MASTER THESIS

INFLUENCING THE CROWD

Analysis of the effects of short-term crowd management measures on crowd flow characteristics in station environments

I.M. (Ivo) Bruijl

ET – Civil Engineering

GRADUATION COMMITTEE
E.C. van Berkum
T. Thomas
I. Oude Vrielink
G. Huisman

Final version

18 February 2022

ARCADIS

UNIVERSITY OF TWENTE.

The digital version of this report has clickable (cross-)references. Moreover, all graphs are implemented in vector-format, making zooming-in without quality loss possible.

Influencing the Crowd

Analysis of the effects of short-term crowd management measures on crowd flow characteristics in station environments

Thesis presented for the degree of
Master of Science

18 February 2022
Final version
Defended on 1 March 2022

Policies & Smart Innovation
Infrastructure
Arcadis
Amersfoort, The Netherlands

Department of Civil Engineering
Faculty of Engineering Technology
University of Twente
Enschede, The Netherlands

Author

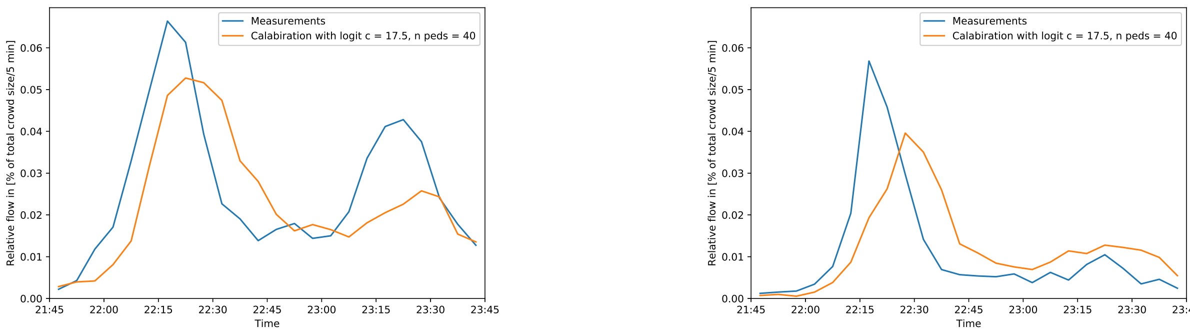
I.M. (Ivo) Bruijl — i.m.bruijl@alumnus.utwente.nl

Graduation Committee

prof. dr. ir. E.C. van Berkum — University of Twente
dr. T. Thomas — University of Twente
I. Oude Vrielink, MSc — Arcadis
ir. G. Huisman — Arcadis

ABSTRACT

Events like concerts and sports matches attract large crowds that should be managed to keep the event itself and its in- and outflow safe. Crowd management is specifically relevant for station environments as they often from an important bottleneck for crowd flow. Historic crowd disasters, like the stampede at the Love Parade music festival in 2010 in Duisburg, Germany, often can be attributed to wrong (crowd management) decisions [Helbing and Mukerji, 2012]. Therefore, it is beneficial for crowd managers to have a tool that can analyse the effect of certain types of crowd intervention measures so a substantiated decision can be made regarding what measure to take. This research investigated the development and usefulness of such a tool.
The research is subdivided into two parts. The first part concerns an investigation into the monitoring of crowds and the identification of potentially relevant measures. This is done through a literature review and interviews with crowd management experts. The second part concerns a micro-simulation modelling study into the effects of certain measures on a case study environment. The case study used in this research is the Amsterdam Bijlmer ArenA train and metro station. This station is located next to the Johan Cruijff ArenA, Ziggodome and AFAS Live event venues and therefore commonly deals with peak crowd flows after events.
The literature review and interviews found that crowd density and crowd flow are the main indicators that are monitored to keep a crowd safe. Nonetheless, incorporating 'human factors' into crowd management has growing attention. Human factors are not often incorporated in a real-time manner, but the incorporation of social media in crowd management is seeing an increase. Four different types of measures could be identified: providing information, limiting flow, separating flow and increasing capacity. Moreover, behavioural influencing can be relevant from the human factor perspective. However the interviewees had mixed opinions whether it will be effective enough to see substantial results.
For the modelling study, specific attention should be paid to calibration of the model, as there are reliability issues, illustrated by the Root Mean Square Normalised Error (RMSNE) with a value of 0.69. Nonetheless, the model is deemed reliable enough to analyse the effects of measures as it does capture the overall trend of division of people over the various station entrances, but with a delay. Figure 1 illustrates this for the two main station entrances of the case study.



(a) Entrance 1.

(b) Entrance 2.

Figure 1: Normalised inflow profile through the entrance sections after calibration of the model.

Four measures that are based around the aforementioned types have been analysed in detail. These measures have been analysed based on five Key Performance Indicators (KPIs): station inflow, density in the buffer section (outside the station), density in front of the check-in gates (inside the station), density on the platforms and travel time to the platforms. The measure, their most relevant outcomes and their wider applicability are presented in Table 1.

Table 1: Overview of analysed measures, their (dis-)advantages and applicability in station environments.

Measure	**(Dis-)advantages**	**Applicability**
Spreading of peak flow	+ Positive effects on all KPIs − Not investigated how the spreading effect itself can be achieved	Targeting and convincing of specific audience to postpone (event) departure possible
Barriers *outside the station*	+ Move high density locations out of the station − Not really applicable on short-term	Sufficient buffer space available outside station
Stream separation *inside the station*	+ Spread flows over entrances − Increases densities in station	Conflicting streams and (near) infinite discharge capacity
Behavioural influencing *through background music*	+ Seems to spread out waiting crowd − Key problems with modelling of measure, as results show unexpectedly large crowding issues	Unclear, more research needed into behavioural influencing to conclude exact effects

While in Table 1 it becomes clear that different effects of the various measures can be identified, it is also clear that the used model has some issues. First off, the relatively course calibration. When accounting for a 5-minute delay visible in Figure 1, the RMSNE becomes 0.52 which is better, but still not very good. This is likely caused by the routing method in the model. The used method bases route choice solely on historic travel times, while in real life crowd members will (also) include observations regarding (expected) density on a route. This leads to some unrealistic behaviour in the model. Moreover, it is mentioned that the behavioural measure has issues regarding its implementation in the model. A relatively coarse approach has been used to implement the behavioural measure, but since the results are very unexpected, it is unsure if the coarse approach is sufficient to conclude anything about the effects of the measure.

All in all, the research shows that it is possible to determine the effects of various crowd management measures in station environments based on a tool like the modelling software. Therefore, such a tool can be of benefit to crowd managers regarding selection of measures. Nonetheless, there still are aspects that deserve further interest, like:

- Further analysis of the routing method for a better calibration;
- Analysis of other case studies to see whether the translation of measures to other environments yields similar results
- Further research into the effects of behavioural influencing, and
- Ways to influence the crowd in order to spread its departure pattern over a longer time span.

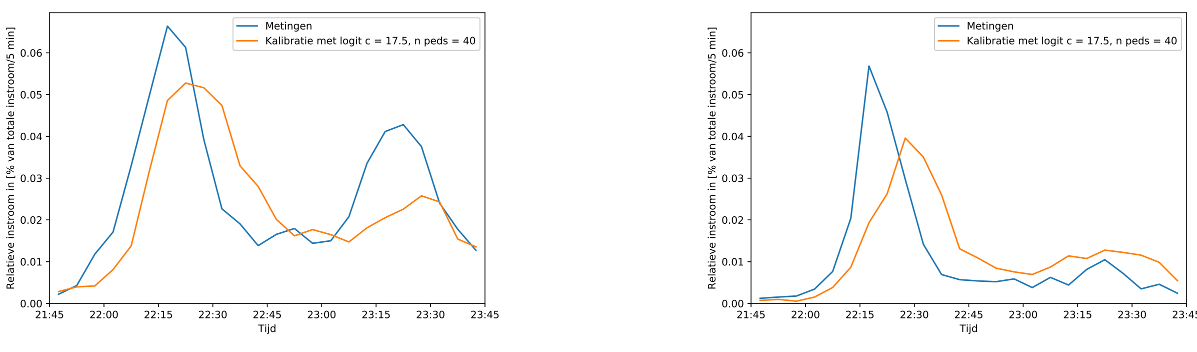
SAMENVATTING

Evenementen als concerten en sportwedstrijden trekken vaak een groot publiek, welke beheersbaar moeten blijven om het evenement zelf en de in- en uitstroom ervan veilig te laten verlopen. Stationsomgevingen in de buurt van evenementenlocaties zijn in het bijzonder belangrijk omdat deze vaak een bottleneck vormen tijdens de uitstroom. In het verleden is gebleken dat rampen met mensenmassa's, zoals tijdens het Love Parade muziekfestival in 2010 in Duisburg, vaak veroorzaakt worden door verkeerde beslissingen van crowd managers [Helbing and Mukerji, 2012]. Het is daarom nuttig om een tool te hebben waarmee de effecten van maatregelen bepaald kunnen worden. Dit onderzoek gaat in op een dergelijke tool.

Het onderzoek is onderverdeeld in twee delen. Het eerste deel gaat in op het monitoren van een mensenmassa en het identificeren van mogelijke maatregelen door middel van een literatuuronderzoek en interviews met ervaringsdeskundigen op het gebied van crowd management. Het tweede deel behelst een modelonderzoek op basis van micro-simulatie naar de effecten van mogelijke maatregelen met een casus rondom station Amsterdam Bijlmer ArenA. Vlak bij dit station zijn de Johan Cruijff ArenA, de Ziggodome en AFAS Live gevestigd, waardoor dit station met enige regelmaat te kampen heeft met mensenmassa's na evenementen.

Uit het literatuuronderzoek en de interviews bleek dat dichtheid in en doorstroom van de mensenmassa voornamelijk in de gaten worden gehouden met het oog op veiligheid. Desalniettemin groeit de interesse vanuit crowd managers in het 'menselijke aspect' van een menigte. Dit wordt meestal nog niet in real-time meegenomen, maar er komt steeds meer interesse in het actief monitoren van social media. Wat betreft de mogelijke maatregelen kunnen vier types van maatregelen onderscheiden worden: informatieverstrekking, stroombeperking, stromenscheiding en capaciteitsverhoging. Bovendien krijgt gedragsbeïnvloeding steeds meer interesse, maar waren de geïnterviewden verdeeld wat betreft de mogelijke effecten daarvan.

Bij de modelstudie verdient de kalibratie specifieke aandacht, aangezien de RMSNE-indicator een waarde heeft van 0.69 terwijl deze idealiter 0 moet zijn. Desalniettemin wordt het model voldoende capabel geacht om de effecten van verschillende maatregelen te analyseren, aangezien de trend met betrekking tot het verdelen van de instroom over verschillende ingangen duidelijk meegenomen is, zoals zichtbaar voor de twee belangrijkste ingangen in Figuur 2.



(a) Ingang 1.

(b) Ingang 2.

Figuur 2: Genormaliseerde instroom door de stationsingangen na kalibratie van het model.

Vier maatregelen gebaseerd op de eerdergenoemde types zijn specifiek geanalyseerd op basis van hun effect op vijf Key Performance Indicators (KPIs): station instroom, dichtheid in buffer sectie (buiten het station), dichtheid voor de check-in poortjes (in het station), dichtheid op de perrons en reistijd naar het perron. De voor- en nadelen per maatregel en de algemene toepasbaarheid van de maatregel zijn zichtbaar in Tabel 2.

Tabel 2: Overzicht van de geanalyseerde maatregelen, hun voor- en nadelen en algemene toepasbaarheid in stationsomgevingen.

Maatregel	**(Voor-) en nadelen**	**Toepasbaarheid**
Uitspreiden van piekstroom	+ Positief effect op alle KPIs − Niet onderzocht hoe het spreidingseffect behaald kan worden	Mogelijkheid tot het overtuigen van een specifieke doelgroep om vertrek uit te stellen
Barrières *buiten het station*	+ Verplaatst hoge dichtheden naar buiten het station − Niet toepasbaar op korte termijn	Voldoende bufferruimte beschikbaar voor het station
Scheiding van stromen *in het station*	+ Verspreid instroom over ingangen − Verhoogt dichtheden in het station	Veel kruisende stromen en (nagenoeg) oneindige afvoer capaciteit
Gedragsbeïnvloeding *door middel van achtergrondmuziek*	+ Lijkt de menigte uit te spreiden − Grote problemen met het modelleren van de maatregel, resultaten geven onverwachte drukte problemen	Onduidelijk, meer onderzoek nodig naar gedragsbeïnvloeding voor sluitende conclusie

In Tabel 2 wordt het duidelijk dat de effecten van maatregelen kunnen worden geïdentificeerd, maar ook dat het model enkele problemen had. Allereerst blijft de kalibratie een belangrijk punt. Zelfs wanneer er rekening wordt gehouden met een verschuiving van 5 [minuten] van de stromen zoalszichtbaar in Figuur 2 houdt de RMSNE een waarde van 0.52. Dit komt waarschijnlijk door de routering van voetgangers in het model. De achterliggende methode gebruikt alleen historische reistijden, terwijl in werkelijkheid mensen ook eigen observaties over bijvoorbeeld dichtheid gebruiken om een route te kiezen. Dit leidt tot onrealistisch gedrag in het model. Bovendien heeft de implementatie van de gedragsbeïnvloeding zijn beperkingen, aangezien het op een relatief grove manier is geïmplementeerd. Aangezien de resultaten van de maatregel onverwacht zijn, is het onduidelijk of de grove implementatie voldoende inzichten geeft om een waardevolle conclusie te trekken.

Al met al laat het onderzoek zien dat het mogelijk is om de effecten van verschillende crowd management maatregelen in stationsomgevingen te bepalen, gebaseerd op een tool als de modelleringssoftware. Daarom kan een dergelijke tool een waardevolle toevoeging zijn voor crowd managers bij het kiezen van een gepaste maatregel. Desalniettemin zijn er ook nog steeds punten die nadere aandacht verdienen, zoals:

- Verdere analyse van de routering voor een betere kalibratie;
- Analyse van andere casussen om te zien of een vertaling van de maatregelen naar andere omgevingen tot vergelijkbare resultaten leidt;
- Verder onderzoek naar de effecten van gedragsbeïnvloeding, en
- Manieren om bezoekers te beïnvloeden zodat het uitstroomprofiel over een langere tijdsspanne uitgespreid wordt.

This page is intentionally left blank

PREFACE

This thesis marks the finalisation of my time as a Civil Engineering student at the University of Twente. In the past six months I have been working on this research into crowd management, a subject that does not necessarily seem to be connected to the field of civil engineering. It has been an exciting and interesting way to apply my knowledge on traffic management and modelling to a field of knowledge that is new to me. Hopefully it can contribute to a safe way of managing crowds.

I would like to take this opportunity to thank the supervisors of my research for their guidance and feedback. On the Arcadis side: Ilse and Gerco, it has been really interesting to brainstorm with you about the future steps to take regarding my research and also to get to know Arcadis via you. On the University of Twente side: Tom and Eric, thank you for your guidance and for taking the scientific level of my research higher every time you provided me with feedback.

