31 (8.1)	0.28 (0.09)	0.34 (0.06)	0.48	0.95	0.53
65	Shl	1	ICM	7	59	0.45	45.37 (8.31)	0.43 (0.09)	0.22 (0.04)	0.52	0.89	0.49
66	Shl	1	SLT	4	142	0.43	49.85 (2.91)	0.33 (0.03)	0.17 (0.05)	0.32	0.82	0.70
67	Shl	2	DDZ	6	74	0.50	39.99 (5.59)	0.37 (0.05)	0.16 (0.03)	0.49	0.96	0.40
68	Shl	2	SLT	4	225	0.49	44.06 (2.67)	0.42 (0.03)	0.23 (0.05)	0.40	0.84	0.72
69	Shl	2	SLT	6	363	0.45	45.88 (2.17)	0.31 (0.02)	0.09 (0.03)	0.35	0.86	0.70
70	Shl	6	ICM	4	50	0.55	59.96 (3.82)	0.28 (0.06)	0.29 (0.1)	0.30	0.90	0.42
71	Tb	1e	DDZ	6	119	0.47	53.1 (3.33)	0.1 (0.04)	0.15 (0.04)	0.24	0.49	0.90
72	Tb	1e	ICM	3	83	0.57	44.14 (4.02)	0.28 (0.04)	0.47 (0.08)	0.43	0.52	0.94
73	Tb	1e	ICM	4	78	0.56	50.59 (3.45)	0.16 (0.03)	0.39 (0.07)	0.35	0.50	0.95
74	Tb	1e	ICM	7	240	0.41	47.78 (2.7)	0.1 (0.02)	0.18 (0.03)	0.29	0.43	0.90
75	Tb	2	FLIRT	4	275	0.47	46.25 (1.65)	0.55 (0.04)	0.12 (0.02)	0.17	0.86	0.75
76	Tb	3	FLIRT	6	72	0.43	45.64 (3.74)	0.18 (0.04)	0.13 (0.05)	0.31	0.86	0.88

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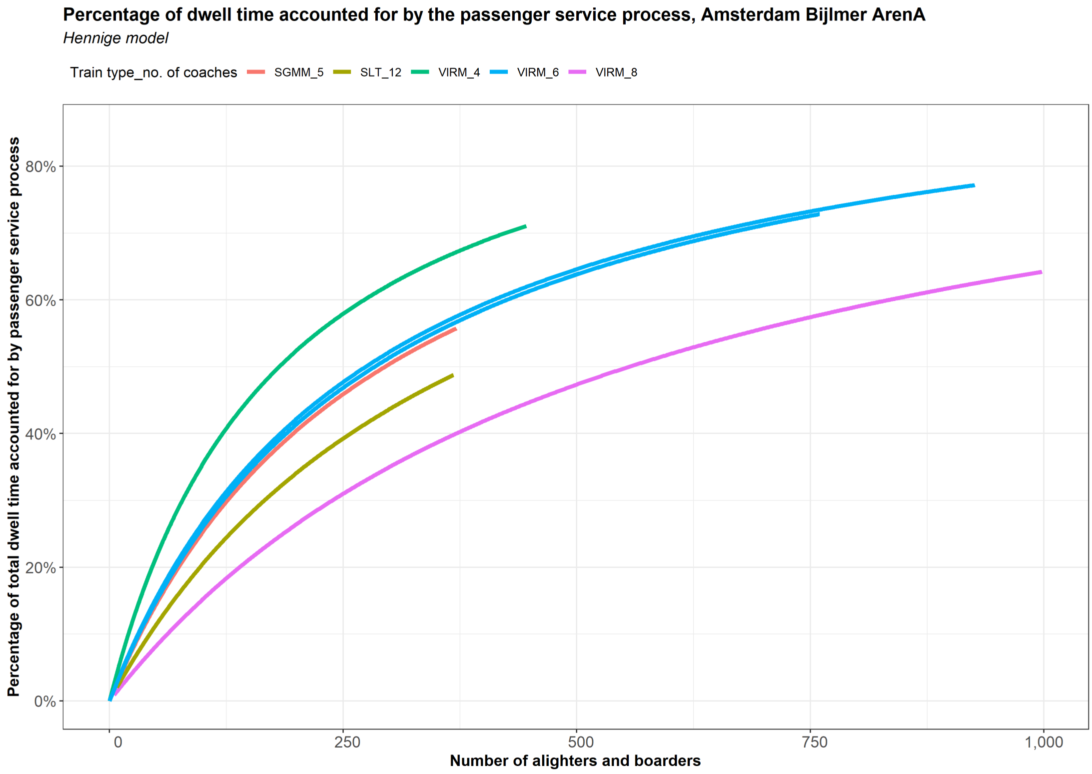
Table J.7 – *Continued from previous page*

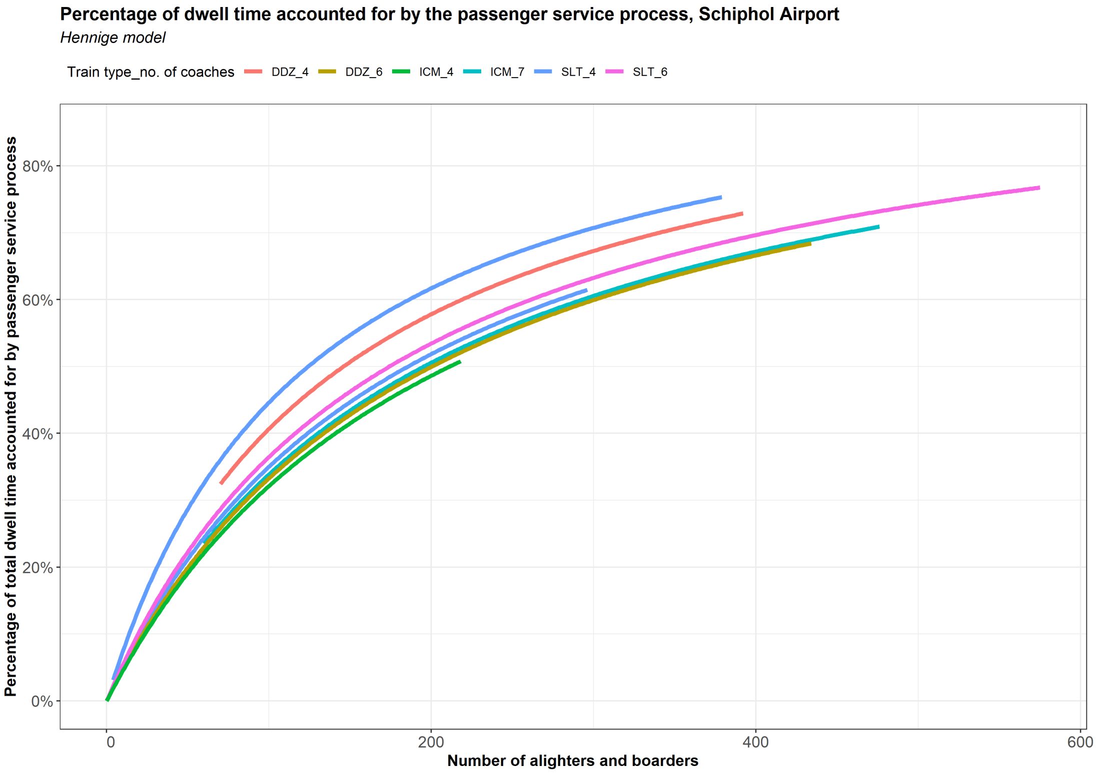
Lam-Puong model scenarios													
No.	Station	Platform	Stock	Len.	n	$Adj.R^2$	β_0 (SD)	β_1 (SD)	β_2 (SD)	%PST	%laat	%lang
77	Ut	18	VIRM	4	259	0.42	50.25 (3.39)	0.16 (0.02)	0.13 (0.02)	0.43	0.69	0.71
78	Ut	19	VIRM	4	137	0.47	53.69 (5.5)	0.2 (0.03)	0.12 (0.03)	0.47	0.70	0.80
79	Wd	5	ICM	3	51	0.68	33.96 (1.49)	0.3 (0.05)	0.24 (0.08)	0.18	0.68	0.53
80	Wd	5	ICM	6	144	0.45	36.56 (2.01)	0.36 (0.05)	n.s.	0.30	0.86	0.60
81	Wp	5	SLT	4	95	0.43	32.41 (3.87)	0.6 (0.08)	n.s.	0.36	0.66	0.65
82	Wp	6	SLT	4	60	0.46	34.9 (2.77)	0.39 (0.09)	0.23 (0.1)	0.26	0.61	0.88
83	Zd	1	VIRM	4	146	0.46	43.16 (1.6)	n.s.	0.24 (0.03)	0.02	0.93	0.57
84	Zd	4	SLT	4	60	0.68	35.27 (3.47)	0.57 (0.05)	n.s.	0.21	0.80	0.72
85	Zd	4	SLT	6	181	0.46	35.17 (1.72)	0.24 (0.03)	0.27 (0.05)	0.32	0.85	0.75