Regarding the content of the research, I would like to thank the interviewees for making time in their schedules to have really engaging and fascinating talks about crowd management. I specifically want to thank Rik Schakenbos, as he also provided the data that I used to built the model. Moreover, I specifically want to thank Henk Rovers and the personnel of the Amsterdam Bijlmer ArenA station for their kindness of showing me around the station on 19 October 2021 during, and most importantly after, the Ajax - Borussia Dortmund football match as it gave me some really relevant insights into actual crowd management carried out in practice.

In the past six-and-a-half years, I have had a wonderful time constructing concrete canoes, managing the study association for civil engineering, representing students in the university council and having interesting discussions on Tuesday nights. I want to thank everyone that has been part of these six-and-a-half years: from my fellow board members of the study association, to my dispuutsgenoten, to my housemates, to anyone else that I have had a laugh with. Thanks to you guys, my student life has been truly unforgettable. Regarding the past few months, I specifically would like to thank Carmen for making me laugh and bringing some distraction when I was too fixated on the research. Moreover, I want to thank her for reading through the research to give some final feedback.

Finally, I want to thank my family, specifically my parents, for their support during the past six-and-a-half years. It has been really wonderful to be able to pursue my ambitions throughout my student life, knowing that they would support me. Thank you so much for that.

I hope you will enjoy reading this report.

Ivo Bruijl
Enschede, February 2022

This page is intentionally left blank

Contents

List of Figures

List of Tables

1 INTRODUCTION

This introductory chapter presents the relevance of the research subject. Moreover, the goal of the research is presented.

1.1 Relevance

Events ranging from sport events and concerts to pilgrimages attract large numbers of visitors. In order to make sure that the (traffic) streams of both arriving and departing visitors are safe and efficient, crowd management is needed. Also historically, guiding crowds in a proper and safe manner has been a topic that got attention, as already illustrated by the Colosseum in Rome and its large number of exits for quick evacuation [Helbing and Mukerji, 2012].
In recent decades, crowd management is receiving more attention due to disasters where the crowd management was not sufficient. Relevant examples are the traffic chaos at the Dance Valley music festival in 2001 in Spaarnwoude, the Netherlands, resulting in hypothermia of many visitors [NIBRA, 2001] or the stampede occurring at the Love Parade music festival in 2010 in Duisburg, Germany, resulting in 21 deaths [Helbing and Mukerji, 2012]. At both events a chain of wrong crowd management decisions lead to the eventual problems. This indicates that there is a desire to create insights into how specific measures might impact crowd states in a near real-time time span.
Currently, Arcadis is involved with crowd and traffic flow management for various events where transport hubs play a key role, such as the Formula 1 Dutch Grand Prix in Zandvoort and the start of the Vuelta a España in Utrecht in 2022. These events are unique in their own respect, but nevertheless all have similar uncertainties concerning the in- and outflow of event visitors at key locations around the event venues. Moreover, Arcadis is involved in the re-development of certain train stations in the Netherlands that have to cope with high peak passenger flows. Considering these aspects, it is valuable for Arcadis to have a tool that can forecast the flow of event visitors and passengers (i.e. crowds), spatial bottlenecks and the effect of possible intervention measures to mitigate possible negative effects of crowding.

1.2 Goal of research

Whereas both of the aforementioned disasters were caused by chains of wrong decisions [NIBRA, 2001, Helbing and Mukerji, 2012], there is a need for a way to analyse the impact of possible decisions/measures a priori. While many researches show interest in collecting crowd data in real-time and the modelling of crowds for evacuations, few attention has been paid to supporting crowd managers in analysing possible interventions [Martella et al., 2017]. Since station environments coping with peak crowd flows are widespread throughout the world and can also be valuable as reference for other transport hubs that have to cope with peak crowd flows, it is relevant to conduct a study into the way crowd behaviour can be influenced around station environments. Therefore, the goal of the research can be stated as follows:

Design a method that can forecast effects of crowd flow interventions in station environments.

2 RESEARCH CONTEXT

This chapter presents the context of other researches in which this research should be seen. This is done through an analysis of literature into two main subjects: short-term traffic forecasting and crowd behaviour. Based on the analysed literature, it is identified where a knowledge gap lays concerning the forecasting of crowds.

2.1 Short-term traffic forecasting

While short-term traffic forecasting is part of traffic engineering researches since the end of the 1970s [Ahmed and Cook, 1979], due to computational developments in recent years more and more sophisticated researches are conducted [Vlahogianni et al., 2014]. Most interest is however paid to vehicular forecasting [Snelder and Calvert, 2015, Groenendijk, 2018]. While certain forecasting aspects are certainly relevant for both vehicular and non-vehicular forecasting, it is important to also distinguish between the two perspectives.

2.1.1 Short-term vehicular forecasting

It is found that within short-term vehicular forecasting most attention has been paid to motorways, uni-variate statistical models, predicting traffic volume or travel time and using data from single point data collectors [Vlahogianni et al., 2014]. Moreover, several subjects of interest are identified, like issues with data resolution [Boto-Giralda et al., 2010, Chen et al., 2012, Oh et al., 2005] and fusion [Zhao et al., 2019, Sun et al., 2019, Grau et al., 2018, Majumdar et al., 2021], analysing temporal and spatial characteristics simultaneously [Zou et al., 2009] and improving explanatory power of algorithms [Karlaftis and Vlahogianni, 2011].

2.1.2 Short-term crowd forecasting

Research into short-term crowd-related forecasting mainly focuses on (public transport) passenger forecasting [Wei and Chen, 2012, Sun et al., 2015], though there are also some studies that try to forecast passenger demand specifically during events [Chen et al., 2020, Li et al., 2017] or try to forecast overall crowd movements in cities [Su et al., 2017, Fan et al., 2015]. Public transport passenger forecasting often concerns analysis of re-occurrence of patterns in data, and base their next estimate based on information gathered from previous data patterns in some way or another. These analyses are often done through artificial intelligence methods [Wei and Chen, 2012, Sun et al., 2015]. However, difficulties occur when approaching forecasts from a more event-related perspective, as incidental events of which not many data is available need to be incorporated [Li et al., 2017, Chen et al., 2020].

2.2 Crowd Behaviour

Understanding the behaviour of crowds is key in proper crowd management. Therefore, the research context of crowd behaviour will be analysed through the monitoring of crowds, the modelling of crowds and the (possible) influencing of crowd behaviour.

2.2.1 Monitoring crowds

Gathering data from crowds is a sensitive issue. It requires to gather data from individuals, while the privacy of the individual who's data is gathered should be guaranteed [Martella et al., 2017]. Different methods can be used to solve this. An example is the use of camera images [Marana et al., 1997], that when combined with privacy guaranteeing extensions give a relevant data source for crowd monitoring around events [Papacharalampous et al., 2016].
The wide presence of smartphones from about 2010 onward gives new opportunities for data gathering, related to the sensors in the phones. Relevant sensors include GPS [Wirz et al., 2013, Duives et al., 2019], WiFi [Jarvis et al., 2019, Zhao et al., 2019], Bluetooth [Van den Heuvel et al., 2015, Grau et al., 2018] and RFID technology [Ibrahim et al., 2016]. Besides direct sensor detection, a more indirect approach can also be used through e.g. the use of geolocated social media records [Celes et al., 2019, Grau et al., 2018]. Key issue regarding the use of smartphones is the penetration rate of the technology among the crowd [Martella et al., 2017]. The use of pedestrian fundamental diagrams can be valuable in determining crowd characteristics with low penetration rate of smartphones [Wirz et al., 2013].

2.2.2 Pedestrian & crowd modelling

There are various modelling types available for modelling pedestrians. For a macroscopic approach, it is possible to see a crowd flow as a fluid flow and use fluid conservation theories adapted for human movement [Appert-Rolland, 2015].
A cellular automata approach leads to a complete discretisation of a traffic system as space is divided into cells, time into steps and flow characteristics into integer multiples of corresponding basic units [Treiber and Kesting, 2013]. While for vehicular traffic, the discretisation can be rather straightforward as vehicles can only properly move in one direction, for pedestrians this is more difficult as they change travelling directions more easily [Appert-Rolland, 2015].
On a microscopic level, the pedestrian-following model, similarly to car-following models, bases the acceleration of a pedestrian on the characteristics of the pedestrian and the pedestrian in front of him [Appert-Rolland, 2015]. Kinetic models deal with flows using probability distributions of the presence of a pedestrian at a specific location, which is mainly applicable to situations with 'lanes' of pedestrian movement [Bellomo and Dogbe, 2011]. Social force models describe pedestrian flows based upon external influences and internal motivations leading to attraction or repulsion of flow in a similar way as Newtonian mechanics [Moussaïd et al., 2011]. For long-range interactions, it allows for aggregation of individuals to form a group [Bellomo and Dogbe, 2011]. Important to note is that the social force model does not control the strategic and tactical (i.e. destination and route choice) level.

2.2.3 Influencing crowd behaviour

Martella et al. [2017] interviewed 10 different 'crowd experts' involved in various Dutch organisations concerning crowd management, ranging from railway stations to theme parks and stadiums to security companies. They investigated what the current practices are concerning situation awareness, (real-time) monitoring and intervening with the crowd. It is mentioned that crowd managers have the need for better measures that increase situation awareness and instruments that support decision making. Moreover, influencing the crowd through e.g. fixed screens and smartphone application notifications can be a very promising way to go, though it should be kept in mind that the 'human'-aspect should remain leading. In this sense, aspects like possible personal needs and privacy (as also mentioned in Section 2.2.1) are key to incorporate in the crowd management approach.

Accompanying the human factors and more specifically the personal needs are the experiences of people being part of a crowd. Filingeri et al. [2017] conducted a research into the experiences of crowd members through focus groups and analysis of events. They identify a large number of positive and negative experiences, based on aspects like the physical design of crowd spaces, crowd movement, communication to the crowd, comfort and public order. It is concluded that it would be beneficial for both crowd experience and crowd management to use a more human factor related approach than is currently often used, as was also mentioned by Martella et al. [2017].

Concerning the actual influencing of crowd flows, many studies have been done into evacuation strategies. Researches into that topic can be categories into mathematical, architectural/infrastructural and behavioural studies. Architectural/infrastructural approaches are reviewed most often, though its effectiveness is highly dependent on the (geometrical) context in which it is implemented. Behavioural approaches are gaining more and more attention and shows promising effects concerning effectiveness and practicality, though proper experimental and numerical methods to investigate strategies from a behavioural point of view should be further investigated [Haghani, 2020].

As evacuation strategies focus on removing people from a certain location as quickly as possible, this is often not relevant or necessary for regular crowd management at events. At regular events it is however relevant to manage crowds in such ways that in- and outflow patterns of visitors happens in a safe and for the crowd satisfactory manner.

2.3 Knowledge gap

Through the analysis of literature, it becomes clear that while many researches have been carried out with regard to (vehicular) short-term forecasting, the forecasting of pedestrians flows can see more investigation. More specifically, the effect of a measure on pedestrian flows is not often covered, let alone an analysis of different measures.

It is seen that the monitoring of crowds is not necessarily an issue in crowd management: many different possibilities exists in which crowds can be analysed and tracked while keeping privacy into account. Some hints are given concerning interesting metrics that can be used for crowd management, however no clear insights are presented on what metrics are actually desired by crowd managers themselves. Besides crowd monitoring, the influencing of crowds deserves specific attention. The analysed literature mainly goes into influencing crowds on a meta-level: what aspects influence the behaviour of crowds? No specific insights are gained concerning the impact of specific crowd management measures, leaving room for further investigations there.

Based on the findings in literature, it can be concluded that while many different methods regarding crowd forecasting are present in researches, no specific literature is found that describes a method for forecasting the effect of intervention measures on crowds flows at station environments. Nonetheless, relevant side-aspects, like crowd flow forecasting in general and crowd monitoring, are covered and can therefore serve as relevant inputs for a research into the matter.

3 RESEARCH STRUCTURE

This chapter presents the structure of the research. It introduces the research questions based on the found conclusions of previous research and the identified knowledge gap in Chapter 2. Besides the research questions, the case study that is analysed in the research is introduced and the basics of the methodology of the research is elaborated upon.

3.1 Research questions

With the goal of the research as mentioned in Section 1.2 and the analysed literature in mind, the following main research question has been established:

Is it possible to develop a tool that can forecast future crowd states and assess the effectiveness of short-term crowd management interventions in order to optimise crowd flows in station environments?

This main research question specifies the fact that there has been looked at station environments in this research, which is relevant in the context of the goal of the research as mentioned in Section 1.2. Aspects like infrastructural and behavioural measures are analysed best at a micro-level (where individual pedestrians are simulated as part of a crowd), therefore a micro-simulation approach has been used for answering this main research question and establishing a possible crowd management tool. With this in mind, three sub-questions have been formulated, based on monitoring of crowds, the modelling of crowds and the implantation of measures. These sub-questions are in turn accompanied by sub-sub-questions to structure the research. Elaboration on the sub-questions is given below.

1. *What monitoring insights are desired by crowd managers concerning (short-term) crowd management?*
   - 1.1. *What crowd management aspects are considered in previously created tools and dashboards?*
   - 1.2. *What crowd characteristics are currently not captured in monitoring techniques?*
   - 1.3. *What data sources are needed to create a reliable crowds forecasting model?*

Sub-question 1 and its sub-sub-questions go into the monitoring aspect of crowds. In order to get insights into the current crowd status, crowd managers often use dashboards based on specific sensors or count locations [Papacharalampous et al., 2016]. However, for each (type of) event and location these dashboards require different insights based on the event characteristics and the (infrastructural) environment. Nonetheless, there will be overlapping characteristics which are in general used for monitoring whether dangerous situations are likely to occur, which need to be identified in order to develop a new tool, even when specified towards a certain environment like a station environment. Sub-sub-question 1.3. is also relevant in the modelling perspective, as it is dependent on the model which input data is needed for creating a reliable model.

2. *What (potential) measures are available to influence crowds in station environments within 3 hours?*

    2.1. *To what extend are measures translatable between station environments?*

    2.2. *Can crowd management interventions be used to spread peaks in crowd flows?*

Sub-question 2 and its sub-sub-questions go into the (short-term) measures that can be used to influence crowds. A time span of 3 hours is set as a time horizon for short-term measures, as most events that are applicable to the case study area (which will be introduced in Section 3.2) last 3 hours at maximum. Potential measures are dependent on the available resources and the infrastructure, which might differ widely for various station environments. Nonetheless, different station environments might have tried different crowd management approaches which might be translatable to other station environments in some way or another. Besides, especially for regularly reoccurring events like professional football matches, it can be expected that crowd managers mainly rely on their own experiences and intuition to solve possible crowds problems in ad hoc situations, while no reference work is available for it. It is therefore relevant to investigate what measures are or can be used in different circumstances in station environments. Finally, whereas it is seen that most measures try to mitigate negative effects of a certain crowd flow, changing the crowd flow pattern in the first place also is a relevant topic of research.

3. *Can the effects of crowd management measures in station environments be modelled and forecast for different scenarios using micro-simulation?*

    3.1. *What are relevant scenarios for peak crowd flow analysis?*

    3.2. *What behaviour-related measures can be modelled using the social forces model?*

    3.3. *Is the social forces model sufficiently capable of modelling dangerous situations and waiting crowds?*

    3.4. *How can crowd intervention measures in station environments be modelled using micro-simulation?*

Sub-question 3 and its sub-sub-questions finally go into the modelling of crowds and crowd management interventions in different circumstances. First of all, it is relevant to define scenarios to which measures should be applied, as it can be expected that e.g. regular rush hour peaks might not be very interesting as these likely do not cause special circumstances where crowd management measures are needed. As some measures following from sub-question 2 are to be oriented to changing the behaviour of individual pedestrians, it is also key to understand the social forces model and its wide range of parameters with respect to behavioural aspects. Moreover, it is unclear how capable this model is of modelling large waiting crowds and identifying potential dangerous crowd situations, as the models are mostly used for subjects like evacuation analysis where waiting is often avoided in the first place. Finally, based on outcomes of the other sub-sub-questions, through question 3.4. a method needs to be developed that is able to incorporate the intervention measures as identified through sub-question 2 as good as possible.

3.2 Case study

As aforementioned, station environments can have large differences concerning (infrastructural) characteristics. Moreover, peak flows on different stations also differ based on aspects like characteristics of neighbouring zones, scale of events and target audience of events. In order to have a clear analysis of a station environment, a case study is selected for a common event-venue with high peak crowd flows. This case study revolves around the Amsterdam Bijlmer

ArenA train station, which is located next to the Johan Cruijff ArenA, the Ziggodome and AFAS Live. These are all venues where (sports) events and concerts take place on a regular basis. Moreover, trials have been held at this location concerning crowd flow intervention and data is available concerning crowd flows in the station.
A visualisation of the Amsterdam Bijlmer ArenA station and its surroundings is presented in Figure 3.1. Besides the train station itself, attention is paid to the Johan Cruijff Boulevard, which is the pedestrian boulevard that connects the three venues to the train station.

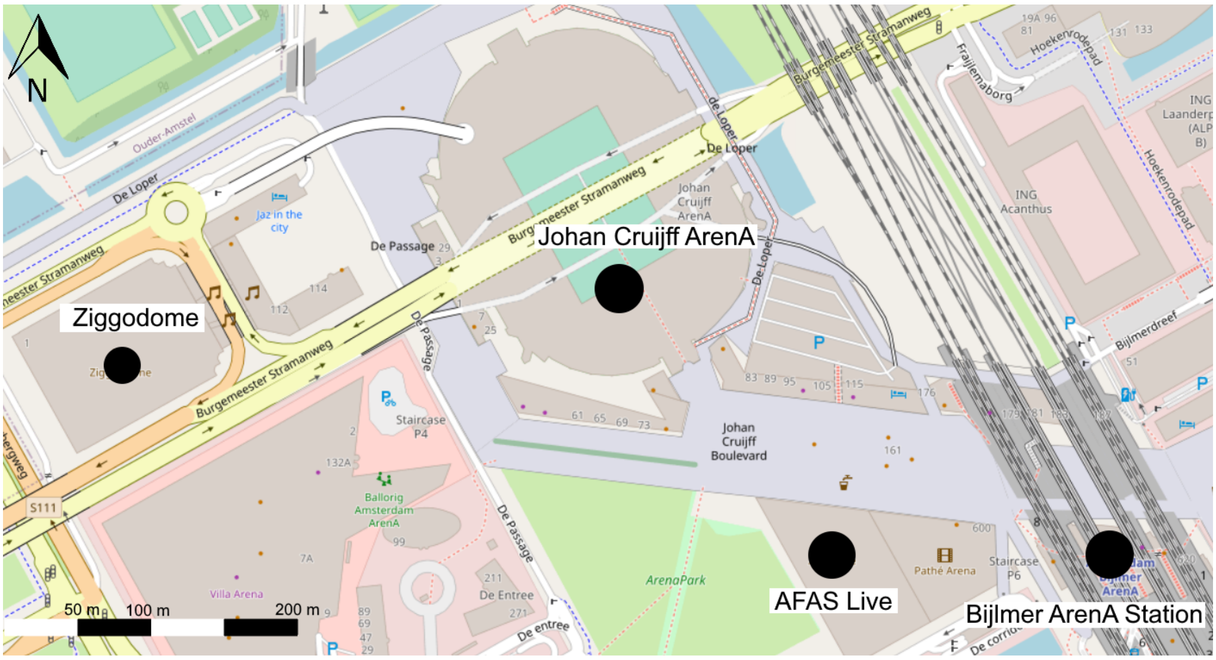


Figure 3.1: Amsterdam Bijlmer ArenA train station and its surroundings [OpenStreetMap, 2021].

Using the case study, it is analysed whether it can be expected that a translation of the measures implemented in this research to other event situations will result in similar outcomes in another station environment or possibly even another type of transport hub. Such transport hubs might range from a multi-modal (train) station as is the case in the case study to small park-and-ride locations, as also the latter needs to process an inflow of visitors towards a certain outflow location with a given bottleneck.

3.3 Methodology

The research questions as stated above have the need for different types of approaches in order to answers each question. Therefore, based on the monitoring-measures-modelling structure which is also applied to the sub-questions, different methods are set out for answering the research questions. A simplified overview of the research structure including brief elaborations on how the methodology to answer the various research questions are intertwined is presented in Figure 3.2.
As might become clear from both the research questions and the structure in Figure 3.2, this research consists of out of two parts: knowledge gathering with regards to the monitoring of crowds and possible measures to influence crowd flows on one hand and modelling of specific measures to indicate their effects on the other. Therefore, the next two chapters deal with these two parts separately. Also, a detailed overview of methodological approach per part is given in the respective chapters.

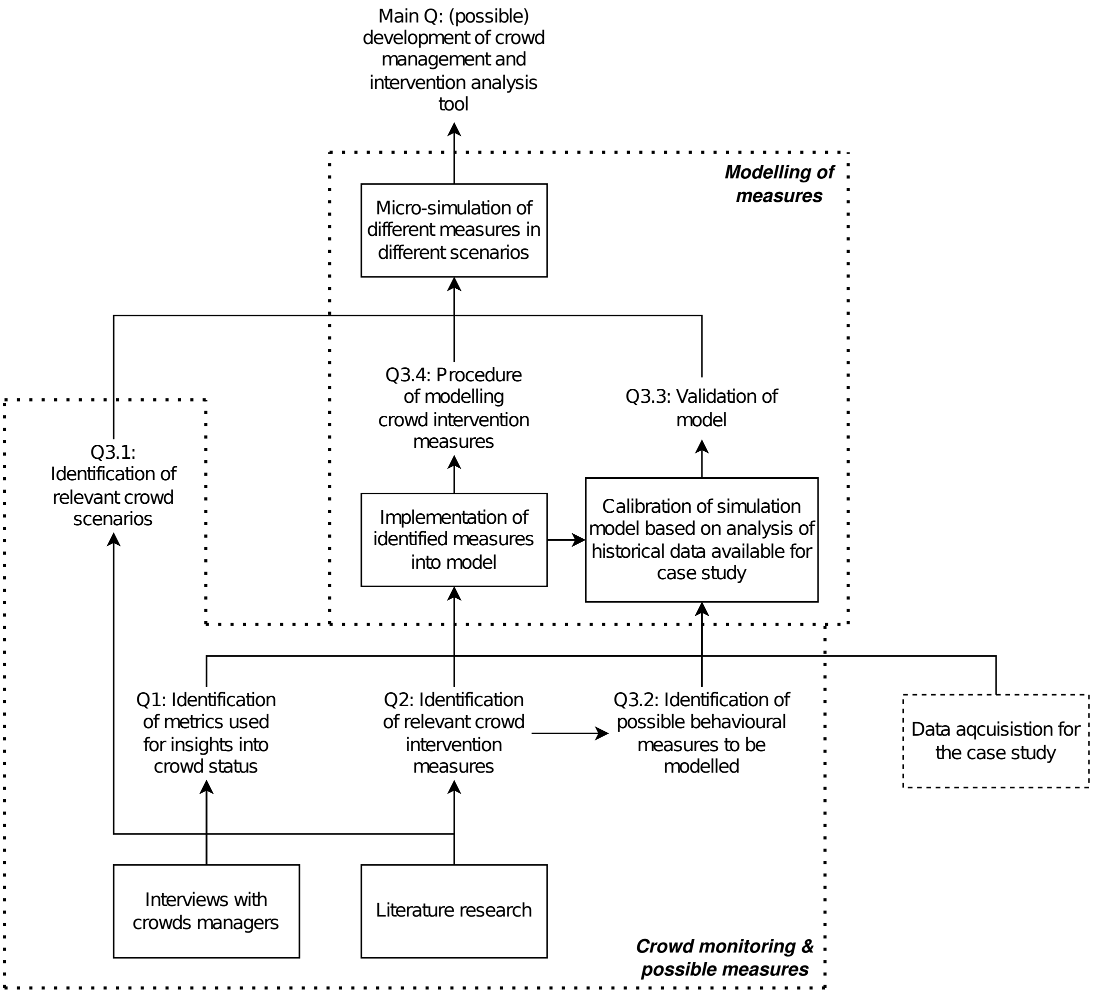


Figure 3.2: Simplified structure of the research questions and accompanying methodology used to answer the research questions. Outputs with regards to the research questions are shown in plain text, methodological aspects are boxed. Data acquisition is dashed-boxed as the gathering of the data itself is not part of the research, though it is a key aspect. Grouping based on the dotted lines indicates which research aspect the research question or methodological aspect is (mainly) involved in.

4 CROWD MONITORING & POSSIBLE MEASURES

Identification of relevant crowd monitoring aspects and potential measures is the first part of the research. This chapter presents the methodology used to identify these aspects and elaborates on the results of this part of the research.

4.1 Methodology

The methodology to investigate the monitoring of the crowd and the identification of possible measures consists of two parts: a literature review and interviews.

4.1.1 Literature review

In order to gain initial insights into the practices of crowd management, literature is reviewed. This review is especially relevant for sub-questions 1 and 2, with regards to monitoring of the crowd and potential measures that can be taken to influence the crowd respectively.
Sub-question 1 specifically goes into the metrics that are used as input for crowd management tools and models and what metrics are used to identify the 'degree of optimality' of the crowd flow. Therefore, an exploratory literature review was carried out to see what information is publicly available with regards to crowd monitoring and dashboarding. The outcomes of this review are used as input for interviews with crowd managers, which are further elaborated upon in Section 4.1.2.
Sub-question 2 goes into the possible measures that can be implemented to influence crowds in station environments. It tries to create an overview of historically implemented and promising other measures and see whether measures and experiences can be translated to other environments with a limitation of the time horizon in which the measures have to be implemented of 3 hours. A possible tool should be able to support crowd managers with their decision making concerning the implementation of measures in real-time, which is why such a time limit is explicitly mentioned. Literature is analysed to gain insights about such measures that potentially meet such criteria, or measures that can potentially be altered to satisfy such criteria. Again, the conclusions of the literature review can be used for setting up the interviews with crowd managers as is elaborated upon in Section 4.1.2.
The search queries and databases used for the literature review are presented in Appendix A.

4.1.2 Interviews

In order to get more in-depth insights into crowd management practices, interviews are carried out with crowd managers. The conclusions with regards to crowd monitoring and measures from the literature research serve as an starting point for the content of the interviews. Besides those conclusions from the literature review, attention is also paid to scenarios which are important to incorporate in both general crowd management situations and the case study situation. While the scenario aspect is structured to be part of the modelling sub-question (see sub-question 3), it is already brought up here. The interviews are semi-structured, in order to have a clear

scheme of subject to discuss, but also the possibility to elaborate on a specific topic that the interviewee brought up. An overview of the interview structure is available in Appendix B.1.
A wide range of professionals have been contacted that have experience in the field of crowd management. An overview of the interviewees is available in Table 4.1. Some of the interviewees are familiar with crowd management in the Bijlmer ArenA area in order to get specific insights into relevant crowd management aspects for the case study. Others have experiences in other geographical locations in order to get non-location specific insights into crowd management.

Table 4.1: Details of interviewees that took part in this research, presented in chronological order of moment of interviewing.

Interviewee	**Organisation**	**Experiences with crowd management**
Marion Vos	Self employed	Crowd management during Bevrijdingsfestival Zwolle and mobility management during the Zwarte Cross festival.
Rik Schakenbos	Dutch Railways	Research into crowd management at platforms and stations infamous for overcrowding and into crowd management during large events at the Amsterdam Bijlmer ArenA station.
Dave van Schaick	Van Schaick Projectbeheersing	Mobility & crowd management for the Lowlands and Down the Rabbit Hole festivals and concerts at the Goffertpark Nijmegen.
Daniël Pardijs	Mojo	Safety and mobility planning of Mojo events, safety coordinator during events.
Nnuss van der Veer	Municipality of Amsterdam	Crowd management during events in Amsterdam, member of 'Regie Zuidoost' (the municipal department involved with (road)works in the Zuidoost city district).
Rob van Beek	Municipality of Amsterdam	Traffic management in Amsterdam, former director of event mobility in Amsterdam Zuidoost
Sherman Bonofacio	TSC	Consultant with respect to crowd management and safety & security.
Daniël van Motman	Municipality of Amsterdam	Crowd management during events in the public spaces of Amsterdam. In the past year involved in crowd management with respect to COVID-19 measures.
Henk Rovers	Dutch Railways	Safety & crowd management at stations during events in the greater Amsterdam area.
Maurits van Hövell	Johan Cruijff ArenA	Mobility & environment manager of the stadium involved in accessibility.

4.2 Results

Based on the methodology described above, the literature review and interviews are carried out. The results of these aspects of the research are described below.

4.2.1 Literature review

In order to gain relevant insights before conducting the interviews, a literature review is carried out concerning the use of crowd monitoring systems/dashboards and applied crowd management measures. Using the outcomes of this literature, the content of the interviews is set up.

Dashboards

Crowd management dashboards provide insights into the current status of the crowd through graphical visualisations of the historical or current behavioural patterns of the crowd. What however is noteworthy, is the fact that most dashboards are solely based upon a single data source [Duives et al., 2020]. The lack of fusion of data sources means that there is still room for improvement there [Wijermans et al., 2016, Luchetti et al., 2017, Duives et al., 2020], even if it solely would concern a possibility to compare the data from one source with another.
In this context, it is important to know what variables are usually shown on crowd management dashboards. Scientific literature most often does not go into depth of the exact design of various crowd management dashboards. However, various researches do highlight which variables are of importance with regards to crowd management decisions. An overview of the various researches that discuss different variables is given in Table 4.2.

Table 4.2: Overview of variables that are discussed as relevant for crowd monitoring dashboards or for crowd management decision making in literature.