Table J.7: Overview of results obtained using the Lam-Puong model

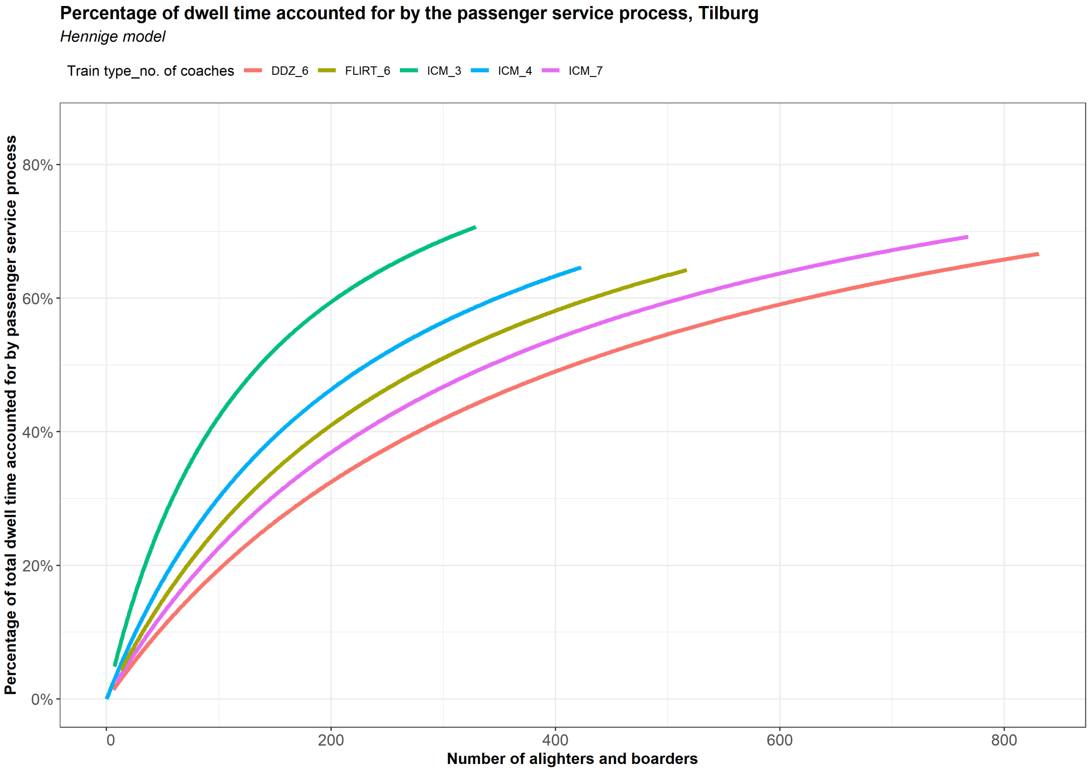
J.6 Influence of platform (and station)



(a) Amsterdam Bijlmer ArenA



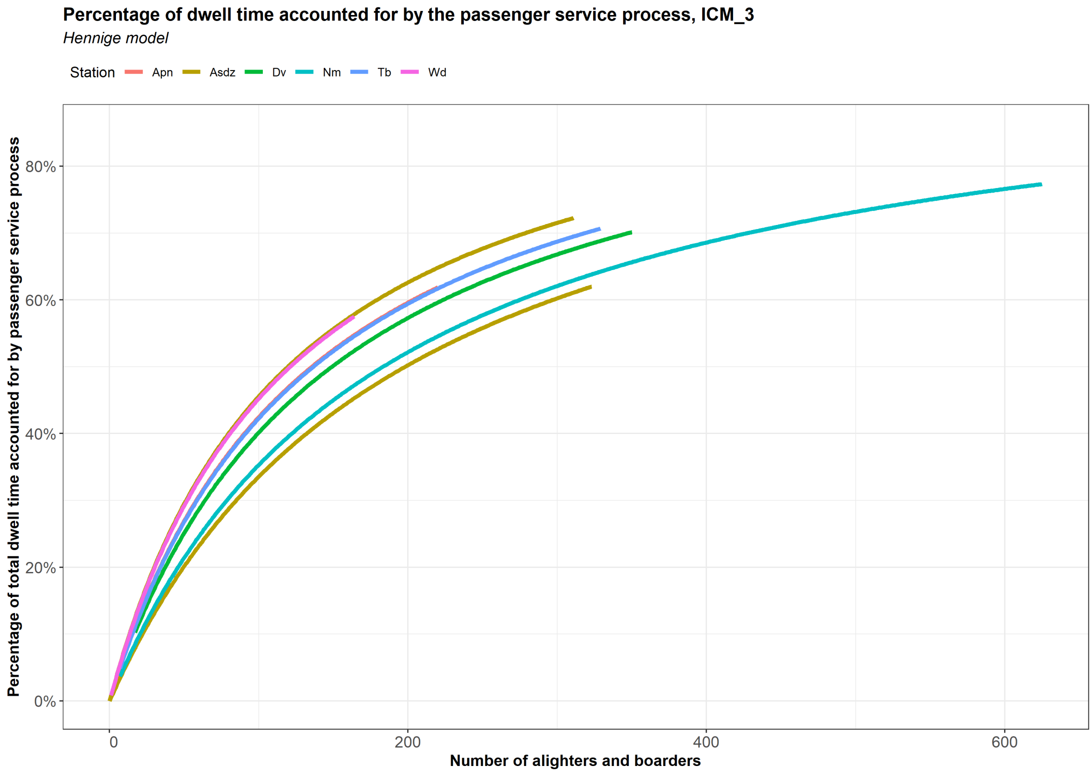
(b) Schiphol Airport



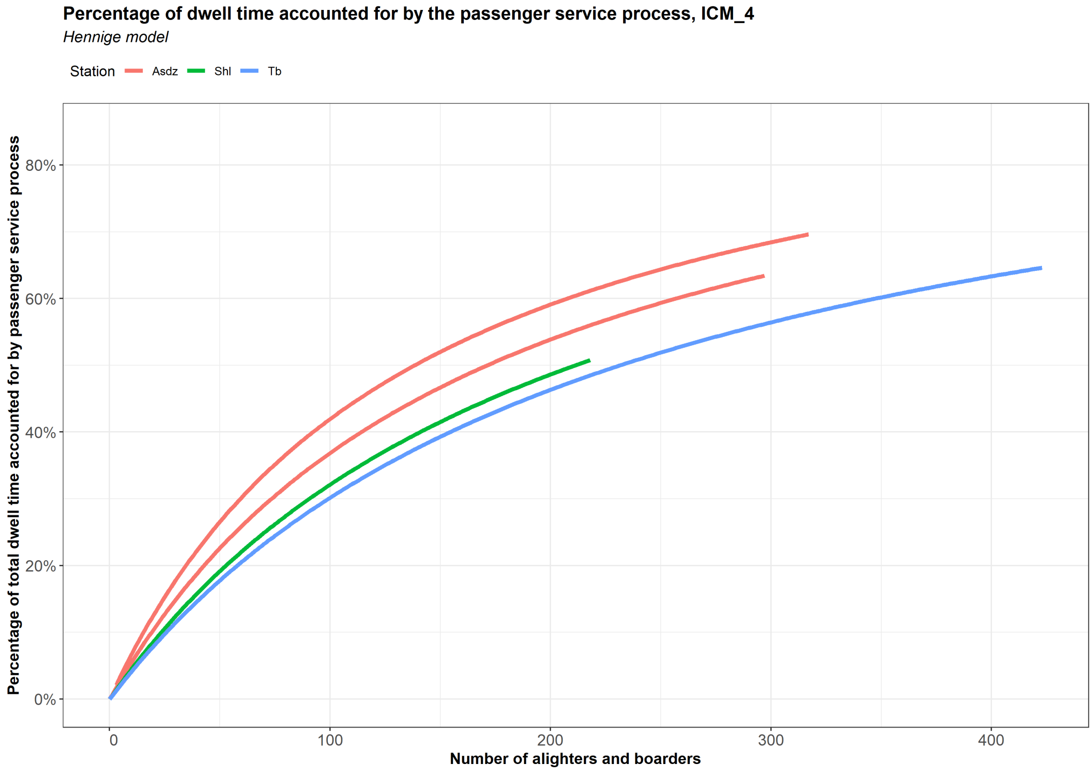
(c) Tilburg

Figure J.2: Percentage of dwell time accounted for by the passenger service process, as a function of the number of alighters and boarders at other selected stations with more than two different train types and lengths