Research	**Crowd density**	**Crowd flow**	**Crowd speed**	**Crowd count**	**Dir.[1]/ paths**	**Travel times**	**Crowd charac.[2]/**
Wirz et al. [2013]	X	X	X				
Schauer et al. [2014]	X	X					
Van den Heuvel et al. [2015]	X			X	X	X	
Ibrahim et al. [2016]	X		X				
Wijermans et al. [2016]	X	X	X	X	X	X	X
Yuan et al. [2016]	X	X	X			X	
Luchetti et al. [2017]	X						
Nasser et al. [2017]				X	X		
Gong et al. [2018]	X	X					
Li et al. [2018]	X			X			
Duives et al. [2019]	X	X			X		X
Jarvis et al. [2019]	X	X			X		
Li et al. [2019]	X	X		X	X	X	
Al-Shaery et al. [2020]	X				X		X
Aylaj et al. [2020]	X		X		X		
Baqui and Löhner [2020]	X		X		X		
Duives et al. [2020]	X	X	X		X		X
Tripathi et al. [2020]							X
Garcia-Retuerta et al. [2021]	X				X		

[1]Direction
[2]Characteristics

Looking at Table 4.2, crowd density seems to be the single most important aspect in crowd monitoring. This is logical, as high densities of crowds are a key contributor to crowd disasters. Other important aspects to consider are the direction, flow and speed of movement of the crowd. Besides these spatio-temporal variables, crowd characteristics are deemed important as well, though those are not yet widespread in literature and are often not incorporated in a structured and well-designed manner in crowd monitoring. Variables that can be seen in the light of crowd characteristics are for example age distribution, social identity and mood. Though difficult to measure, especially for the mood of a crowd, sources like geo-located social media records might give insights into the crowd characteristics.
All in all, it can be stated that the classical spatio-temporal variables crowd density, crowd flow and crowd direction/paths are of most relevance concerning the monitoring of the status of the crowd. However, in order to have a more human factor oriented approach as was identified in the researches of Filingeri et al. [2017] and Martella et al. [2017] in Section 2.2.3, crowd characteristics are important to keep in mind regarding dashboards.

Crowd management measures

Crowd management measures come in many different shapes and sizes. Also the goal of the measures can differ based on the desired way the crowd should be managed: should a crowd leave a certain area as soon as possible (i.e. evacuation) or should a crowd leave a certain area in a safe and structured manner. The former of course does not need to exclude the latter, evacuations should also be safe, though the guiding principles of facilitating a high peak flow and spreading a flow are different.

General crowd management measures
Common crowd management strategies can be divided into static and dynamic pedestrian management strategies [Bierlaire et al., 2020]. In the context of this research, dynamic management strategies are relevant. Examples include the regulation of doors to control the flow of passengers into a train station [Bauer et al., 2007]. Gating [Molyneaux et al., 2018] is a similar strategy which has also been tried and applied to the Amsterdam Bijlmer ArenA station during large scale events by means of so-called Mojo-barriers. An example of these barriers applied to the Bijlmer ArenA station is visible in Figure 4.1. Other physical strategies include use of traffic lights for conflicting flows [Molyneaux et al., 2017] and physical separation of streams [Molyneaux et al., 2021].

Figure 4.1: Mojo barriers as applied to the Bijlmer ArenA station during special event situations.

Besides the physical measures, there are also measures that use a more behavioural approach, like floor markings, the use of 'attractors' (e.g. ticket machines or kiosks) [Molyneaux et al., 2017] and the placement of static and dynamic signage [Wagner et al., 2020]. The effect of the different signage types has been specifically investigated. It is shown that correct placement of (digital) static signage can clearly influence the locations where crowding occurs in the terminal: the more static signs, the more spreading out of the crowd. If people only rely on dynamic signage (i.e. smartphones), a lot more crowding occurs in a station, as people slow down throughout the station to check the signage [Wagner et al., 2020].

Measures based on evacuation strategies

While crowd management is more than evacuations, evacuation strategies can serve as relevant starting points for 'regular' crowd management. As mentioned in Section 2.2.3, three different categories of evacuation strategies can be identified: architectural, behavioural and mathematical [Haghani, 2020].

Various studies in the architectural field conclude that the strategic placement of an obstacle before a bottleneck location can increase flow through the bottleneck due to locally reduced crowd density [Yanagisawa et al., 2009, Zhao et al., 2020]. It should however be noted that the size, shape and location of the obstacle is key in the exact effectiveness of the measures [Cristiani and Peri, 2017, Wang et al., 2018, Shi et al., 2019]. An interesting approached is to create buffer zones by using longitudinal obstacles (e.g. crowd barriers) [Wang et al., 2019]. Longer buffer zones result in reduced evacuation times as a result of lower crowd densities within the obstacle section which in turn lead to less conflicts at the bottleneck.

Studies into behavioural measures are still rather new, and therefore widespread evidence of the effects of measures in specific environments is not always present. Nonetheless, there are some studies that show interesting results, like the active deployment of stewards that provide the crowd with information, seems to have promising effects [Song et al., 2017]. Moreover, the use of information provision through mobile devices shows promising effects, as also here information is provided on a personal level, which is deemed 'intuitive' by the crowd [Zhou et al., 2019]. Nonetheless, the quality of such an crowd guidance system is dependent on aspects like wireless signal and crowd size for proper functioning. Another interesting measure is the effect of (background) music on a high density crowd, which leads to a more erratic stop and go behaviour of the crowd as a potential result of larger desired headways [Zeng et al., 2019].

Finally mathematical strategies go into the computer-aided optimisation of evacuations. It mainly concerns the introduction of algorithms [Chu, 2009] or (multi-variable) metrics [Cassol et al., 2017] to determine the effectiveness of an evacuation strategy. Using different configurations in a simulation model, the algorithm and metrics are able to identify which configuration is most suitable concerning e.g. peak crowd densities and/or evacuation time.

Application of measures to station environments

The measures that are seen in literature are sometimes already applied to station environments, either in a case study as part of the research or through implementation in real life. As aforementioned, gating has for example already been used at the Amsterdam Bijlmer ArenA station during events by placing closable Mojo-barrier gates in front of the station.

While separation of bi-directional flows is not very relevant in this research, as after events there often is only one dominant direction of flow, it can still be beneficial to separate the flows in station environments. Interfering crowd flows can significantly influence the safety of a crowd, therefore separation can be beneficial to combat overcrowding.

The use of attractors can be important in the light of short-term implementable measures. Not at a station platform level, but possibly at the station entrance/square level, e.g. by placing food and drink vending stalls, or smaller scale streetscape items like rain shelters or patio heaters at strategic locations to (temporarily) attract crowd members to spread out the entire crowd.

While evacuations strategies focus on lowering evacuations times and maximising crowd flows, this is not the necessary key for station environments as people simply will need to wait for trains to arrive. However, evacuation strategies can have very relevant aspects in them that can also be applied to creating safe situations for crowds in station environments. For example,

the placement of obstacles in front of bottlenecks like doors, stairs and escalators might create safer pedestrian flows.
While it seemed to have negative effects for evacuation purposes, playing background music might have more positive effects for controlling crowds in stations. As flow maximisation is not the necessary purpose, the fact that people try to keep a larger headway might be beneficial for crowd safety. Moreover, coordinated messaging on an individual level might be efficient in order to spread out crowds through informing them about the (expected) crowdedness.

4.2.2 Interviews

The interviews are carried out to get up-to-date and case specific insights into current practices of crowd management. Whereas case specific insights for the Bijlmer ArenA station are relevant, also interviewees have been approached who do not specifically have experiences with this environment in order to also gain insights into other crowd management practices. An overview of the interviewees was presented in Table 4.1 in Section 3.3.
This section presents a synthesis of the interviews. This synthesis is done based on the topics that have also been applied in the research questions as indicated in Section 3.1: crowd monitoring & dashboarding, relevant scenarios and potential (short-term) measures. A summarised version of each individual interview can be seen in Section B in the Appendix.

Crowd monitoring & dashboarding

Based on the outcomes of the interviews, this subsection has been subdivided into three parts: crowd characteristics & event preparation, metrics to monitor and crowd atmosphere monitoring.

Crowd characteristics & event preparation
An important conclusion that can be drawn from most interviews is that preparations for an event are key. Whereas the exact preparations are different for different events, the procedures carried out to identify the needed preparations are often the same. A prominent place in the overall procedures is given to the identification of the target audience, specifically regarding two aspects: modal split and risk analysis. The modal split is key for the mobility related measures, like capacity and signage. The risk analysis serves to identify possible risks, ranging from mobility risks, like differences in the expected modal split, to crowding aspects, like constrained outflow capacity. Both aspects are often based on data of similar historic events, ideally at the same geographic location, and use the crowd characteristics of the target audience go give better predictions.
Important to note with respect to the measures taken at the Bijlmer ArenA station is that the most physical measure implemented there, the placement of Mojo barriers, is not specifically altered based on different crowd volumes or crowd characteristics. On a more general note for events also outside of the scope of Bijlmer ArenA area, the risk analysis is used to base aspects like steward and signing deployment on.

Metrics to monitor & dashboards
Different insights are gained when comparing metrics to monitor during an event itself and during the outflow of an event. For outdoor events, crowd densities are often not the main relevance, as often such events have a suitable degree of available space to let the crowd spread out naturally. It is more relevant to keep a look at (bottleneck) locations at the terrain where people move between stages. Therefore, crowd flow can be a better indicator for detecting crowding problems at such events as bottlenecks lead to a sudden drop in flow.
For indoor events, flow is of less interest and more attention is paid to density. Indoor events often only have one stage, so people do not move from one place to another during the event. Even though indoor events almost always have a limited number of available tickets, (local)

overcrowding might be an issue. From that perspective, it is important to keep track of the crowd density in such situations.
As the Bijlmer ArenA station is not an event venue by itself, some different aspects play a role here. It can be best compared with the outflow of the crowd at an event venue: first of all the moment where crowding occurs at the station is after outflow of an event and secondly crowding at a station is caused by a constrained capacity (i.e., size of exits at event venues and number of trains for stations), leading to bottleneck locations (i.e., exits at event venues and platforms/station hall for stations). Therefore, while a station can be considered an outdoor venue on one hand, it can be considered an indoor venue on the other. The outdoor aspects mainly concerns station hall: as it is a location where people move, flow should be monitored there. The indoor aspects are mainly applicable to the platforms: as a platform can be seen as a 'confined space' until a train arrives, density is most relevant here. Similarly, the waiting areas created by the Mojo barriers and check-in gates can be best seen from the indoor-perspective, as people want to move towards the gates similar to people wanting to move towards a stage, meaning that crowd density is most relevant there.
The dashboard used for crowd monitoring at Bijlmer ArenA mainly goes into the flow of people in the station. During the inflow of one or multiple events in the Bijlmer ArenA area, it is monitored how many people exit the station so a prediction can be made about how many will also will return to the station once the events are finished. For actively steering the inflow of the station using the Mojo barriers, the total flow of people in the station hall is monitored during the event outflow. If the flow in the hall becomes larger than 400 to 450 [people per minute], the gates in the barriers are closed as it is known that flow breaks down in the station if it exceeds 500 people per minute. The fact that the dashboard is focused on flow in the station hall highlights the relevance of flow monitoring in station (hall) environments. Though there is interest in it by different parties, relatively few is done with regards to monitoring outside of the station.

Crowd atmosphere monitoring

Incorporating the atmosphere of a crowd is not very straightforward. Most interviewees indicated that atmosphere-related aspects are incorporated in the risk analysis, as specifically a (sudden) turnaround in atmosphere in the crowd can imply serious risks for the crowd. In order to identify such a turnaround, almost all interviewees motioned that they rely on stewards and policemen in the field for monitoring such aspects.
A couple of interviewees mentioned that there is monitoring of social media, but only relatively few is done with this in actual crowd management. Nonetheless, almost all interviewees indicated that social media can be of great relevance with regards to crowd monitoring and steering and steering on an individual level, but some doubted its usefulness for thorough analysis of an entire crowd. It was highlighted multiple times, most often by interviewees that have a connection to the Bijlmer ArenA area, that the company LiveCrowd has the capabilities to actively monitor and interact with the crowd in order to adapt (mobility) measures to the crowd status.

Relevant scenarios

Different types of events have different relevant scenarios with respect to crowd management. Scenarios to analyse often involve aspects like overcrowding (either overall or of specific locations within an event venue), evacuations and public disturbances. Similar to the dashboarding aspects, the relevant scenarios for a station are different compared to event venues themselves. The NS uses three main scenarios that are relevant for the activities at the Bijlmer ArenA Station:

- A regular Ajax match;
- A triple event, where the three main event venues in the area all host an event, and
- A disruption in the train service.

For the situation when only a (regular) Ajax match is taking place, it is quite well known how many people will use public transport to go to the ArenA stadium beforehand, as the modal split does not differ that much for each Ajax game. Moreover, the origins of event visitors (i.e. train line used for arrival at and departure from event) are likely to be quite similar as well.
For a triple event, it might be possible that the end time of events at all three events venues (the Johan Cruijff ArenA, the Ziggo Dome and AFAS Live) are potentially similar, so the crowds of the three venues exit their events and want to enter the Bijlmer ArenA station at similar moments, possibly leading to overcrowding. In the worst-case scenario, all events end at the same time, which is highly likely to lead to overcrowding.
A disruption in the train service leads to the fact that there is fewer or no capacity to transport the visitors away from the station. It might be that there is a small, temporary disruption, but a larger disruption that persists throughout the entire event duration and specifically during the outflow of the event(s) can also be possible. Such disruptions and accompanying crowding can have serious implications on crowd safety.
Besides these three, public disturbances and riots can also still be of relevance for crowds at stations. However, it was noticed by multiple interviewees that crowds, even football fans, exiting an event often simply want to go home after an event. There might be some unrest in a crowd, but if this does not calm down naturally and it escalates, this is not part of crowd management but becomes part of police tasks and therefore is out of scenario-scope.

Potential measures

A fascinating notion made by one of the interviewees is that management of crowd flows can be seen similarly as the management of vehicle flows. For vehicles, there are four key types of influencing a (motorway) flow: advising drivers, limiting the vehicle inflow at a buffer location, separation of local and through traffic streams and increasing capacity. These aspects can also be translated to pedestrian flows at stations: advising crowd members, limiting pedestrian inflow into the station, separating streams based on destination platform and increasing train frequencies.
Moreover, during every single interview, the importance of informing the crowd of the situation came up. In order to make people aware of the (undesired) situation, it is best to inform them in order to create acceptance among the crowd for measures that might interfere with their habits or expectations. When people are not informed about measures that (potentially) conflict with their habits, they are less likely to respond to it in a positive way and there will be more unrest and potential disobedience if active involvement of the crowd is needed to make the measure work.

Advising and informing the crowd

There are various ways in which a crowd can be informed and advised, the currently most commonly implemented one is the use of LED screens. This method of informing was explicitly brought up by almost all interviewees. Such screens can display messages about the situation and give an overall advice with action perspective for the entire crowd by one-to-many communication.
It is also possible to inform people in a more tailored way using SMS or push messages. These messages can give individual advice if necessary, but can also be used for advice for the entire crowd, similar to the LED screens. Push messages can be sent through an app, which might also provide other event-related information. What is however important to keep in mind is that a proliferation of applications and tools for visitors might work counterproductive.
Most interviewees brought up the downside of informing with advice: it is likely that only a limited number of people will comply to the advice. One interviewee mentioned that as a rule of thumb 65-70% of people ignore advice sent through a push notification at an irregular event, this might even be higher for regular event visitors like football supporters.

Limiting flow

Besides giving advice to the crowd, it is possible to more actively steer the crowd through infrastructure adjustments, like the Mojo barriers that limit the inflow of the station after events. These, however, are not possible to implement on a short-term notice due to the fact that they are relatively costly and are not necessarily available on demand.

Therefore, strategies for decreasing the peak flow might be relevant to look into. Trials have been held during EURO2020 in the Johan Cruijff ArenA, where people were assigned time slots with regards to entering the station. This was effective as entrance to the stadium could be withheld when scanning entry tickets. For the outflow, however, it was less effective as there is no 'barrier' to limit the flow since the stadium gates are simply opened and only an advice is given to visitors to adhere to an outflow time slot. It was expected that it was less effective as people 'simply want to go home' after an event.

One interviewee mentioned that some trials have been held in the ArenA-area with side-events like quizzes and keeping the bars in the stadium open for longer after the event, but these only had limited effects. Also here the aforementioned principle that people often want to go home after the main event that they visit is true and few people seem to be interested in a side-event after seeing their main goal of visiting.

Nonetheless, multiple interviewees indicated that influencing the (out)flow might be the most promising potential measure, as it does not necessarily require physical changes to the environment. Moreover, a lower peak and a more constant flow is better for the crowd safety and, in the case of side events, extra income can also be generated through e.g. consumption sales, making possible measures pay for themselves.

Separating flows based on destination

A couple of interviewees indicated interest into the separation of crowd flows. Separation of crowd flows increases crowd safety, as conflicting crowd flows cause stop-and-go waves and other adverse effects that increase the possibility of accidents. Currently, a 'soft' separation of flows is implemented at the Bijlmer ArenA station during events: by the use of LED screens the crowd is informed that it is best to queue for specific directions at specific entries. However, this is often neglected as most passengers often simply want to enter through the entrance closest to the event venues and walk through the station to the right platform.

It is possible to enforce a more strict separation of flows by placing regular crowd barriers in the station. Regular crowd barriers can be implementable at a short notice, but this comes with some issues as well. First of all, people who are unaware of the separation of streams will queue up in the wrong queue so once they have entered the station they might still have to cross the barriers in some way or another to get to the right platform. Secondly, it should be noted that such barriers might not be strong enough to cope with the pressures exerted by a standing or moving crowd. Also, regular crowd barriers are more easily dismountable as a structure, meaning that the crowd itself might actually dismount them. Thirdly, specifically for the case of Bijlmer ArenA but also relevant for other larger stations, there are some shops located within the station that are still opened after events end. When hard separation of streams is implemented within the station, people cannot go to these shops anymore if the shops are not part of 'their stream', leading to discontent of the crowd and shop owners.

Increasing capacity

Increasing capacity is rather straightforward with regards to vehicular traffic: add more lanes to a road. With regards to pedestrians at train stations this would mean increasing train frequencies. By letting more trains travel it is possible to let more people exit the station by train in the same time frame. Interestingly, there were only few interviewees that brought up this aspects, as timetables of public transport are often not within the scope of influence of a crowd manager.

This is a measure that is easier said than done. In the first place, trains and train personnel should be available. Whereas this aspect is surmountable, the wider timetable aspect is more difficult. Even during the evening hours and especially around events, the timetable already

is quite packed with (extra) trains. Also, adding a train to the timetable can have significant network-wide effects. Finally, since the end time of events can be variable (an artist can perform an encore or a football match can have overtime), implementing extra trains can also mean that more trains pass through the station (almost) empty, leading to unnecessary costs.
NS has held trials by using a 'sweeping train': a train that is ready for deployment at the call of a train controller. This can be very beneficial to create extra capacity at a short notice. Nonetheless, this train suffers from the timetabling aspect mentioned above: there should be room on the tracks to let the train travel in between other trains.

Other measures
There are some measures discussed during the interviews that are not necessarily classifiable based on the four measure types mentioned above or share overlapping aspects. One of these that has been brought up by multiple interviewees is the spreading of people over multiple stations in the neighbourhood of an event venue. In the Bijlmer ArenA case, this is possible since there is a metro station, Strandvliet, and another train station, Duivendrecht, within walking distance. While the station/platform capacities are not as large as at the Bijlmer ArenA station, the stations themselves can help in accommodating specific flows. This can, for example, be people coming from specific venues or stadium sections or people with specific destinations. With respect to implementing such a spreading aspect on a short term, informing of the crowd is key, where a message including an incentive to use one of the other stations is given. This is necessary, as people are very likely to use the same route out of a venue/event area as the route through which they entered. A more structural solution can be to provide instructions in the trains and metros that alighting at Duivendrecht and Strandvliet is an option as well or to renaming these station with the suffix 'ArenA', in order to lure people into using these stations more in the first place. This, however, is not viable as a short term measure.
The use of background music, as identified as a potential measure in the literature review, has seen various responses by the interviewees. The ones that saw it as an interesting innovation deemed it a great opportunity to use human behavioural in a somewhat subconscious way for crowd management. Similar aspects has been used in the past specifically for open air festivals using lighting and music volume. The interviewees that were sceptical about the effectiveness of background music mainly pointed towards the fact that most people that leave an event often simply want to go home, especially the ones that already exited the event venue. Moreover, due to the bustling of the crowd people might not be able the hear music except for when it is played very loudly, which in turn might not give the expected effects

4.3 Discussion

What is seen in the results of the literature review and the interviews is that most of the remarks regarding the monitoring of crowds are in line with one another: spatio-temporal aspects like crowd density and flow are most relevant to monitor to make sure that a crowded situation remains safe, though the monitoring of crowd characteristics deserves more attention. Nevertheless, there is an aspect that the interviewees disagreed on, which should be kept in mind: the relevance of social media for monitoring crowd characteristics. It can give relevant insights in individuals, but can it genuinely say something about the state of the crowd?
With regards to the scenarios, it became clear that the idea of a 'scenario' depends on the type of organisation that an interviewee is involved in. When involved in event organisation and safety, attention is paid to scenarios *within* an event venue. When involved in mobility aspects, more mobility-oriented scenarios where put forward. In the context of this research, mostly the mobility-related scenarios are relevant though venue-related scenarios can play a role as well.
Finally, concerning the measures, it became clear that different interviewees held different perspectives on the effectiveness of the measures. Some deemed behavioural measures to be key in solving crowd issues, others doubted whether the effects will be substantial enough.

Moreover, cooperation with regards to measures and sharing of gathered data is something that was brought up by most interviewees, specifically the ones who have been involved in the Bijlmer ArenA area. Multiple interviewees stated that it sometimes is unclear who's responsibility it is to manage the crowd:

- NS', as the main safety issues arise at the station;
- the venues', as they host the event and the crowd;
- the event organiser's, as they are responsible that the crowd comes to the area in the first place, or
- the municipality's, as they issue the permits for the events and the crowd traverses through public space from the venue to the station.

Besides the division of responsibilities, is was also mentioned multiple times that the different parties could enhance the quality of measures if information is shared in a better way, both concerning historic and real-time data. E.g., event organisers often have insights into the exact crowd origins, the municipality has insights into the status of people in the public space and the NS has data with regards to the status within the station. If such information is shared and stored in a better way, it is possible to adapt even better to different crowd situations.

4.4 Conclusion

As indicated in Figure 3.2, the literature review and interviews serve as a key input for the modelling in the next step of the research. Therefore, it is of most relevance to conclude by listing the identified important crowd status indicators, relevant scenarios and measures to analyse.
Table 4.3 shows the most important crowd status indicators. Noteworthy is the fact that crowd characteristics are not included in this table. This is due to the fact that crowd characteristics that change during event outflow are mainly observed in the field and since crowd modelling software does not include aspects like crowd atmosphere, it is not possible to include this in the model. Therefore it is decided to fall back on spatio-temporal aspects.

Table 4.3: Overview of the indicators relevant for analysis.

Indicator	Explanation
Crowd density	Important to take into account at locations where waiting occurs, like on a platform and in front of (check-in) gates.
Crowd flow	Important to take into account at locations where movement occurs, like in a station hall.

Table 4.4 shows the relevant scenarios to analyse, specified for the Bijlmer ArenA area. The regular Ajax match is not explicitly incorporated in the scenarios, as the situation of a 'regular triple' will be set-up in such a way that an Ajax match will lead to an almost independent peak flow compared to the other peaks. This makes an Ajax-only scenario redundant. Instead, a scenario is added where a 20% increase in public transport passengers in order to be able to analyse a situation where there is a modal split with a (potentially unexpected) high share of public transport users. Also, the situation with a disruption in the train service is not considered; a complete disruption will simply lead to a situation where it is undesirable for passengers to enter the station and a 'partial' disruption can happen in many different ways, making it difficult to create a representative scenario. Moreover, measures for solving partial disruptions regarding train deployment, like rerouting trains to other tracks, are considered to be out of the scope of the research.

Table 4.4: Overview of the scenarios relevant for analysis of the case study.

Scenario	Explanation
Regular triple	Situation where an independent peak is present for visitors of an Ajax match compared to the peaks of visitors of AFAS Live and Ziggodome.
20% increase	Similar to the regular triple scenario, except a 20% increase in boarding passengers is incorporated to simulate a different (unexpected) modal split.
Extreme triple	Worst-case scenario where outflow peaks of all the events line up.

Table 4.5 presents the measures that are deemed relevant for analysis, based on the different types of measures. It presents a short elaboration concerning the way the measure will be implemented in a real-life situation and each measure is given an individual substantiation on why it is relevant to analyse the respective measure. Important to note is that only one explicit behavioural measure is analysed as there is too few background information about the effects of possible behavioural measures. Moreover, increasing capacity is left out of further analysis, as it is deemed out of scope to influence the time table of the trains and metros.

Table 4.5: Overview of the measures relevant for analysis.

Measure	Implementation	Substantiation
No measure	-	Relevant to see how a scenario will turn out if no measures are implemeted at all.
Peak spreading *advising and informing*	Delay of portion of the crowd by e.g. informing the crowd on travel times to station or organising a side-event.	While tried measures (like organising a side event or assigning outflow time slots) were said to show limited effect, it can be relevant to analyse effects of spreading the crowd in order to encourage more interest in the subject.
(Mojo) barriers *limiting flow*	Placement of barriers and gates outside of station.	Though not necessarily implementable within a short-term notice, it has been implemented in the case study area before and in order to know whether other measures have similar, better or worse effects it is important to analyse the effects of barriers in the first place.
Stream separation *separating flows*	Placement of barriers inside the station.	Deemed to be a potentially efficient measure. Though there are key issues accompanying the measure, analysis whether it potentially has benefits is important as it can be implemented in a relatively short time span.
Behavioural influencing *behavioural measure*	Playback of music for the crowd travelling to the station.	Though very experimental as there are few researches into exact effects of possible measures, behavioural influencing is deemed relevant with regards to a human factor approach. Background music is chosen as there is a research that shows detailed effects of a single experiment on the topic.

5 MODELLING OF MEASURES

With more insights into crowd management established based on the literature review and the interviews, it is possible to analyse the effect of possible measures. This chapter elaborates on the modelling of specific measures as mentioned in Table 4.5 when applied to the case study environment.

5.1 Methodology

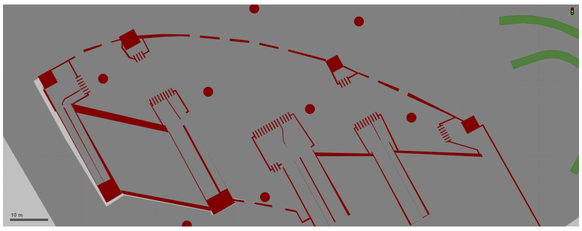
Sub-question 3 goes into the modelling and forecasting of crowd flows, which will be specifically oriented towards the case study. As part of the interviews, the aspects regarding scenarios in sub-sub-question 3.1. has already been investigated, as seen in Table 4.4. The other sub-sub-questions encompass the simulation of crowds and analysis of the suitability of modelling software for the intended purposes. The measures that are up for analysis have been presented in Table 4.5.
The Vissim/Viswalk traffic micro simulation software is used as it allows for the dynamic simulation of crowds. Dynamic simulation is needed as short-term measures are likely to change the flow of the crowd to a alteration of the environment or a behavioural measure.
The first step is to establish a correct model that incorporates the geographical lay-out of the case study area. Besides the geographical lay-out, it is also important to define the input data of the model based on historical data. Subsequently it is possible to calibrate the model in order to make sure that the model will mirror reality as good as possible.
When the model is deemed sufficiently capable of simulating crowd flows, the various experiments are defined. Experiments consists of the analysis of a measure applied to a specific scenario. Accompanying the setting-up of experiments is the identification of Key Performance Indicators (KPIs) that will be used to analyse the effects of measures on crowd flows.
After simulation of the various experiments, it will be analysed what the effect of specific measures are on the KPIs. Moreover, it is possible to determine whether the effect of a measure is statistically significant.

5.2 Model details

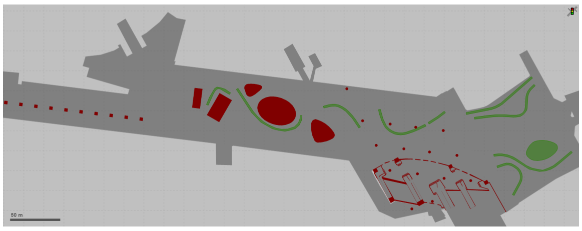
In order to construct a dynamic model, a good model lay-out and proper input data is needed. Only when those are established and gathered, it is possible to set up experiments. All details with regard to creation of the model are presented in Appendix C. An overview of the most relevant aspects is given in this section.

5.2.1 Model lay-out

In order to model the existing situation in the Vissim/Viswalk traffic micro simulation software, construction drawings of the station are used. Elevators are left out of scope, as they are barely used during events and only few counting details are available concerning elevator use. Moreover, the shops in the station hall are left out of scope for the model, as also no data is available concerning shop visitors. Shop visiting might nonetheless be relevant as it delays people going to the station and potentially increases conflicting flows. Platform-wise, the waiting passengers will be spread over the platform based on the location where the train will stop. An overview of the modelling of the station hall is provided in Figure 5.1(a).



(a) Top view of the Bijlmer ArenA station hall as modelled in Vissim. The red items indicate obstacles.



(b) Top view of the entire Johan Cruijff Boulevard including the station hall as modelled in Vissim.

Figure 5.1: Top views of the Vissim model without any measures.