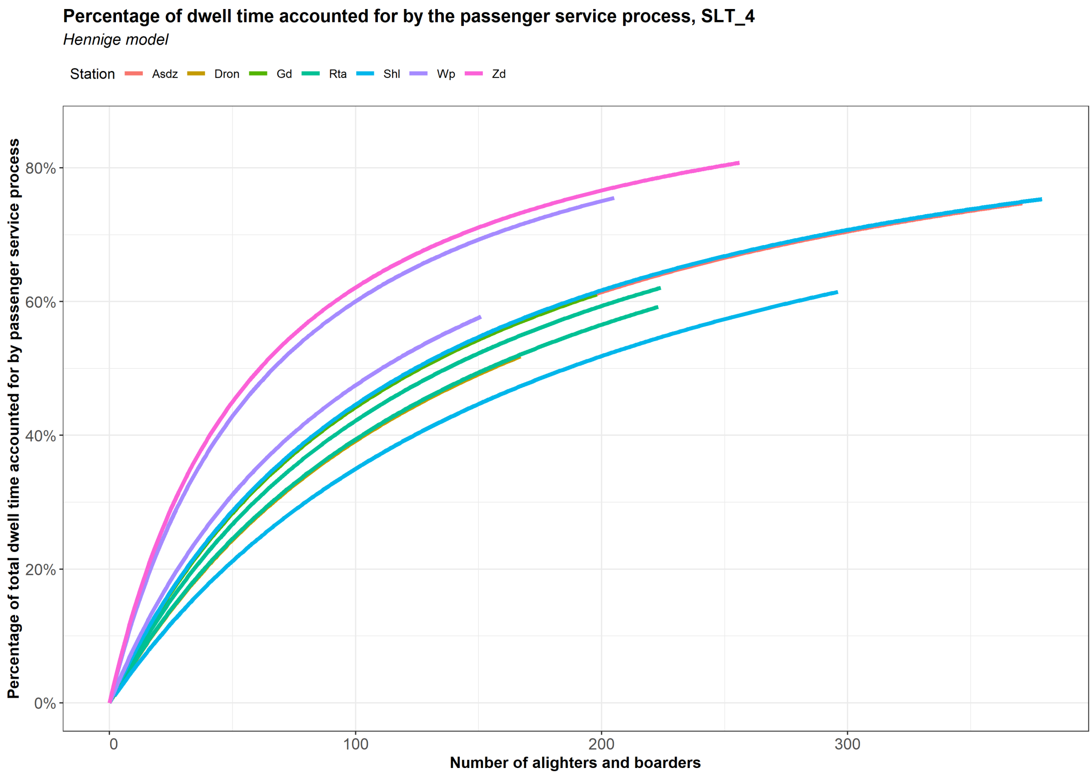
J.7 Influence of train type and length



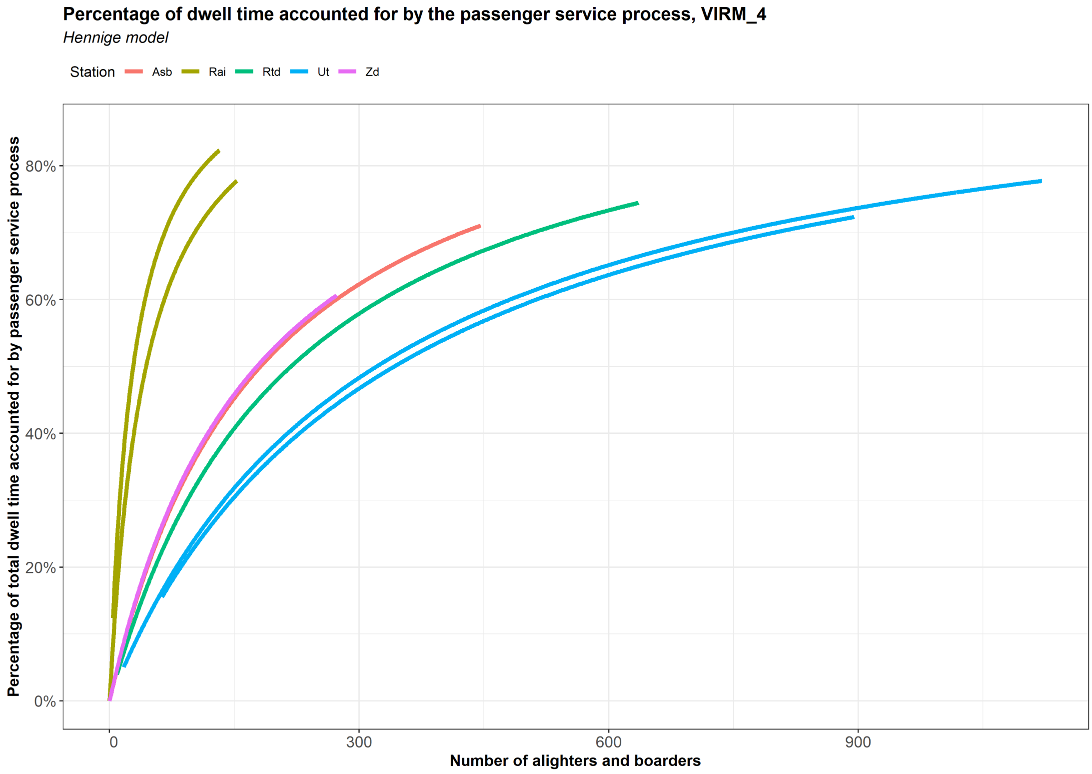
(a) ICM with three coaches



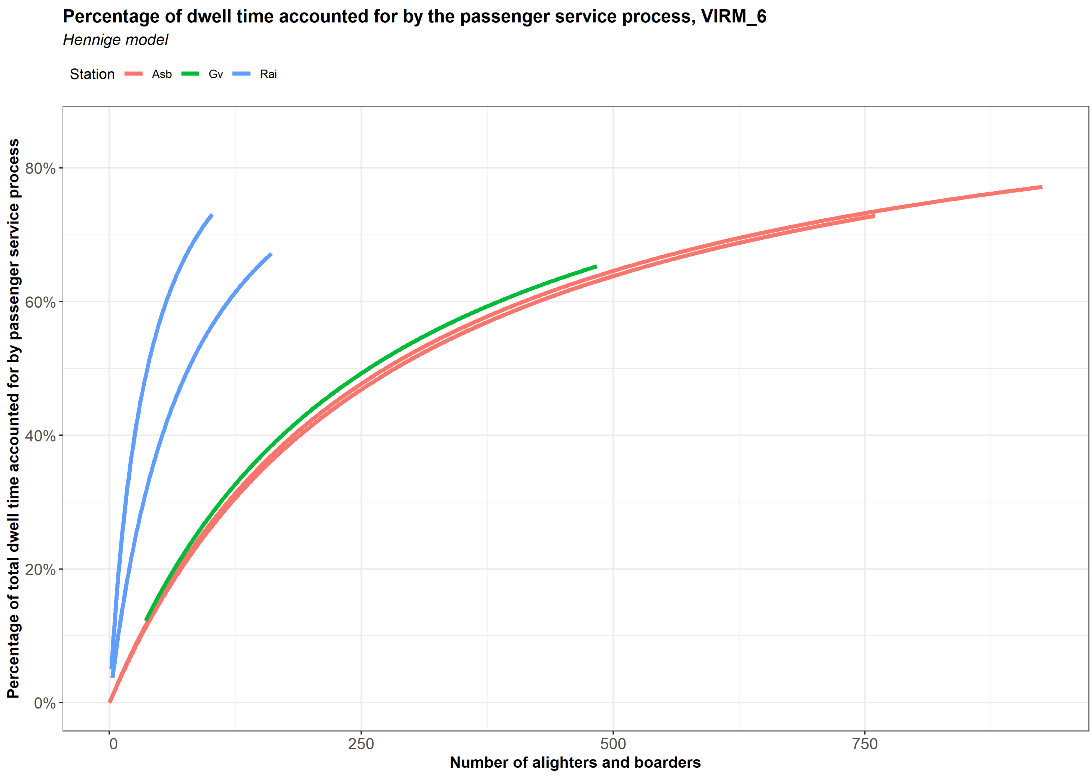
(b) ICM with four coaches



(c) SLT with four coaches



(d) VIRM with four coaches



(e) VIRM with six coaches

Figure J.3: Percentage of dwell time accounted for by the passenger service process, as a function of the number of alighters and boarders for different train types

Bibliography

[1] Paul Elberding. Roger van Boxtel: 'Doen we nix, dan lopen we muurvast'. *De Telegraaf*, 2018.

[2] Het Financieele Dagblad. Prorail waarschuwt voor bereiken limiet spoorgebruik. 2018.

[3] RTL Nieuws. Politie sluit perrons Amsterdam CS. 2013.

[4] Frans van den Berg. Amsterdam CS wacht mega-operatie. *Het Parool*, 2019.

[5] ProRail. Capaciteitsanalyse Utrecht Centraal (transferknelpunt perron 5/7). N.a.v. overbelastverklaring 2017/03 van 8 december 2016. Technical report, 2017.

[6] Frans van den Berg. NS heeft handen vol aan drukte Schiphol. *Leidsch Dagblad*, page 4–5, July 2017.

[7] NRC Handelsblad. NS vreest extra drukte op station Amsterdam-Zuid door Noord/Zuidlijn. 2018.

[8] Martijn Verburg. Extra maatregelen op Utrecht Centraal: perrons zijn vaak overvol. *De Gelderlander*, 2019.

[9] Ministerie van Infrastructuur en Milieu. Nationale Markt- en Capaciteitsanalyse 2017 - Hoofdrapport. Technical report, 2017.

[10] David Bremmer. Spoorchaos Randstad door werkzaamheden Leiden, treinreizigers vallen flauw. *Algemeen Dagblad*, 2019.

[11] Aseniya Dimitrova. Crowd control at Bijlmer ArenA station in Amsterdam. *TheMayor.eu*, 2019.

[12] J Vessen. Gevaarlijk station Wijchen krijgt voor 2012 tweede perron. *De Gelderlander*, 2010.

[13] Hein Eikenaar. Perron station Tilburg Universiteit aangepakt. *Brabants Dagblad*, 2017.

[14] Sandra Veltmaat. Gevaarlijk station eindelijk aangepakt. *De Stentor*, 2017.

[15] Ministerie van Verkeer en Waterstaat. Rapportage en voorkeursbeslissing over het Programma Hoogfrequent Spoorvervoer. Technical report, 2010.

[16] ProRail. NMCA Spoor 2030-2040 - Achtergrondrapportage. Technical report, Ministerie van Infrastreuctuur en Milieu, 2017.

[17] Ira Helsloot and Jacco Vis. Review risicomodel 2.0 perronveiligheid. Technical report, CrisisLab, 2020.

[18] Inspectie Leefomgeving en Transport. Hoe veilig is het spoor in 2016? Jaarverslag Spoorveiligheid. Technical report, Ministerie van Infrastructuur en Waterstaat, 2017.

[19] Inspectie Leefomgeving en Transport. Veiligheid op de rails. Jaarverslag Spoorwegveiligheid 2018. Technical report, Ministerie van Infrastructuur en Waterstaat, 2019.

[20] Ministerie van Infrastructuur en Waterstaat. Ontwikkelagenda Toekomstbeeld OV. Nu instappen naar 2040. Technical report, 2021.

[21] Rail Technology Magazine. Network Rail blames rocketing dwell times for poor performance, September 2015. [Last accessed: 4 September 2017].

[22] Ministerie van Infrastructuur & Waterstaat. *Contouren Toekomstbeeld OV 2040*. Ministerie van Infrastructuur & Waterstaat, 2019.

[23] Aral Voskamp. Measuring the influence of congested bottleneck on route choice behavior of pedestrians at Utrecht Centraal. Master's thesis, Delft University of Technology, 2012.

[24] Danique Ton. Navistation. a study into the route and activity location choice behaviour of departing pedestrians in train stations. Master's thesis, Delft University of Technology, 2014.

[25] Jeroen van den Heuvel. Field Experiments with Train Stopping Positions at Schiphol Airport Train Station in Amsterdam, The Netherlands. *Transportation Research Record: Journal of the Transportation Research Board*, 2546:24–32, 2016.

[26] Flurin S Hänseler, Jeroen PA van den Heuvel, Oded Cats, Winnie Daamen, and Serge P Hoogendoorn. A passenger-pedestrian model to assess platform and train usage from automated data. *Transportation research part A: policy and practice*, 132:948–968, 2020.

[27] Jeroen van den Heuvel, Jasmin Thurau, Martin Mendelin, Rik Schakenbos, Marcel van Ofwegen, and Serge P Hoogendoorn. An application of new pedestrian tracking sensors for evaluating platform safety risks at Swiss and Dutch train stations. In *International Conference on Traffic and Granular Flow*, pages 277–286. Springer, 2017.