With regards to the Johan Cruijff Boulevard, the various obstacles on the Boulevard, ranging from constructions, to benches, to small areas with trees, are incorporated in the model. Important to note is that a fixed number of inflow points,i.e. origin/destination (O/D) locations, on the Boulevard have been implemented, as presented in the satellite image in Figure 5.2

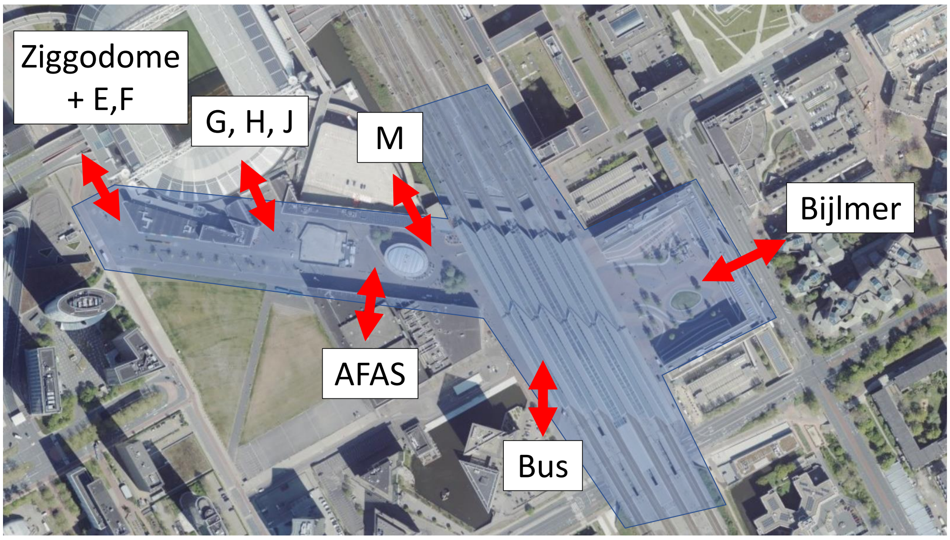
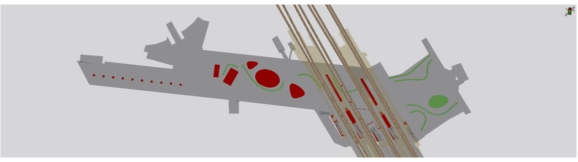


Figure 5.2: Origin/destination locations on the Johan Cruijff Boulevard.

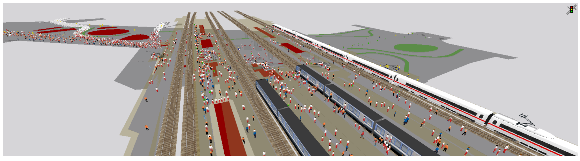
The O/D locations as indicated in Figure 5.2 have their own respective crowds going to or coming from those locations:

- The 'Bijlmer' O/D location is the main entrance to the Bijlmermeer neighbourhood;
- The 'Bus' O/D location is the location of the bus station under the Bijlmer ArenA station;
- The 'AFAS' O/D location is the entrance of the AFAS Live venue;
- The 'Ziggodome + E,F' O/D location is towards the entrance of the Ziggodome, the E and F entrances of the Johan Cruijff ArenA and the entrance of the Villa ArenA shopping mall;
- The 'G,H,J' O/D location concerns the G, H and J entrances of the Johan Cruijff ArenA, and
- the 'M' O/D location is towards the M entrance of the Johan Cruijff ArenA.

As crowding might already occur on the Boulevard, these locations are important to use as separate inflow points in the model, since the different origins of the various parts of the crowd might influence the routing of the crowd towards the station.
The final model lay-out, including platforms, is presented in Figure 5.3.



(a) Top view of the Boulevard including platforms of the station.

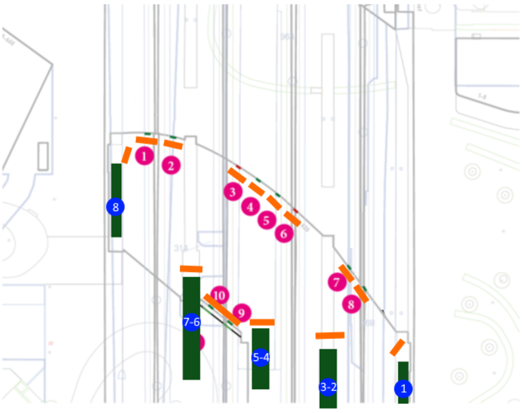


(b) 3D visualisation of the Bijlmer ArenA station during a test run of the model.

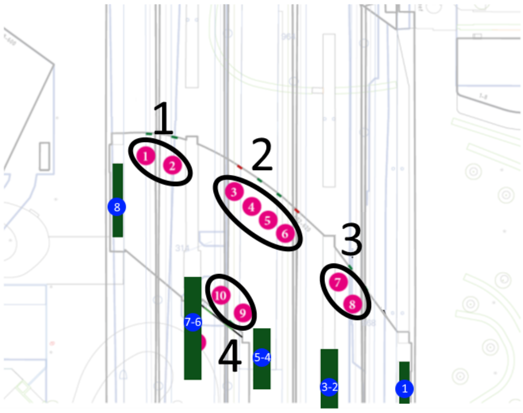
Figure 5.3: Complete overviews of the Vissim model.

5.2.2 Input data

With regards to the input data, the Dutch Railways have put up counting sensors in the station hall of the Bijlmer ArenA station in order to monitor the crowd situation. The locations of these sensors are indicated in orange in Figure 5.4(a). The data of these sensors during 21 (non-) event dates are made available for this research. An overview of these dates is available in Table C.1 in Appendix C.1.



(a) Pink circles indicate entrances, blue circles indicate platforms, orange lines indicate locations of most relevant counting sensors.



(b) Overview of the defined entrance sections of the Bijlmer ArenA station.

Figure 5.4: Top views of the station hall concerning (amongst others) placement of sensors and definition of entrance sections.

Initially, there is looked at creating a normalised outflow profile based on the various types of events, i.e. a normalised profile per event venue. For this aspect, first there is looked at dates where no event is organised, in order to identify the average regular flows at the station. Subsequently, dates on which an event is organised in only one of the venues are analysed to isolate the average increase in flow as a result of the event. Thereafter, the isolated data can be normalised based on the total event outflow volume. For Ajax matches, Ziggodome events and AFAS Live events this results in Figure 5.5. The normalised flow can in turn be used to generate an outflow profile of a day with multiple events using the end time of events and (expected) number of public transport users for each event. As an example, the outflow profile of triple event date 06-12-2019 has been recreated in Figure 5.6. A detailed explanation concerning the procedure of normalising flows and creating a flow profile of a multi-event date is presented in Appendix C.2.1.

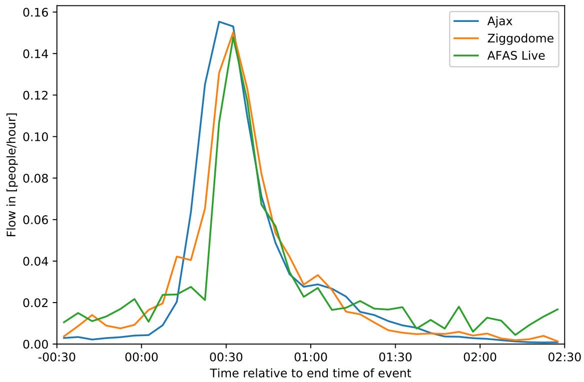


Figure 5.5: Combined visualisation of the normalised outflow profiles of the event venues.

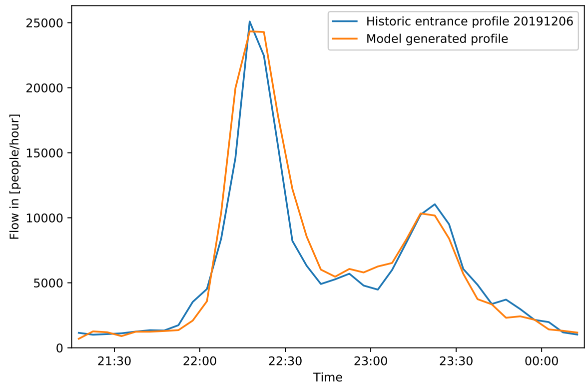


Figure 5.6: Visualisation of historical and model generated station inflow for 06-12-2019.

5.2.3 Calibration

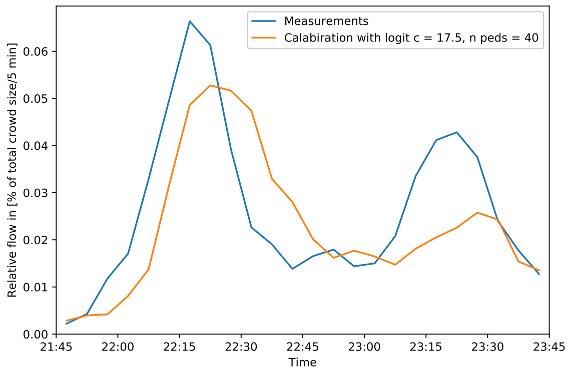
In order to make sure the simulation model mirrors the real-life situation as good as possible, calibration and validation of the model is carried out. Calibration of the model is based on the routing of pedestrians with regards to the 'entrance section' that they use to enter the station. The defined entrance section are presented in Figure 5.4(b).
The calibration is done with the model generated profile as presented in Figure 5.6 and the accompanying historical inflow data per entrance section on 06-12-2019. Important to note with regards to the calibration is that during the pedestrian flows of that date, the Mojo barriers measure has been implemented, so that measure will also be implemented during the calibration process. For more details regarding the Mojo barriers measure, see Section 5.2.5.
The KPI that will be used for the calibration is the normalised inflow per entry section. This KPI is chosen as it involves the route chosen by the pedestrians, which has a key impact on where congestion occurs. Calibration is mainly based around minimising the Root Mean Squared Normalised Error (RMSNE), which penalises larger errors more heavily and gives an indication of the relative error in the model:

$$\text{RMSNE} = \sqrt{\frac{1}{N} * \sum_{i=1}^{N} \left(\frac{x_i - y_i}{y_i}\right)^2} \tag{5.1}$$

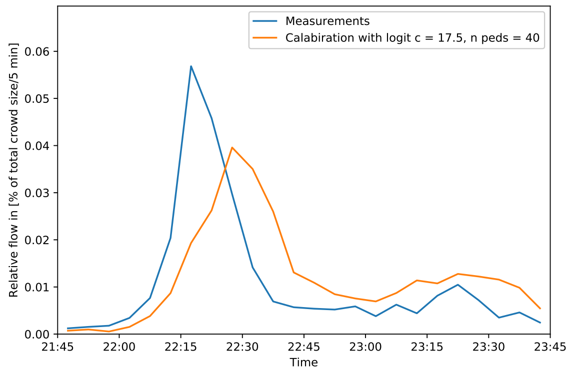
Besides the RMSNE, the Root Mean Squred Error (RMSE) is also analysed, as it gives more insights in the absolute error of the model:

$$\text{RMSE} = \sqrt{\frac{1}{N} * \sum_{i=1}^{N} (x_i - y_i)^2} \tag{5.2}$$

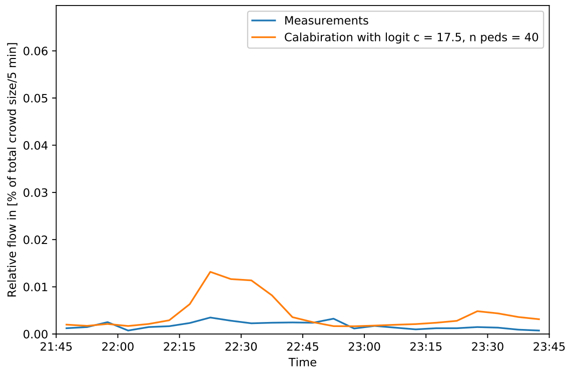
Details of the calibration process are available in Appendix C.4. The calibrated relative entrance choices of the flow over time is presented in Figure 5.7 here in the main report.
It is found that the best routing configuration leads to an RMSNE of 0.69, which is not particularly good as for a completely good fit it should be 0. Moreover, while the first peak is captured quite okay, the second peak seems to have its issues. These are expected to be caused by the fact that the routing of pedestrians in the model is based on *historic* travel times: during the first peak, congestion at and therefore the travel times through entrance section 1 increases,



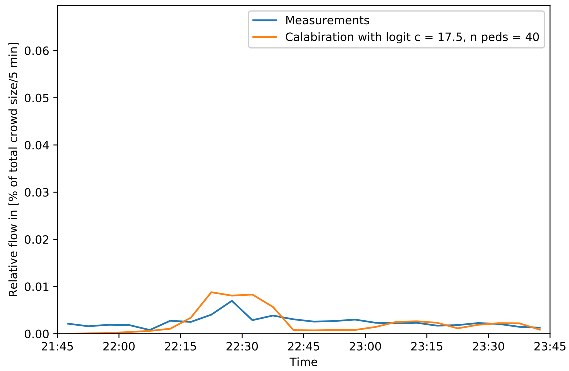
(a) Entrance section 1.



(b) Entrance section 2.



(c) Entrance section 3.



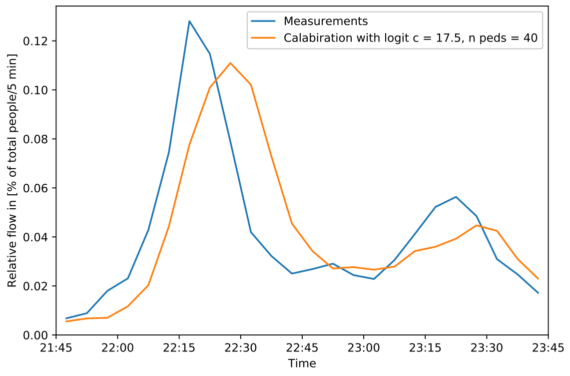
(d) Entrance section 4.

Figure 5.7: Comparison of normalised inflow profiles for different entrance sections of historical and modelled inflows for the best calibrated model.

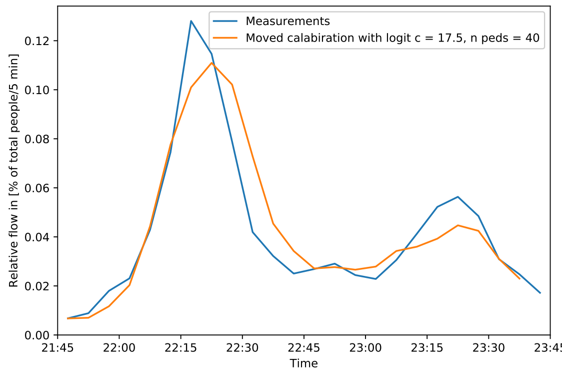
so more people will start using the other entrance sections up to a moment where almost no new pedestrians choose entrance section 1. Therefore, as only few pedestrians used entrance section 1 with a short travel time as congestion dissipates, it is still 'saved' in the model that the travel time using entrance section 1 is relatively high, giving a bias to people to choose one of the other entrance sections as only few to no congestion occurs there, while the congestion already dissipated at entrance section 1.
Nonetheless, as the overall patterns of route choice is captured for the first peak (see Figure 5.7) and the overall inflow has an RMSE of 0.011, the model is deemed good enough to use the model for the analysis of the effects of various measures. What moreover becomes visible when looking at Figures 5.7 and 5.8(a) is that there seems to be a shift regarding the peaks. This is explainable since for the input flows the counts at the entrances are used, while in the model the pedestrian inputs are generated at the event venues, meaning that they have to walk for a bit before entering the station. When accounting for a walking time of about 5 [minutes], Figure 5.8(b) appears, resulting in an RMSNE of 0.52 and an RMSE of 0.078. Especially the RMSNE is still not very good, but it is better, enhancing increasing the likeliness that the model can determine the effect of measures of the entire crowd flow. It still should be considered that the first peak shows more realistic behaviour than a second peak as a result of the route choice method.

5.2.4 Scenarios

As stated in the conclusion of Chapter 4, three relevant scenarios are identified, namely:



(a) Summed normalised inflow profiles.