[28] Arend Clahsen. Zonder Zuidasdok lopen OV en verkeer A10 absoluut vast. *Het Financieele Dagblad*, 2020.

[29] David Bremmer. Station Schiphol ondergaat grote facelift. *Het Parool*, 2019.

[30] Bureau Spoorbouwmeester. *Het Stationsconcept. Visie en toepassing*. Bureau Spoorbouwmeester, 2012.

[31] Jeroen van den Heuvel, Danique Ton, and Kim Hermansen. Advances in measuring pedestrians at Dutch train stations using Bluetooth, WiFi and infrared technology. In *Traffic and Granular Flow'15*, pages 11–18. Springer, 2016.

[32] Mark van Hagen. *Waiting Experience at Train Stations*. PhD thesis, Universiteit Twente, 2011.

[33] Jeroen Van den Heuvel, Koen Dekkers, and Susan De Vos. Estimating pedestrian flows at train stations using the Station Transfer Model. In *European Transport Conference*, 2012.

[34] Van Dale, 2017 (online; accessed 25 September 2017).

[35] Oxford Living Dictionaries, 2017 (online; accessed 25 September 2017).

[36] John J Fruin. *Pedestrian planning and design (Revised Edition)*. Elevator World, Inc., 1987.

[37] Serge Paul Hoogendoorn. *Sturen op verkeersstromen: waarom we niet zonder verkeersmanagement kunnen*. TU Delft Delft University of Technology, 2011.

[38] Dirk Helbing and Pratik Mukerji. Crowd disasters as systemic failures: analysis of the Love Parade disaster. *EPJ Data Science*, 1(1):7, 2012.

[39] Rail Safety and Standards Board (RSSB). *Health and safety effects of crowding. Research Programme Management*. 2005.

[40] Rail Safety and Standards Board (RSSB). *Minimisation of accidents at the train/platform interface. Research Programme Operations.* 2006.

[41] Paul Traub and Glenn Fraser. Safety assessment of CCTV for platform interface tasks - Sydney suburban trains. *Rail Human Factors: Supporting reliability, safety and cost reduction*, page 300, 2013.

[42] Brenda Lobb. Trespassing on the tracks: a review of railway pedestrian safety research. *Journal of Safety Research*, 37(4):359–365, 2006.

[43] Peter T Lin and James R Gill. Subway train-related fatalities in New York City: Accident versus suicide. *Journal of forensic sciences*, 54(6):1414–1418, 2009.

[44] Rail Safety and Standards Board (RSSB). *Improving suicide prevention methods on the rail network in Great Britain Annual Report 2011. Research Programme Operations and Management.* 2011.

[45] Grigore M Havârneanu, Jean-Marie Burkhardt, and Françoise Paran. A systematic review of the literature on safety measures to prevent railway suicides and trespassing accidents. *Accident Analysis & Prevention*, 81:30–50, 2015.

[46] Michiko Ueda, Yasuyuki Sawada, and Tetsuya Matsubayashi. The effectiveness of installing physical barriers for preventing railway suicides and accidents: evidence from japan. *Journal of affective disorders*, 178:1–4, 2015.

[47] Katharine Hunter-Zaworski, Dylan Anderson, Uwe Rutenberg, Ewa Tomaszewska, and James McConnell. Manual to improve rail transit safety at platform/vehicle and platform/guideway interfaces. 2017.

[48] Rail Safety and Standards Board (RSSB). *Controlling trespass and access from the platform end. A guide to good practice.* 2005.

[49] Rail Safety and Standards Board (RSSB). *An investigation into trespass and access via the platform ends at railway stations. Research Programme Operations.* 2005.

[50] Janice Daniel, Naomi G Rotter, and VF Nichnadowicz. Customer behavior relative to gap between platform and train. Technical report, New Jersey Department of Transportation, 2009.

[51] Chris J Baker, Mark Sterling, Gienia Figura-Hardy, Terry Johnson, P Free, G Munley, I Bowman, C Pope, and R Gawthorpe. The effect of train slipstreams on passengers and trackside workers. In *Proceedings of the 7th World Congress on Railway Research, Montreall*, 2006.

[52] Rail Safety and Standards Board (RSSB). *Evaluation of the benefits of yellow lines on non-high speed platforms. Research Programme Operations and Management.* 2010.

[53] Chi-Kin Law and Paul SF Yip. An economic evaluation of setting up physical barriers in railway stations for preventing railway injury: evidence from Hong Kong. *Journal of Epidemiology & Community Health*, pages 915–920, 2011.

[54] Shinya Yamada, Shintaro Terabe, and Makoto Kasai. Safety performance measures for railway stations. In *Transportation Research Board of the National Academies, 2014 Annual Meeting*, 2014.

[55] Ernst Bosina, Samira Britschgi, Mark Meeder, and Ulrich Weidmann. Distribution of passengers on railway platforms. In *15th Swiss Transport Research Conference (STRC 2015).* 15th Swiss Transport Research Conference, 2015.

[56] Chris J Baker, Andrew Quinn, Mikael Sima, Lars Hoefener, and Ricardo Licciardello. Full-scale measurement and analysis of train slipstreams and wakes. Part 1: Ensemble averages. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 228(5):451–467, 2014.

[57] P Connor. A review of platform/train interface protection systems on railways. *Railway Technical Web Pages*, 2015.

[58] Min-Woo Yeo, Seh-Chan Oh, Chang-ho Kim, and Dong-choon Lee. A study on the prevention of accidents in subway station through the surveys on accidents in a subway station. In *SICE-ICASE, 2006. International Joint Conference*, pages 3912–3915. IEEE, 2006.

[59] Rail Safety and Standards Board (RSSB). *Passenger risk at the platform-train interface*. 2011.

[60] Katharine Hunter-Zaworski. Analysis of passenger incident data from five rail transit systems. *Safety*, 3(3):21, 2017.

[61] Rail Safety and Standards Board (RSSB). *Effective management of risk from slipstream effects at trackside and platforms. Research Programme Engineering.* 2007.

[62] Anne Silla and Juha Luoma. Main characteristics of train–pedestrian fatalities on Finnish railroads. *Accident Analysis & Prevention*, 45:61–66, 2012.

[63] Djoen San Santoso, Supapat Mahadthai, Abdul Bari Jahed, and Nandar Tun. How safe is the rail platform? a study of Bangkok Mass Transit System (BTS). In *Proceedings of the Eastern Asia Society for Transportation Studies*, volume 9, 2013.

[64] Miltos Kyriakidis, Robin Hirsch, and Arnab Majumdar. Metro railway safety: An analysis of accident precursors. *Safety science*, 50(7):1535–1548, 2012.

[65] S Cynk, S Tong, N Kinnear, A Weare, E Delmonte, R Hutchins, and A Parkes. Qualitative study of platform-train interface incidents. Technical report, Transport Research Laboratory, 2014.

[66] Adelya Khayrullina, Bert Blocken, Wendy Janssen, and Jochem Straathof. CFD simulation of train aerodynamics: train-induced wind conditions at an underground railroad passenger platform. *Journal of Wind Engineering and Industrial Aerodynamics*, 139:100–110, 2015.

[67] M Sterling, CJ Baker, SC Jordan, and T Johnson. A study of the slipstreams of high-speed passenger trains and freight trains. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 222(2):177–193, 2008.

[68] Chris J Baker, Andrew Quinn, Mikael Sima, Lars Hoefener, and Ricardo Licciardello. Full-scale measurement and analysis of train slipstreams and wakes. Part 2: Gust analysis. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 228(5):468–480, 2014.

[69] Antonis Phasouliotis and Colin Williams. Intelligent platform management. In *IEEE International Conference on Intelligent Rail Transportation (ICIRT) 2016*, pages 145–149. IEEE, 2016.

[70] Jasmin Thurau, Jeroen van den Heuvel, Nicolas Keusen, Marcel van Ofwegen, and Serge Hoogendoorn. Influence of the Pedestrian Density on the Use of the Danger Zone at Platforms of Train Stations. In *Conference on Traffic and Granular Flow (TGF)*, 2017.

[71] Dylan Anderson and Katharine Hunter-Zaworski. Platform Edge Detection and Protection Effects on Platform–Train Interface Safety. *Transportation Research Record: Journal of the Transportation Research Board*, (2534):24–30, 2015.

[72] Wiktoria Heinz. *Passenger service times on trains*. PhD thesis, Royal Institute of Technology Stockholm, 2003.

[73] MS Wilms and HFL Frieling. Risicomodel Perronveiligheid. Technical Report 3665, Intergo, 2015.

[74] Kirrilly Thompson, Lily Hirsch, S Muller, and S Rainbird. A socio-economic study of carriage and platform crowding in the Australian railway industry: Final Report. *CRC for Rail Innovation, Brisbane, Australia*, 2012.

[75] ProRail. *Basisstation 2005, deel A en B. Functionele normen en richtlijnen voor treinstations*. ProRail, 2005.

[76] Hans van Gelderen. *Basisstation. Functionele normen en richtlijnen voor stations/OV-knopen*. Railned, 1999.

[77] ProRail. *Ontwerprichtlijnen, Beheerrichtlijnen en Afkeurnormen voor de transferkwaliteit van treinstations in Nederland (RLN00286)*. ProRail, 2010.

[78] ProRail. *Ontwerpvoorschrift Perrons (OVS00067)*. ProRail, 2012.

[79] ProRail. *Regels voor het functioneel ontwerp van railinfrastructuur*. ProRail, 2016.

[80] SP Hoogendoorn and W Daamen. Toetsing en aanscherping methodiek NPI Transferdrukte. Technical report, Technische Universiteit Delft, December 2005.

[81] Serge P Hoogendoorn, Winnie Daamen, Arwina de Boer, and Ilka Vaatstra. Assessing passenger comfort and capacity bottlenecks in Dutch train station. *Transportation Research Record: Journal of the Transportation Research Board*, (2002):107–116, 2007.

[82] Marc Starmans, Lee Verhoeff, and Jeroen van den Heuvel. Passenger transfer chain analysis for reallocation of heritage space at Amsterdam Central station. In *The Conference on Pedestrian and Evacuation Dynamics 2014 (PED2014)*, pages 651–659, 2014.

[83] Winnie Daamen, Serge Hoogendoorn, and Mario Campanelle. Assessing pedestrian flow condition in Schiphol Plaza: Can Schiphol Plaza cope with future traveller demands? In *Proceedings 10th TRAIL-Congress, Trail in perspective, TRAIL Research School, Delft*, pages 1–15, 2008.

[84] Jeroen van den Heuvel and Jan Hoogenraad. Monitoring the performance of the pedestrian transfer function of train stations using automatic fare collection data. In *The Conference on Pedestrian and Evacuation Dynamics 2014 (PED2014)*, pages 642–650, 2014.

[85] Network Rail. *Station Design Principles for Network Rail (BLDG-SP80-002)*. Network Rail, 2015.

[86] Network Rail. *Station capacity planning guidance*. Network Rail, 2016.

[87] London Underground. *Station Planning Standards and Guidelines (G371A)*. 2012.

[88] Rail Safety and Standards Board (RSSB). *Interface between Station Platforms, Track and Trains (GI/RT7016)*. Rail Safety and Standards Board, 2014.

[89] Rail Safety and Standards Board (RSSB). *Guidance on Interface between Station Platforms, Track and Trains (GI/GN7616)*. Rail Safety and Standards Board, 2014.

[90] Rail Safety and Standards Board. *Platform train interface strategy*. Rail Safety and Standards Board, 2015.

[91] Nicolas Le Glatin, Isabelle Milford, and Andrew Hutton. London Bridge: The Role Pedestrian Modelling Played in Designing the New Station. *Pedestrian and Evacuation Dynamics 2012*, 2012.

[92] Stefan Buchmüller and Ulrich Weidmann. *Handbuch zur Anordnung und Dimensionierung von Fussgängerverkehrsanlagen in Bahnhöfen*. Schweizerische Bundesbahnen (SBB), 2008.

[93] Bundesamt für Verkehr (BAV). Abstände auf Perrons. Gefahrenbereich - Sicherer Bereich. Technical report, Bundesamt für Verkehr (BAV), 2011.

[94] John Fruin and Gregory Benz. Pedstrian Time-Space Concept for Analyzing Corners and Crosswalks. *Transportation Research Record*, 959:18–24, 1984.

[95] B Pushkarev and JM Zupan. *Urban space for pedestrians: a report of the Regional Plan Association*. MIT Press, 1975.

[96] Ulrich Weidmann. *Transporttechnik der Fussgänger. Transporttechnische Eigenschaften des Fussgängerverkehrs (Literaturauswertung)*. IVT, Institut für Verkehrsplanung, Transporttechnik, Strassen- und Eisenbahnbau, 1993.

[97] Verband Öffentlicher Verkehr (VÖV). Planungshilfe Publikumsanlagen. Technical report, 2017.

[98] Ernst Bosina, Mark Meeder, and Ulrich Weidmann. Grundsatzfrage der Sicherheit von Fahrgästen auf Perrons - Vorstudie. Technical report, ETH, 2016.

[99] Julian Ross. *Railway stations: planning, design and management*. Architectual Press, 2000.

[100] Transportation Research Board. *Highway Capacity Manual*. Transportation Research Board of the National Academies, 2010.

[101] Kittelson & Associates, Inc., Parsons Brinckerhoff, KFH Group, Inc., Texas A&M Transportation Institute, and Arup. *Transit Capacity and Quality of Service Manual. Third Edition. TCRP Report 165*. Transportation Research Board, 2013.

[102] Justin D Antos, Wendy Jia, and Jonathan H Parker. Is It Too Crowded in Here?: In Search of Safety Standards for Pedestrian Congestion in Rail Stations. *Transportation Research Record*, 2648(1):126–133, 2017.

[103] Gregory Benz. *Pedestrian Time-Space Concept. A New Approach to the Planning and Design of Pedestrian Facilities*. Parsons Brinckerhoff Quade & Douglas, Inc., 1986.

[104] Tom Parkinson and Ian Fisher. *Rail transit capacity*, volume 13. Transportation Research Board, 1996.

[105] Winnie Daamen. *Modelling passenger flows in public transport facilities*. PhD thesis, TRAIL Research School The Netherlands, 2004.

[106] Stefan Buchmueller and Ulrich Weidmann. Parameters of pedestrians, pedestrian traffic and walking facilities. *IVT Schriftenreihe*, 132, 2006.

[107] Jun Zhang. *Pedestrian fundamental diagrams: Comparative analysis of experiments in different geometries*, volume 14. Forschungszentrum Jülich, 2012.

[108] Serge P Hoogendoorn, Winnie Daamen, Victor L Knoop, Jeroen Steenbakkers, and Majid Sarvi. Macroscopic Fundamental Diagram for pedestrian networks: theory and applications. *Transportation research procedia*, 23:480–496, 2017.

[109] Winnie Daamen, Jeroen van den Heuvel, Victor L Knoop, and Serge P Hoogendoorn. Macroscopic Fundamental Diagram for Train Platforms. In *International Conference on Traffic and Granular Flow*, pages 365–372. Springer, 2017.

[110] Maria Grigoriadou and John P. Braaksma. Application of the Time-Space Concept in Analyzing Metro Station Platforms. *ITE Journal*, May 1986.

[111] W Daamen and SP Hoogendoorn. Pedestrian traffic flow operations on a platform: observations and comparison with simulation tool SimPed. *Computers in Railways IX*, pages 125–134, 2004.

[112] Flurin Hänseler. *Modeling and estimation of pedestrian flows in train stations*. PhD thesis, École Polytechnique Fédérale de Lausanne, 2016.

[113] Ulrich Weidmann. *Der Fahrgastwechsel im Öffentlichem Personenverkehr*. PhD thesis, ETH Zürich, 1994.

[114] Vukan R Vuchic. *Urban Transit Systems and Technology*. Wiley Online Library, 2007.

[115] Douglas M. Mansel, Paul J. Menaker, and Gary Hartnett. High-Capacity Light Rail Transit. Balancing Stationside and Railside Capacities. *Transportation Research Record*, 1623:170–178, 1998.

[116] Fabien Leurent. Transport capacity constraints on the mass transit system. a systemic analysis. *European Transport Research Review*, 3(1):11–21, 2011.

[117] Sivakrishna Srikukenthiran. *Integrated Microsimulation Modelling of Crowd and Subway Network Dynamics For Disruption Management Support*. PhD thesis, University of Toronto, 2016.

[118] Winnie Daamen, Jeroen van den Heuvel, Danique Ton, and Serge Hoogendoorn. Using Bluetooth and WiFi to unravel real-world slow mode activity travel behaviour. In *Forteenth International Conference on Travel Behaviour Research*, 2015.

[119] HVC Howarth, MJ Griffin, C Childs, T Fujiyame, and SG Hodder. Comfortable sardines: the balance between comfort and capacity. Technical report, Southampton Railway Systems Research School of Civil Engineering and the Environment University of Southampton, 2011.

[120] John Alexander Haith. *Understanding the Relationship Between Capacity Utilisation and Performance and the Implications for the Pricing of Congested Rail Networks*. PhD thesis, University of Leeds, 2015.

[121] *Bahnhofs-Passerelle Basel: Rennen Sie noch um Ihr Leben oder schon auf den nächsten Zug?* Barfi.ch, 2016 (online; accessed 25 September 2017).

[122] Jeroen van den Heuvel, Danique Ton, and Kim Hermansen. Advances in Measuring pedestrians at Dutch train stations using Bluetooth, WiFi and infrared technology. In *Traffic and Granular Flow'15*, pages 11–18. Springer, 2016.

[123] Jeroen van den Heuvel, Aral Voskamp, Winnie Daamen, and Serge P Hoogendoorn. Using Bluetooth to estimate the impact of congestion on pedestrian route choice at train stations. In *Traffic and Granular Flow'13*, pages 73–82. Springer, 2015.

[124] Susan de Vos. Transfer Concept. Een veilige en uitnodigende looproute tussen treinen keten, die door de reiziger als logisch en leesbaar wordt ervaren. Technical report, NS Poort, 2011.

[125] Jeroen van den Heuvel, Eelco Thiellier, and Niels van Gerwen. Privacy by Design bij reizigersmetingen op stations. *Privacy and Compliance - Tijdschrift voor de praktijk*, (3):17–21, 2013.

[126] R Core Team. *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria, 2018.

[127] Jan Hoogenraad and Aart de Vos en Jaap de Vries. NS-project Aurora voorspelt voor elke trein het aantal reizigers. *STAtOR*, 3(4):28–31, 2013.

[128] Nikola Besinovic. *Integrated capacity assessment and timetabling models for dense railway networks*. PhD thesis, Delft University of Technology, 2017.

[129] Koninklijk Nederlands Meteorologisch Instituut (KNMI) - Ministerie van Infrastructuur en Waterstaat. Daggegevens van het weer in Nederland, 08 2019.

[130] Ministerie van Infrastructuur en Waterstaat. Voorkeursbeslissing MIRT-verkenning Multimodale Knoop Schiphol. Technical report, 2019.

[131] Jeroen Van den Heuvel. Trajectory data Amsterdam Zuid (track 1-2). 4TU.ResearchData. Dataset. DOI: 10.4121/20683062, 2022.

[132] Jeroen Van den Heuvel. Trajectory data Amsterdam Zuid (track 3-4). 4TU.ResearchData. Dataset. DOI: 10.4121/20691659, 2022.

[133] Jeroen Van den Heuvel. Trajectory data Utrecht Centraal (track 5). 4TU.ResearchData. Dataset. DOI: 10.4121/20692247, 2022.

[134] Jack Liddle, Armin Seyfried, Bernhard Steffen, Wolfram Klingsch, Tobias Rupprecht, Andreas Winkens, and Maik Boltes. Microscopic insights into pedestrian motion through a bottleneck, resolving spatial and temporal variations. *arXiv preprint arXiv:1105.1532*, 2011.