(b) Summed normalised inflow profile when accounting for a walking time of 5 minutes.

Figure 5.8: Summed normalised inflow profiles based on the individual entrance sections in Figure 5.7.

- A regular triple;
- A 20% increase triple, and
- An extreme triple.

An explanation of the relevance of the various scenarios has been given in Section 4.4 and Table 4.4. Here, it will be shortly elaborated on how the various scenarios are established.

Regular triple

As stated in Table 4.4, the regular triple should encompass a situation where a largely independent peak is present for visitors of an Ajax match compared to the peaks of visitors of AFAS Live and Ziggodome. The flow profile of 06-12-2019 as discussed above is deemed to be such a situation. Therefore, the flows as generated for that date are used as inputs for a ‘regular triple’. A visualisation of these flows is presented in Figure 5.9. How this profile relates to the other scenarios can be seen in Figure 5.12.

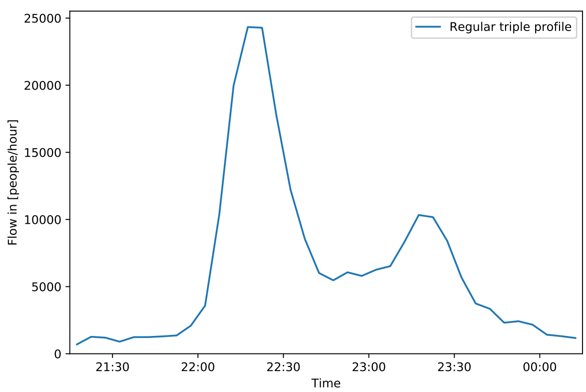


Figure 5.9: Flow profile for the ‘regular triple’ scenario.

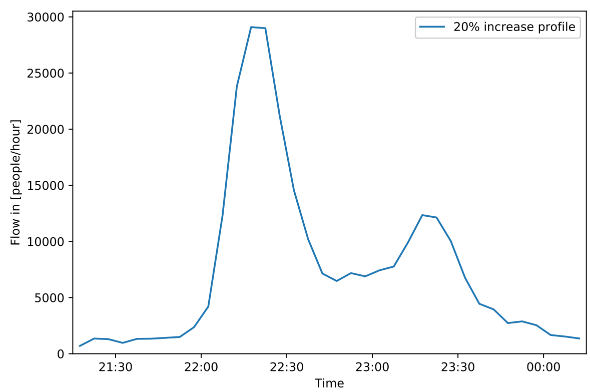


Figure 5.10: Flow profile for the ‘20% increase’ scenario.

20% increase

As stated in Table 4.4, the 20% increase scenario should be based on the regular triple profile, but with a 20% increase in flow. A visualisation of these flows is presented in Figure 5.10. How this profile relates to the other scenarios can be seen in Figure 5.12.

Extreme triple

As stated in Table 4.4, the extreme triple scenario should be a worst-case scenario where the outflow peaks of all possible events line up, i.e. where the end time of events is the same. In order to create this scenario, the situation of the regular triple profile is used, except that the end time of all events is set at 22:00. A visualisation of these flows is presented in Figure 5.11. How this profile relates to the other scenarios can be seen in Figure 5.12.

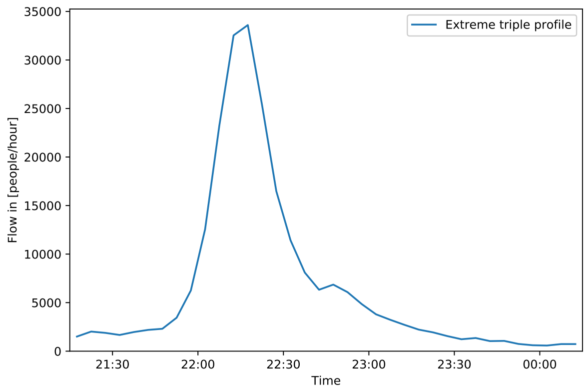


Figure 5.11: Flow profile for the ‘extreme triple’ scenario.

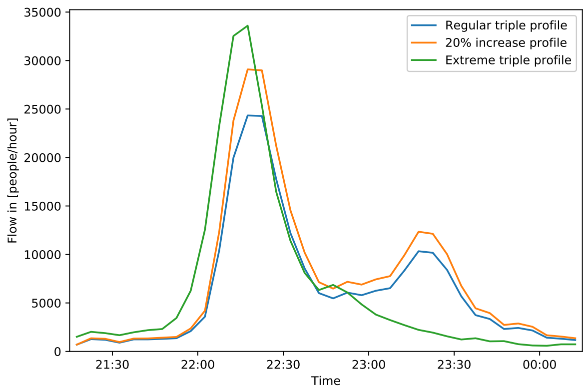


Figure 5.12: Visualisation of all flow scenarios.

5.2.5 Measures

As stated in the conclusion of Chapter 4, four relevant measures are identified (excluding the no measure situation), namely:

- Peak spreading;
- Barriers;
- Stream separation, and
- Behavioural influencing.

A substantiation on the relevance of the various measures has been given in Section 4.4 and Table 4.4 and a basic way on how to implement these measures in real life are mentioned. These implementations should be translated to aspects that can be incorporated in the modelling software. Table 5.1 presents an overview of how the various measures are incorporated into the model. A further explanation of the measures is given below, including the goal of the measure, with a more detailed description on how the measures are set-up given in Appendix C.5.
A relatively simple measure that is implemented in all experiments, also the no measure situation, is that people will not enter the station through entrance section 4 (the entrance at the bus station). This is done to make sure that the effects of the measures apply to all pedestrians. Moreover, it is relatively easy to implement in real life through placement of stewards

Table 5.1: Summarised overview of the measures and the way they can be implemented

Measure	Implementation into model
Spreading of peak flow	Changing the event outflow, i.e. pedestrian inputs based on historical trials to influence event outflow.
Barriers	Placement of obstacles and 'gates' outside of station.
Stream separation	Placement of obstacles inside station so that specific station entrances allow only for entry to specific platforms.
Behavioural influencing	Changing of the social force model parameters that determine pedestrian behaviour based on experiments that tried to influence pedestrian behaviour.

at this entrance section and is also implemented accompanying the Mojo barriers in real-life. While people will not enter the station through this entrance section, people are still able to exit through this section.

Spreading of peak flow

The goal of the spreading of peak flow is to have a lower peak inflow of the station and, accompanying that, a lower peak density at bottleneck locations. For the spreading of the peak flow, there has been looked at the effect of strategies that tried to convince people to change the departure time for their trip. The researches found mainly concerned commuting and investigated financial incentives and information provision to the commuters. Unfortunately, no study has been found that analyses the influencing of event outflow. Therefore, there has been chosen for a more general approach: analyse the effects of 'delaying' a certain portion of a crowd, based on the studies on commuters.

It has been found that it is possible to influence public transport users in such a way that the peak flow decreases up to about 15% by using a changed pricing scheme [Huan et al., 2021]. Moreover, a study investigated advice regarding delaying departure time with 15 [minute] intervals [Arian et al., 2018]. This interval is also deemed to be a logical voluntary waiting period, amongst others because the timetable of trains departing from the Bijlmer ArenA station after events seems to have about 15 [minute] intervals on average for trains having in the same destination.

When 15% of the crowd delays their departure moment with 15 [minutes], the resulting departure profile for a regular triple becomes visible in Figure 5.13. The altered profile has a peak value which is 9% lower than the regular triple peak.

Barriers

Mojo barriers (as already visualised in Figure 4.1) are a measure that have already been implemented historically in the case study area during triple events. The main goal is to keep the crowding outside the station instead of inside the station by creating a bottleneck outside the station, as outside the station there is more room available where people can stand crowded together in a safe manner. A visualisation of how the obstacles that make up the barriers and accompanying gates are implemented in the model is available in Figure 5.14(a).

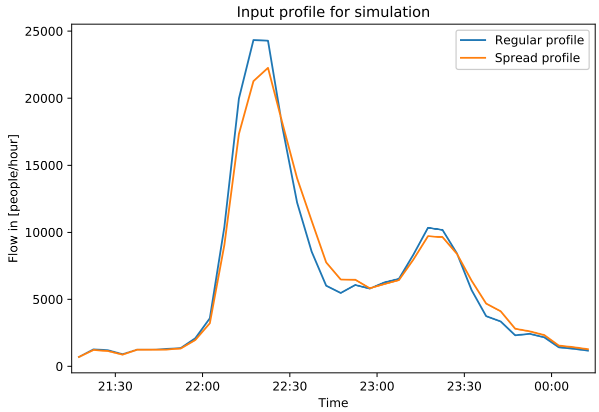
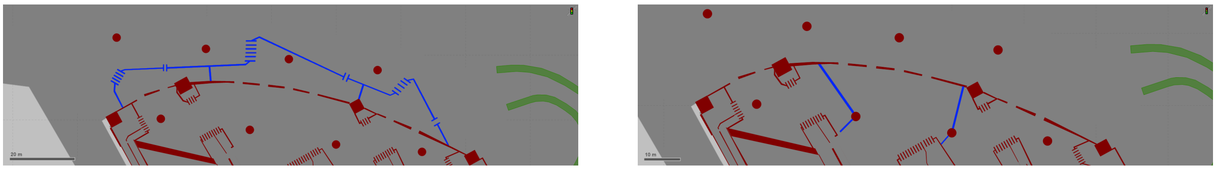


Figure 5.13: Comparison of the station inflow profile as based on the historic flow of 06-12-2019 that is also visible in Figure 5.8(a) and a situation where 15% departs the events 15 [minutes] later.



(a) Barriers highlighted in blue.

(b) Separation barriers highlighted in blue.

Figure 5.14: Visualisation of the implementation of barriers and gates that accompany the barrier and stream separation measures.

Stream separation

The goal of the separation of streams is twofold. First of all, the pedestrians will be spread better over the various station entrance sections, as instead of mainly choosing the first entrance section as it is the first entrance section that they encounter, they should choose the entrance section that is specifically used for their destination platform. Second, there will be fewer to no conflicting flows within the station as pedestrians can only choose for the entrance that is specifically used for their destination platform. A visualisation of how the obstacles that make up the stream separation barriers are implemented in the model is available in Figure 5.14(b). As can be deducted from the figure, entrance section 1 is dedicated to the platforms of tracks 6 to 8, entrance section 2 is dedicated to the platform of tracks 4 and 5 and entrance section 3 is dedicated to the platforms of tracks 1 to 3.

Behavioural influencing

A behavioural influencing aspect that has been found in literature concerns the effect of background music as investigated by Zeng et al. [2019]. The goal of this measure is to influence the crowd in such a way that the crowd will have a lower peak flow and to spread out the crowd over a larger area to have smaller densities in crowded situations. While the research of Zeng et al. [2019] is very experimental and only concerns one-dimensional pedestrian behaviour, it has been tried to apply the relative effects on free flow speed, capacity flow and crowd density that background music has using the fundamental diagrams as mentioned in the research. These effects are about -15%, -10% and -20% for the mentioned aspects respectively. It has been tried to mirror these relative changes by altering the parameter values of the social forces model. This model describes the behaviour of pedestrians in the modelling software. Details with regards to this 'calibration' of the social forces model, that is based on Kretz et al. [2018], can be found in Appendix C.5.4. The resulting changes to the parameter values in the social forces model are presented in Table 5.2.

Table 5.2: Altered parameters of the social forces model to mirror the relative effects of background music.

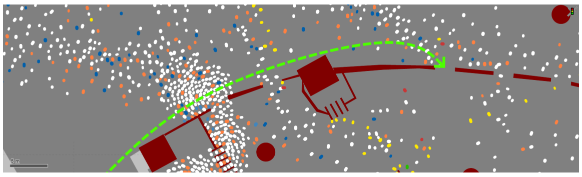
Parameter	Regular value	Altered value
τ in [s]	0.45	0.40
A Social (isotropic)	2.72	2.55
B Social (isotropic)	0.250	0.195

5.2.6 Modelling issues

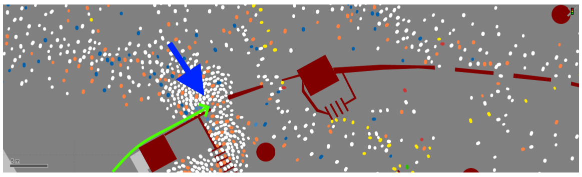
While running the model, various modelling issues where encountered. As most of those issues were discovered before or during the calibration of the model, it has been tried to to solve them as good as possible before running the experiments.The two most prominent and influencing modelling issues are elaborated upon below.

Unexpected and unnecessary blockages

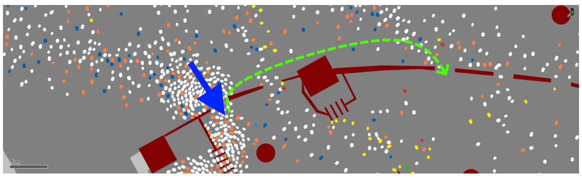
During the initial simulations of the model, it became clear that during some runs non-solving deadlocks occurred, often caused by conflicting streams of pedestrians already outside of the station. Crowding would occur outside of the first entrance section. Some crowd members have entrance section 2 as 'destination', while they approach the crowd waiting in front of entrance section 1 from the south (Figure 5.15(a)). They get caught up in the waiting crowd, and the waiting crowd 'pushes' them into the station through entrance section 1 (Figure 5.15(b)). While having entered the station, these people still want to go to entrance section 2 and therefore want to exit through entrance section 1 again before going to section 2, blocking the inflow through section 1 (Figure 5.15(c)). In order to combat such aspects, some extra routing points have been defined outside the station, making people take a detour around waiting crowds (Figure 5.15(d)).



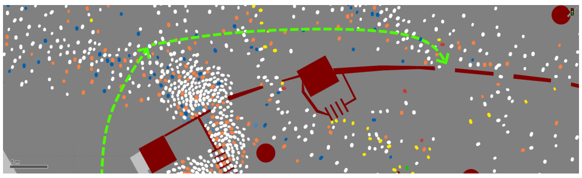
(a) Route of pedestrians from south.



(b) Movement incl. crowd in blue.



(c) Blocking of route by crowd.



(d) Solution by detour.

Figure 5.15: Routing causing deadlocks at entrance section 1.

Similar aspects occur at the check-in gates and (if implemented)gates in the barriers, as approaching people do not have yet been 'assigned' a specific (check-in) gate. These people

might block other people trying to pass through a check-in gate. Therefore, similar detour aspects are implemented there.
Finally, also inside the station conflicting flows can appear, specifically in front of the gates leading to the platform of track 6 & 7. These are mainly the result of pedestrians bumping into each other while there are no clear 'pathways'. While in real way it might be very chaotic so that clear pathways will occur, it is deemed unrealistic that actual deadlocks will occur. Therefore, in order to combat the deadlocks, an extensive number of routing points are placed in the station to recreate some kind of pathway-forming.

Undesired crowding outside of station

As a result of the extra routing points, some other locations arise where undesired crowding occurs. The most striking of these is visible in Figure 5.16: northwest of the station hall, crowding occurs as a result of pedestrians wanting to pass through a routing point.
It has been tried to solve the crowding at this and some similar locations by enlarging the area that the routing point is dedicated to in order to let the crowd pass the routing point over a larger section. This, however, did not always yield the desired effects. As this aspect does not lead to non-solving deadlocks, it is simply concluded that this aspect is part of the model and should be kept in mind when analysing the results.