[135] Dorine C Duives, Winnie Daamen, and Serge P Hoogendoorn. Quantification of the level of crowdedness for pedestrian movements. *Physica A: Statistical Mechanics and its Applications*, 427:162–180, 2015.

[136] Dirk Helbing, Anders Johansson, and Habib Zein Al-Abideen. Dynamics of crowd disasters: An empirical study. *Physical review E*, 75(4):046109, 2007.

[137] Dirk Helbing and Anders Johansson. Pedestrian, crowd and evacuation dynamics. In *Encyclopedia of complexity and systems science*, pages 6476–6495. Springer, 2009.

[138] Michael J Seitz and Gerta Köster. Natural discretization of pedestrian movement in continuous space. *Physical Review E*, 86(4):046108, 2012.

[139] ”queue”. *merriam-webster.com*. 2018. https://www.merriam-webster.com/dictionary/queue (25 December 2018).

[140] ”queue”. *cambridge.org*. 2018. https://dictionary.cambridge.org/dictionary/english/queue (25 December 2018).

[141] ”queue”. *oxforddictionaries.com*. 2018. https://en.oxforddictionaries.com/definition/queue (25 December 2018).

[142] Leon Mann. Queue culture: The waiting line as a social system. *American Journal of Sociology*, 75(3):340–354, 1969.

[143] Shigeyuki Okazaki and Satoshi Matsushita. A study of simulation model for pedestrian movement with evacuation and queuing. In *International Conference on Engineering for Crowd Safety*, volume 271, 1993.

[144] John F Shortle, James M Thompson, Donald Gross, and Carl M Harris. *Fundamentals of queueing theory*, volume 399. John Wiley & Sons, 2018.

[145] Dirk Helbing. Models for pedestrian behavior. *arXiv preprint cond-mat/9805089*, 1998.

[146] Chikashi Arita. Queueing process with excluded-volume effect. *Physical Review E*, 80(5):051119, 2009.

[147] Daichi Yanagisawa, Akiyasu Tomoeda, Rui Jiang, and Katsuhiro Nishinari. Excluded volume effect in queueing theory. *JSIAM Letters*, 2:61–64, 2010.

[148] Chikashi Arita and Andreas Schadschneider. Density profiles of the exclusive queuing process. *Journal of Statistical Mechanics: Theory and Experiment*, 2012(12):P12004, 2012.

[149] Chikashi Arita and Andreas Schadschneider. The dynamics of waiting: the exclusive queueing process. *Transportation Research Procedia*, 2:87–95, 2014.

[150] Angelika Kneidl. How do people queue? A study of different queuing models. In *Traffic and Granular Flow'15*, pages 201–208. Springer, 2016.

[151] Paul Davis and Goutam Dutta. Estimation of capacity of escalators in London Underground. *London School of Economics and Political Sciences, London*, 2002.

[152] ProRail. NS en ProRail blikken vooruit op vernieuwingen Enschede. 2013.

[153] NS. Vijf vragen over stationsroltrappen, 2017.

[154] RTL Nieuws. Rechts staan, links lopen op de roltrap? Stilstaan is sneller, 2016.

[155] Inhi Kim, Ronald Galiza, and Luis Ferreira. Modeling pedestrian queuing using micro-simulation. *Transportation Research Part A: Policy and Practice*, 49:232–240, 2013.

[156] Mingjun Liao and Gang Liu. Modeling passenger behavior in nonpayment areas at rail transit stations. *Transportation Research Record: Journal of the Transportation Research Board*, (2534):101–108, 2015.

[157] Daichi Yanagisawa, Yushi Suma, Akiyasu Tomoeda, Ayako Miura, Kazumichi Ohtsuka, and Katsuhiro Nishinari. Walking-distance introduced queueing model for pedestrian queueing system: Theoretical analysis and experimental verification. *Transportation research part C: emerging technologies*, 37:238–259, 2013.

[158] Xun Zheng, Hai-ying Li, Ling-yun Meng, Xin-yue Xu, and Yi-hui Yang. Simulating queuing behaviour of pedestrians in subway stations. In *Proceedings of the Institution of Civil Engineers-Transport*, volume 170, pages 373–380. Thomas Telford Ltd, 2017.

[159] Jean Louis Berrou, Jonathan Beecham, Philippe Quaglia, Marios A Kagarlis, and Alex Gerodimos. Calibration and validation of the Legion simulation model using empirical data. In *Pedestrian and Evacuation Dynamics 2005*, pages 167–181. Springer, 2007.

[160] Andreas Schadschneider and Armin Seyfried. Empirical results for pedestrian dynamics and their implications for modeling. *Networks & Heterogeneous Media*, 6(3):545–560, 2011.

[161] Nuria Pelechano, Jan M Allbeck, and Norman I Badler. Controlling individual agents in high-density crowd simulation. In *Proceedings of the 2007 ACM SIGGRAPH/Eurographics symposium on Computer animation*, pages 99–108. Eurographics Association, 2007.

[162] Gerta Köster and Benedikt Zönnchen. Queuing at bottlenecks using a dynamic floor field for navigation. *Transportation Research Procedia*, 2:344–352, 2014.

[163] Felix Dietrich and Gerta Köster. Gradient navigation model for pedestrian dynamics. *Physical Review E*, 89(6):062801, 2014.

[164] Gerta Köster and Benedikt Zönnchen. A queuing model based on social attitudes. In *Traffic and Granular Flow'15*, pages 193–200. Springer, 2016.

[165] Dorine C Duives, Winnie Daamen, and Serge P Hoogendoorn. State-of-the-art crowd motion simulation models. *Transportation research part C: emerging technologies*, 37:193–209, 2013.

[166] Michael H Kutner, Christopher J Nachtsheim, John Neter, and William Li. *Applied linear statistical models*. McGraw-Hill New York, 2005.

[167] Douglas C Montgomery, Elizabeth A Peck, and G Geoffrey Vining. *Introduction to linear regression analysis*, volume 821. John Wiley & Sons, 2012.

[168] SC Wirasinghe and David Szplett. An investigation of passenger interchange and train standing time at LRT stations:(ii) estimation of standing time. *Journal of advanced transportation*, 18(1):13–24, 1984.

[169] David Szplett and SC Wirasinghe. An investigation of passenger interchange and train standing time at LRT stations:(i) alighting, boarding and platform distribution of passengers. *Journal of advanced transportation*, 18(1):1–12, 1984.

[170] Yongyan Wu, Jian Rong, Zhonghua Wei, and Xiaoming Liu. Modeling passenger distribution on subway station platform prior to the arrival of trains. In *2012 Annual Meeting Transportation Research Board of the National Academies*, 2012.

[171] Nikola Krstanoski. Modelling passenger distribution on metro station platform. *International Journal for Traffic & Transport Engineering*, 4(4), 2014.

[172] Michael J Seitz, Stefan Seer, Silvia Klettner, Oliver Handel, and Gerta Köster. How Do We Wait? Fundamentals, Characteristics, and Modelling Implications. In *Traffic and Granular Flow'15*, pages 217–224. Springer, 2016.

[173] Tom Cox, Jonathan Houdmont, and Amanda Griffiths. Rail passenger crowding, stress, health and safety in Britain. *Transportation Research Part A: Policy and Practice*, 40(3):244–258, 2006.

[174] Gary W Evans and Richard E Wener. Crowding and personal space invasion on the train: Please don't make me sit in the middle. *Journal of Environmental Psychology*, 27(1):90–94, 2007.

[175] Walter Dirmeier. Die Bedeutung der Haltezeit im Stadtschnellbahnbetrieb. *Eisenbahntechnische Rundschau*, 27(5):273–276, 1978.

[176] Yu-chen Lee, Winnie Daamen, and Paul Wiggenraad. Boarding and alighting behavior of public transport passengers. 2007.

[177] Marshall S Fritz. Effect of crowding on light rail passenger boarding times. *Transportation Research Record*, 908:43–50, 1983.

[178] JG Weston and JP McKenna. London underground train service model: a description of the model and its uses. *Computer applications in railway planning and management*, pages 133–147, 1990.

[179] Tyh-ming Lin. Dwell time relationships for urban rail systems. Master's thesis, Massachusetts Institute of Technology, 1990.

[180] Tyh-ming Lin and Nigel HM Wilson. Dwell time relationships for light rail systems. *Transportation Research Record*, (1361), 1992.

[181] K Hennige and U Weiger. Höhere Leistungsfähigkeit der S-Bahn durch kürzere Aufenthaltszeiten. *Der Nahverkehr*, 12(9), 1994.

[182] William HK Lam, CY Cheung, and YF Poon. A study of train dwelling time at the Hong Kong Mass Transit Railway system. *Journal of Advanced Transportation*, 32(3):285–295, 1998.

[183] William HK Lam, Chung-Yu Cheung, and CF Lam. A study of crowding effects at the Hong Kong light rail transit stations. *Transportation Research Part A: Policy and Practice*, 33(5):401–415, 1999.

[184] Nicola Lehnhoff and Solveigh Janssen. Untersuchung und Optimierung der Fahrgastwechselzeit. *Nahverkehr*, 21(7/8):14–20, 2003.

[185] Nigel G Harris. Train boarding and alighting rates at high passenger loads. *Journal of Advanced Transportation*, 40(3):249–263, 2006.

[186] Stefan Buchmüller, Ulrich Weidmann, and Andrew Nash. Development of a dwell time calculation model for timetable planning. *WIT Transactions on The Built Environment*, 103:525–534, 2008.

[187] Rodrigo Fernández, M de A del Campo, and Cristóbal Swett. Data collection and calibration of passenger service time models for the Transantiago system. In *European Transport Conference*, pages 6–8, 2008.

[188] Nigel G Harris, Daniel J Graham, Richard J Anderson, and Haojie Li. The impact of urban rail boarding and alighting factors. 2014.

[189] Qi Zhang, Baoming Han, and Dewei Li. Modeling and simulation of passenger alighting and boarding movement in Beijing metro stations. *Transportation Research Part C: Emerging Technologies*, 16(5):635–649, 2008.

[190] Sebastian Seriani and Rodrigo Fernandez. Pedestrian traffic management of boarding and alighting in metro stations. *Transportation Research Part C: emerging technologies*, 53:76–92, 2015.

[191] Catherine Holloway, Roselle Thoreau, Tyng-Rong Roan, Derrick Boampong, Theresa Clarke, David Watts, and Nick Tyler. Effect of vertical step height on boarding and alighting time of train passengers. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 230(4):1234–1241, 2016.

[192] Nigel G Harris, Øystein Risan, and Sven-Jöran Schrader. The impact of differing door widths on passenger movement rates. *WIT Transactions on The Built Environment*, 155:53–63, 2014.

[193] Paul BL Wiggenraad. Alighting and boarding times of passengers at Dutch railway stations. *TRAIL Research School, Delft*, 2001.

[194] Gonzalo de Ana Rodríguez, Sebastián Seriani, and Catherine Holloway. Impact of platform edge doors on passengers' boarding and alighting time and platform behavior. *Transportation Research Record*, 2540(1):102–110, 2016.

[195] Dewei Li, Winnie Daamen, and Rob MP Goverde. Estimation of train dwell time at short stops based on track occupation event data: A study at a Dutch railway station. *Journal of Advanced Transportation*, 50(5):877–896, 2016.

[196] Vlootmanagement NS Techniek. Kenmerken rollend materieel voor treinpersoneel. Technical report, NS, 2018.

[197] Andre Puong. Dwell time model and analysis for the MBTA red line. Technical report, Massachusetts Institute of Technology, 2000.

[198] N Douglas. Modelling Train & Station Demand & Capacity. Technical report, Douglas Economics, 2012.

[199] Sidney Siegel. *Nonparametric statistics for the social sciences*. McGraw-Hill, 1988.

[200] David G Jenkins and Pedro F Quintana-Ascencio. A solution to minimum sample size for regressions. *PloS one*, 15(2):1–15, 2020.

[201] S.P. Hoogendoorn, M.C. Campanella, and W. Daamen. Fundamental diagrams for pedestrian networks. In Richard D Peacock, Erica D Kuligowski, and Jason D Averill, editors, *Pedestrian and Evacuation Dynamics*, pages 255–264, Boston, MA, 2011. Springer US.

[202] Mark van Hagen and Menno de Bruyn. Typisch NS. Elk station zijn eigen rol. In *Colloquium Vervoersplanologisch Speurwerk*, 2002.

[203] ProRail. Netverklaring 2020. Technical report, ProRail, 2020.

[204] Augustus J Veenendaal. *Spoorwegen in Nederland: van 1834 tot nu*. Boom, 2004.

[205] Piet Brouwer, Gerard van Kesteren, and Antia Wiersma. *Berigt aan de heeren reizigers: 400 jaar openbaar vervoer in Nederland*. Sdu Uitgevers, 2008.

[206] Johannes Alle Faber. *Het spoor: 150 jaar spoorwegen in Nederland*. Meulenhoff Informatief, 1989.

[207] Peter Saal and Flip Spangenberg. *Kijk op stations*. Elsevier, 1983.

[208] Nederlandse Spoorwegen. *Spoor naar '75: Plan voor de toekomst van NS in de Nederlandse samenleving in de jaren 1970-1975*. Nederlandse Spoorwegen, 1968.

[209] Nederlandse Spoorwegen. *Rail 21: sporen naar een nieuw eeuw*. Nederlandse Spoorwegen, 1988.

[210] Ministerie van Verkeer en Waterstaat. De derde eeuw spoor - Marktordening personenvervoer per spoor. Technical report, 1999.

[211] R van der Wouden, Spaans M, G Foeken, K Hollander, J Trip, J Milder, and P de Wit. *Evaluatie sleutelprojecten - Onderzoek in opdracht van het Ministerie van VROM*. Bureau Stedelijke Planning bv, 2009.

[212] Ministerie van Infrastructuur & Milieu. *Rapportage en voorkeursbeslissing over het Programma Hoogfrequent Spoorvervoer*. Ministerie van Infrastructuur & Milieu, 2010.

[213] Michiel van Ballegoijen de Jong. De vernieuwing van station Utrecht Centraal. *Op de Rails*, August 2006.

[214] Ingrid Koenen. ProRail steekt 1 miljard in spoorplan Noorden. *Cobouw*, November 2017.

[215] ProRail, Ministerie van Infrastructuur & Milieu en Nederlandse Spoorwegen. *ERTMS Kennisboek versie 2.0*. ProRail, Ministerie van Infrastructuur & Milieu en Nederlandse Spoorwegen, 2014.

[216] Paul van den Boogaard. Prorail zet eerste stap in uitbreiding energievoorziening tractie. *spoorpro.nl*, April 2020.

[217] Bert van Eekelen, Remco Schnieders, and Sebastiaan de Wilde. *De Dokwerkers. Reconstructie van planontwikkeling en bestuurlijke besluitvorming bij Zuidas en Zuidasdok*. Neerlands diep, 2014.

[218] Ministerie van Infrastructuur en Waterstaat. Uitbreiding spoor van en naar Amsterdam. Technical report, 2018.

[219] H de Herder. Een dag op het station Alkmaar anno 1949. *Op de Rails*, 1989.

[220] C Douma. *Stationsarchitectuur in Nederland 1938/1998*. Walburg Pers Zutphen, 1998.

[221] Leon van Meijel and Teake Bouma. Cultuurhistorische waardestelling station Almere Centrum. Technical report, NS Stations & ProRail & Bureau Spoorbouwmeester, 2012.

[222] AlmereZaken. Verbouwing station Almere Centrum kan beginnen. 2019.

[223] Leon van Meijel and Teake Bouma. Cultuurhistorische waardestelling station Amersfoort. Technical report, NS Stations & ProRail & Bureau Spoorbouwmeester, 2016.

[224] M Blokker. Capaciteitsanalyse transfer Amersfoort. Technical report, ProRail, 2013.

[225] Movares. Dive Under Amersfoort in dienst genomen. 2013.

[226] Paul Meurs, Merel Stolker, Chawwah Six, and Johanna van Doorn. Cultuurhistorische waardestelling station Amsterdam Amstel. Technical report, NS Stations & ProRail & Bureau Spoorbouwmeester, 2014.

[227] Annet van Aarsen. Grote klus aan het spoor afgerond: weer treinen tussen Amsterdam Centraal en Bijlmer Arena. *Noordhollands Dagblad*, 2020.

[228] Kees Rouw and Jaap Huisman. *The Making of Station Amsterdam Bijlmer ArenA*. Sdu Uitgevers BV Den Haag, 2008.

[229] Vera Franken and Joyce van Sprundel. Cultuurhistorische waardestelling station Amsterdam Centraal. Technical report, NS Stations & ProRail & Bureau Spoorbouwmeester, 2015.

[230] Dionne van Heteren and Ton Honing. De Westtunnel. Technical report, NS Railinfrabeheer, 1999.

[231] JM ten Broek. Het Amsterdamse Centraalstation uitgebreid. *Op de Rails*, (11):433–441, 2004.

[232] ProRail. *Informatiedocument Programma Hoogfrequent Spoorvervoer Amsterdam Centraal*. ProRail, 2014.

[233] Richard Mooyman. Station Lelylaan moet aangenaam en veilig worden. *De Westkrant*, 2019.

[234] Jan van der Male. Dertig jaar Hemspoortunnel. *Railmagazine*, (310), 2013.

[235] Jaap Huisman and Jannes Linders. De Nieuwe Sleutelprojecten. Op Weg naar 2030. Technical report, Bureau Spoorbouwmeester, 2016.

[236] Sybilla M Dekker. Voortvarend bouwen voor de toekomst. Technical report, Ministerie van Infrastructuur en Waterstaat & Gemeente Amsterdam & Vervoerregio Amsterdam & Provincie Noord Holland, 2020.

[237] Movares. Restauratie station Apeldoorn zet trend. *infrasite.nl*, 2008.

[238] Pien Heuts. Arnhem trots op supercompact station. *OV-Magazine*, 2015.

[239] Pien Heuts. Breda Centraal. Alles onder één dak. *OV-Magazine*, 2012.

[240] Vera Franken. Cultuurhistorische waardestelling station Delft. Technical report, NS Stations & ProRail & Bureau Spoorbouwmeester, 2013.

[241] Juliska Wijsman. Laatste trein over viaduct in Delft. *de Architect*, 2015.

[242] Marieke van Gompel. Arcadis past stationsgebied Nijmegen aan voor PHS. *spoorpro.nl*, 2018.

[243] Frits van der Sluijs. *Haagse stedebouw: mijn ervaringen in de jaren 1946-1983*. Matrijs, 1989.

[244] Joyce Hoogland. Wat is er mis met de ongebruikte sporen 11 en 12 op Den Haag CS? *indebuurt.nl*, 2020.

[245] Paul Meurs, Merel Stolker, and Chawwah Six. Cultuurhistorische waardestelling station Den Haag HS. Technical report, NS Stations & ProRail & Bureau Spoorbouwmeester, 2010.

[246] Marieke van Gompel. Nieuwe reizigerstunnel Den Haag Hollands Spoor ligt op zijn plek. *spoorpro.nl*, 2017.

[247] CJBP Frank, FAC Haans, CHJM van den Broek, V Delmee, JHJ. van Hest, G Korenberg, M Lemmers, and L Valckx. Cultuurhistorische waardestelling station Deventer. Technical report, NS Stations & ProRail & Bureau Spoorbouwmeester, 2013.

[248] M Blokker. Capaciteitsanalyse transfer Deventer. Technical report, ProRail, 2013.

[249] Paul Meurs, Joost Emmerik, Henriette Sanders, and Lara Voerman. Cultuurhistorische waardestelling station Dordrecht. Technical report, NS Stations & ProRail & Bureau Spoorbouwmeester, 2014.

[250] Projectburau Spoorzone. Spoorzone Ede. Ontwerp OV knoop. Technical report, Gemeente Ede & NS & ProRail, 2016.

[251] Ewout Dorman, Wouter Vanstiphout, and Cassandra Wilkins. Cultuurhistorische waardestelling station Eindhoven. Technical report, NS Stations & ProRail & Bureau Spoorbouwmeester, 2010.

[252] Carlijn Kruidhof. Nieuwe reizigerspassage station Eindhoven geopend. *spoorpro.nl*, 2018.

[253] Ewout Dorman, Cassandra Wilkins, and Jan van Ballegooijen. Cultuurhistorische waardestelling station Enschede. Technical report, NS Stations & ProRail & Bureau Spoorbouwmeester, 2015.

[254] Korneel Aschman. Cultuurhistorische waardestelling station Gouda. Technical report, NS Stations & ProRail & Bureau Spoorbouwmeester, 2013.

[255] Christa Eekhuis. Mysterie opgelost: waarom heeft station Gouda twee verlaten kopsporen? *indebuurt.nl*, 2019.

[256] Stefanie Weser, Claudia van Kouwen, and Eva Dubbelboer. Cultuurhistorische waardestelling station Groningen. Technical report, NS Stations & ProRail & Bureau Spoorbouwmeester, 2013.

[257] Paul van den Boogaard. Strukton start begin 2020 met verbouwing station Groningen. *spoorpro.nl*, 2019.

[258] Ewout Dorman, Cassandra Wilkins, and Jan van Ballegooijen. Cultuurhistorische waardestelling station Haarlem. Technical report, NS Stations & ProRail & Bureau Spoorbouwmeester, 2012.

[259] Marcel de Veen. Station Heerlen officieel geopend: 'Een pronkstuk voor de hele regio'. *De Limburger*, 2019.

[260] Jeroen Visser. Het einde van de autoslaaptrein. *De Volkskrant*, 2015.

[261] Jos van de Ven. Station Den Bosch moet het station van de toekomst worden. *bd.nl*, 2019.

[262] Paul Meurs, Lara Voerman, Johanna van Doorn, and Annemarie Kuijt. Cultuurhistorische waardestelling station Leeuwarden. Technical report, NS Stations & ProRail & Bureau Spoorbouwmeester, 2015.

[263] Leon van Meijel and Teake Bouma. Cultuurhistorische waardestelling station Leiden. Technical report, NS Stations & ProRail & Bureau Spoorbouwmeester, 2014.

[264] Paul Meurs, Lara Voerman, Johanna van Doorn, and Annemarie Kuijt. Cultuurhistorische waardestelling station Maastricht. Technical report, NS Stations & ProRail & Bureau Spoorbouwmeester, 2014.

[265] Paul Meurs, Lara Voerman, Paolette Holst, and Desiree Kerlaan. Cultuurhistorische waardestelling station Nijmegen. Technical report, NS Stations & ProRail & Bureau Spoorbouwmeester, 2012.

[266] Dolf Broekhuizen, Cees Boekraad, and Arjan Hebly. Cultuurhistorische waardestelling station Roosendaal. Technical report, NS Stations & ProRail & Bureau Spoorbouwmeester, 2014.

[267] Marieke van Gompel. Vernieuwd station Rotterdam Alexander virtueel geopend. *spoorpro.nl*, 2020.

[268] Gijs Mom, Marc Dierikx, Adrienne van den Boogaard, and Charley Werff. *Schiphol. Haven — Station — Knooppunt*. Walburg Pers Zutphen, 1999.

[269] Ton Honing and Margreet de Visser. Schiphol Dubbel Spoorlijn. Technical report, NS Railinfrabeheer, 1997.

[270] Ewout Dorman, Cassandra Wilkins, and Jan van Ballegooijen. Cultuurhistorische waardestelling station Tilburg. Technical report, NS Stations & ProRail & Bureau Spoorbouwmeester, 2015.

[271] Marieke van Gompel. Station Tilburg benoemd tot rijksmonument. *spoorpro.nl*, 2015.

[272] Stephan Jongerius. Zo komt perron 4 op station Tilburg eruit te zien: nieuwe kap, kroepoekdak blijft de baas. *bd.nl*, 2019.

[273] Ilka Vaatstra. Capaciteitsanalyse Utrecht Centraal (transferknelpunt perron 5/7). Technical report, ProRail, 2017.

[274] OV-Magazine. Dak van Utrecht Centraal golft over het OV. *OV-Magazine*, 2016.

[275] Ministerie van Infrastructuur en Milieu. Doorstroomstation Utrecht. Versie 1.0. Technical report, 2013.

[276] Ewout Dorman, Cassandra Wilkins, and Jan van Ballegooijen. Cultuurhistorische waardestelling station Venlo. Technical report, NS Stations & ProRail & Bureau Spoorbouwmeester, 2015.

[277] Jeroen Kreule. Zaandam bouwt aan traverse bij station. *Cobouw*, 2018.

[278] Paul Meurs, Henriette Sanders, and Joost Emmerik. Cultuurhistorische waardestelling station Zwolle. Technical report, NS Stations & ProRail & Bureau Spoorbouwmeester, 2012.

[279] Guus Puylaert. Zwolle krijgt minder wissels én nieuw perron. *OV-Magazine*, 2018.

[280] ZwolleNieuws.nl. Wat gaat er gebeuren op het spoor tussen Zwolle en Herfte? 2018.

About the author

Jeroen was born on 9 January 1979 in Apeldoorn, the Netherlands. After completing his secondary education at the Stedelijk Gymnasium Arnhem, he studied Civil Engineering and Management at the University of Twente, Enschede. During his studies, Jeroen worked for Keypoint Consultancy (Enschede) and Movares (Utrecht). These roles brought him into contact with political and public administration, prompting him to study for a master's in public administration, also at the University of Twente. Jeroen successfully completed both courses in 2004 and took up a post as a consultant for NS Projectconsult, part of Dutch national rail operator Nederlandse Spoorwegen, working in the fields of timetable development, rail logistics and strategy. In 2006, Jeroen became an advisor to the Corporate Strategy team of the NS Board of Directors. Alongside this role, he studied for an Executive MBA at the Rotterdam School of Management, which he obtained at the beginning of 2010.

Jeroen has been working for NS Stations since that same year. His experience in a variety of roles has enabled him to develop his current specialisms: passenger flows, functional station design and crowd management. He has participated in large-scale station projects, including Amsterdam Centraal and Schiphol Airport. In parallel with these activities, Jeroen led the development and use of pedestrian-flow data sources at NS and has been working with rail infrastructure manager ProRail and the Ministry of Infrastructure and Water Management on policy and standards for station safety and capacity. He has contributed to the implementation of crowd control at several stations, including Amsterdam Bijlmer ArenA, which serves a major stadium. Jeroen has also worked on projects involving the railways of other European countries, including Switzerland. He currently holds the position of Strategic Advisor and Research Manager.

This thesis is the result of cooperation between NS Stations, Delft University of Technology and the author. That cooperation began in 2010 and in 2012 acquired the status of an in-service doctoral project; an external doctorate. It has resulted not only in the present thesis but also in publications, contributions to conferences, much debate and an inspiring learning experience.

Publications

Journal papers

1. Van den Heuvel, J. (2016). Field experiments with train stopping positions at Schiphol Airport train station in Amsterdam, Netherlands. *Transportation Research Record*, 2546(1), 24-32.

2. Hänseler, F. S., Van den Heuvel, J.P.A., Cats, O., Daamen, W., & Hoogendoorn, S. P. (2020). A passenger-pedestrian model to assess platform and train usage from automated data. *Transportation Research Part A: Policy and Practice*, 132, 948-968.

Peer-reviewd Conference Contributions

1. Starmans, M., Verhoeff, L., & Van den Heuvel, J. (2014). Passenger transfer chain analysis for reallocation of heritage space at Amsterdam Central station. *Transportation Research Procedia*, 2, 651-659.

2. Van den Heuvel, J., Voskamp, A., Daamen, W., & Hoogendoorn, S. P. (2015). Using Bluetooth to estimate the impact of congestion on pedestrian route choice at train stations. In *Proceedings of traffic and granular flow* (Vol. 13, pp. 73-82).

3. Ton, D., van den Heuvel, J., Daamen, W., Hoogendoorn, S. (2015). Route and activity location choice behaviour of departing passengers in train stations. In *hEART (European Association for Research in Transportation) 2015 Conference*. Copenhagen, Denmark (pp. 9-11).

4. Daamen, W., Van den Heuvel, J., Ton, D., & Hoogendoorn, S. (2015). Using Bluetooth and WiFi to unravel real-world slow mode activity travel behaviour. In *14th International Conference on Travel Behaviour Research*, Windsor, United Kingdom.

5. Van den Heuvel, J., Ton, D., & Hermansen, K. (2016). Advances in Measuring Pedestrians at Dutch Train Stations Using Bluetooth, WiFi and Infrared Technology. In *Traffic and Granular Flow'15* (pp. 11-18). Springer, Cham.

6. Van den Heuvel, J., Thurau, J., Mendelin, M., Schakenbos, R., Van Ofwegen, M., & Hoogendoorn, S. P. (2017). An application of new pedestrian tracking sensors for evaluating platform safety risks at Swiss and Dutch train stations. In *International Conference on Traffic and Granular Flow* (pp. 277-286). Springer, Cham.

7. Thurau, J., Van den Heuvel, J., Keusen, N., Van Ofwegen, M., & Hoogendoorn, S. P. (2017). Influence of pedestrian density on the use of the danger zone at platforms of train stations. In *International Conference on Traffic and Granular Flow* (pp. 287-296). Springer, Cham.

8. Daamen, W., Van den Heuvel, J., Knoop, V. L., & Hoogendoorn, S. P. (2017, July). Macroscopic fundamental diagram for train platforms. In *International Conference on Traffic and Granular Flow* (pp. 365-372). Springer, Cham.

Other Publications

1. Van den Heuvel, J.P.A., Thiellier, E., & Van Gerwen, N. (2013). Privacy by design bij reizigersmetingen op stations. *Privacy & Compliance*, 2 (3), 2013.

2. Van Oort, N., Van den Heuvel, J.P.A. (2014). No data, no glory. *OV Magazine: vakblad voor openbaar vervoer*, 1, 2014.

3. Van den Heuvel, J.P.A. & Daamen, W. (2015). Efficiency drive. Case Study. *Railway Terminal World. The International Review of Rail Station and Terminal Technology and Design*, 2015 showcase.

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