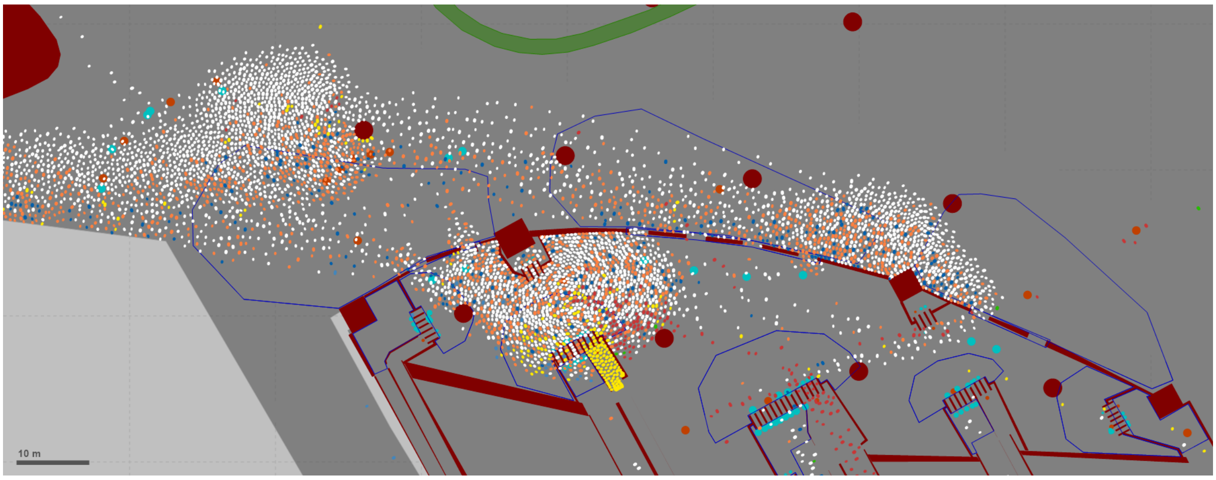


Figure 5.16: Visualisation of crowding towards the northwest of the station.

5.2.7 Key performance indicators

In order to be able to to analyse the effects of specific measures, it is important to identify which KPIs are relevant to take a look at. In Chapter 4 it has already been identified that crowd density and flow are the most important indicators to analyse from a crowd manager perspective, as explained in Section 4.4 and Table 4.3. The procedure used to identify the specific KPIs and their measurement locations is based on the two key perspectives regarding station usage: the perspective of the owner of the station environment (in this case the Dutch Railways) and the perspective of the (boarding) passenger.

Dutch Railways

The Dutch Railways has the obligation to make sure that the passengers that use the station are served and that this is done in a safe manner. Safety in the station hall mainly concerns the degree of crowding at bottleneck locations in the station. Relevant bottleneck locations are the check-in gates and the platforms. It is in the interest of the Dutch Railways that these locations do not overcrowd in order to ensure safety of people in the station. As mentioned during the interviews, this is incorporated through analysing the total inflow of the station, as it is known that when the station inflow exceeds 400-450 [people/minute], overcrowding is likely to occur. Therefore, the following KPIs are examined from the perspective of the Dutch Railways:

- Crowd density before check-in gates;
- Crowd density on platforms, and
- Station inflow.

With regards to the crowd density KPIs, specific data-collection zones are identified within the model, of which the ones on the ground floor of the station are visible in Figure 5.17. To determine crowd density, Vissim/Viswalk offers the ability to determine 'experienced density'. This attribute determines the density of a pedestrian incorporating all other pedestrians that are in a 2 [m] radius around said pedestrian. Such KPI gives a better indication than an overall density, as the overall density simply determines the number of pedestrians in the data-collection zone and divides it by the total area of the zone.

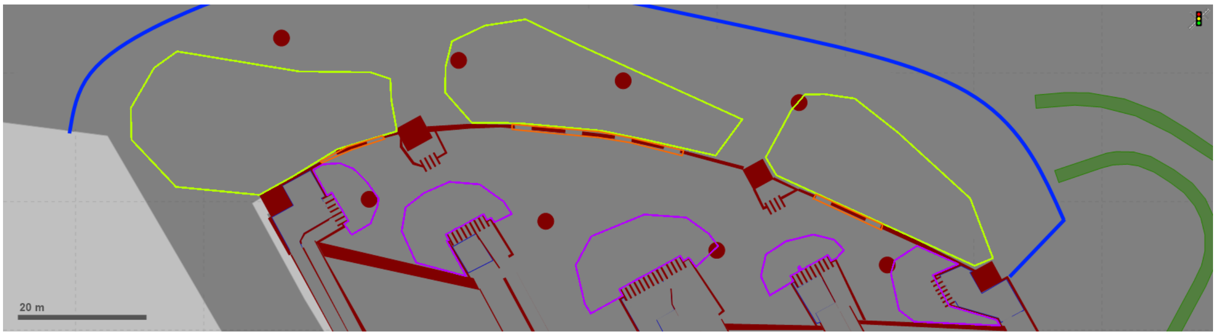


Figure 5.17: Data-collection zones on the ground floor of the Bijlmer ArenA station model. Blue line indicates the boundary after which the travel time measurement starts, yellow zones are the 'buffer sections', orange zone indicates the entrance sections, purple zones indicate the areas before the check-in gates.

Passengers

Boarding passengers desire to have the highest possible level of service and comfort on their way to the train or metro, even in crowded situations. The most direct indicator of service for a travelling passenger is travel time: a lower travel time indicates a higher level of service. Therefore, the time it takes for a passenger to reach the platform is a relevant KPI. Interestingly, this indicator was not mentioned in Table 4.3, as the indicators mentioned there did not necessarily come from the perspective of a boarding passenger.
With further regards to comfort, the safety aspects mentioned at Dutch Railways play a role here as well, as a feeling of unsafety is not beneficial for comfort. Where for the Dutch Railways the responsibility and therefore relevance of safety KPIs stops outside of the station. it is still very relevant for a passenger's experience to incorporate density at potential bottleneck locations outside of the station. These bottleneck locations are the station entrances and (when applicable) the gates in the Mojo barriers, which together can be described as 'buffer sections'. Therefore, the following KPIs are examined from the perspective of boarding passengers:

- Travel time to the platforms, and
- Crowd density at buffer sections.

5.3 Results

Based on the model and measures set-up as defined in Section 5.2, the model is simulated. For each of the KPI0,s the needed number of replications is elaborated upon in Appendix C.3, where eventually it was decided to use 30 replications. The output of the simulations is elaborated upon in the next sub-sections. The results are presented in a tabular form for each possible measure independently in Tables 5.6 to 5.9. A reading guide for these tables is presented in Table 5.4 on page 38.

The effects of a measure are reflected upon with respect to a situation without any measures. First, the inflow KPI is analysed as it serves as input for the assessment of safety by the Dutch Railways. Secondly, the density KPIs are analysed to see whether there are potential safety issues. These are accompanied with a spatial density plot of the station hall environment at the visually-determined worst moment in time regarding high-density areas. Finally, attention is paid to the travel time KPI. The peak value of each KPI is assessed for its statistical significance using a paired-t test comparing the measure situation to the situation without any measures, given a significance level of $\alpha = 0.05$. An elaboration on the calculation of statistical significance is available in Appendix D.1.

With regards to the colours used in the spatial density plots in Tables 5.5 to 5.9, Figure 5.18 serves as a legend. The threshold values for the colours are based on the 'level of service' concept for walkways as stated by Fruin [1971].

After the case-study specific results are analysed, there is looked at whether the expected goal of the measure as mentioned in Section 5.2.5 seems to be achieved. Subsequently, there is looked at the applicability of the measure to a more general station-environment-perspective in order to give some insights into the translatability of a measure to other station environments. This is done through a more abstract analysis of the identified effects of a measure.

Density in [peds/m^2]	Colour
≤ 0.308	blue
≤ 0.431	cyan
≤ 0.718	green
≤ 1.076	yellow
≤ 2.153	orange
> 2.153	red

Figure 5.18: Legend applicable to the spatial density plots in Tables 5.5 to 5.9

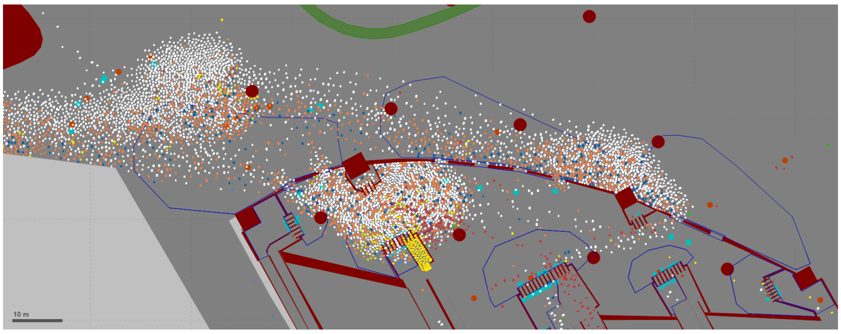


Figure 5.19: Copy of Figure 5.16: deadlock occurring within the station in front of the check-in gates leading to track 6 & 7.

5.3.1 Remaining deadlocks during simulation

Even though it has been tried to work around the occurrence of deadlocks using abundant routing points, still non-solving deadlocks seemed to arise when analysing the data. When visually checking some of the simulations, it became clear that this still had to do with the situation before the check-in gates of the platform leading to tracks 6 & 7, as also visible in Figure 5.19. It was mainly seen that these deadlocks occurred during the extreme triple scenario. Due to high intensities in this scenario, the deadlock did not solve naturally. Such situations should not be incorporated into the result analysis as it gives wrong and not necessarily realistic indications about the situations in the station and therefore the effect of a measure. Therefore, it has been decided to exclude the simulations where deadlock occurs from the result analysis.

The exclusion of individual runs is based on the number of people completing their trip to the platform of tracks 6 & 7, as in the situation of a deadlock, only few to no pedestrians will reach this destination platform. An elaborate description of this procedure is given in Appendix D.2. Table 5.3 presents the remaining number of runs incorporated for the result analysis for the various measures and scenarios.
With regard to the paired-t approach for determining statistical significance, only the runs that do not lead to a deadlock in both the measure and no measure situation are incorporated.

Table 5.3: Number of simulation runs per measure and scenario where no deadlock as visible in Figure 5.19 occurs.

Measure	**Nr. of runs without deadlock**		
	Regular triple	20% increase	Extreme triple
None	30	30	22
Barriers	30	30	20
Separation	30	30	30
Behaviour	21	18	15
Spread	30	30	30

5.3.2 No measure

While the no measure situation serves as a reference situations to which all the measures are reflected, also some notes can be presented with regards to crowd situation. Specifically regarding the spatial spatial density plots, as these have difficulties to explicitly show the differences between a reference and a measure situation. Table 5.5 shows the density plots for the no measure situation in the various scenarios. The presented density plots are chosen as 'worst-case' situations based on visual inspection of density plots that are made every minute of a representative model run.
For the regular triple, it becomes clear that the main density issues occur at the buffer section of entrance section 1 and in front of the check-in gates of the platforms of tracks 6 to 8. Nonetheless, also the other check-in gates sections see high densities as do the other buffer sections to a lesser extend.
For the 20% increase, similar conclusions can be made as for the regular triple, but with higher densities. This is logical, as there is a 20% higher demand at the same moment in time. Also striking are the higher densities and larger areas taken up by the crowd within the station hall.
For the extreme triple, it becomes clear that the extreme increase in people wanting to enter the station at the same moment has severe issues for the densities and areas covered by the crowd. Buffer section 1 sees an extreme increase in the size of the waiting crowd. As a result, also a significant part of the crowd is using entrance section 2, leading to a crowded situation there as well. Within the station, specific increase in crowding seems to occur before the check-in gates leading to the platform of track 8.

5.3.3 Spreading of peak

The results of the spreading of the peak measure when reflected to the situation without a measure are presented in Table 5.6 on page 40. An elaboration on the results is given below. Looking at Table 5.6, it becomes clear that spreading of the peak can:

- slightly decreases station inflow;
- seemingly reduces size of crowded areas;

- decrease peak buffer densities;
- decrease densities in front of check-in gates;
- decrease peak platform densities, and
- in extreme situations greatly decrease travel time.

From the perspective of the Dutch Railways, spreading of the peak seems to be an effective way to manage the crowd, as it only seems to have positive effects: all relevant safety KPIs regarding peak density decrease. Problems could however be in the implementation, as there has not been a thorough investigation on how to achieve the effect of convincing 15% of the crowd to depart 15 [minutes] later. Key in this might be the cooperation between parties, as was also indicated during the interviews.
With regards to the passenger perspective, the measure also seems to be beneficial. The travel time is reduced, even substantially in the extreme triple scenario, leading to a higher level of service. Since all the densities are reduced as well, the level of comfort is increased as well.
The goals of the measure are achieved: the peak inflow is slightly decreased, but most importantly the peak densities are significantly decreased. As an effect the peaks seems to last slightly longer, which is logical as a part of the crowd is 'delayed'.
In general, the spreading of the peak flow is useful in a situation where it is possible to target a portion of the crowd and convince them to wait. This will have beneficial effects on all analysed KPIs. How the convincing of the crowd can be done exactly is up for research, but as it seems to only have positive effects, it sure is something that sees great potential.

5.3.4 Barriers

The results of the barrier measure when reflected to the situation without a measure are presented in Table 5.7 on page 43. An elaboration on the results is given below.
Looking at Table 5.7, it becomes clear that barriers can:

- spread the flow over the various entrances;
- moves high density locations to outside the station;
- increase the peak densities in buffer sections;
- reduces the peak densities at check-in gates;
- has small effects on peak platform density, and
- increases the travel time.

From the perspective of the Dutch Railways, the barriers measure seems to be effective. The density in the station (in front of the check-in gates) can be reduced by making use of the buffer in the form of the ArenA Boulevard. There seem to be slight increases on peak platform densities, but this might simply be a result of aspects like people arriving at their destination platform when their initial train has left as a result of the buffer. This is something that is always possible at a station during event outflow.
With regards to the passenger perspective, there might be some nuisance as travel time and density at the Boulevard are increased. Nonetheless, as safety aspects with regards to density in the station hall are decreased, the increase in travel time and density on the Boulevard should be acceptable.
The measure seems to be effective in achieving its expected goal, as it decreases the density in the station hall. As a consequence of the measure, the density in the buffer sections increases, but this was also expected.

Since the barriers seem to move the high crowd densities away from the check-in gates sections to the buffer sections, the measures seems to be efficient in moving the waiting crowd to a further upstream location. Therefore, the barriers measure is applicable in a situation where overcrowding within the station can be an issue and there is the possibility to buffer the passengers on a square or street. Moreover, as the inflow seems to spread over the various entrance sections, barriers might also be useful for spreading the crowd over various (station) entrances.

5.3.5 Separation of streams

The results of the separation of streams measure when reflected to the situation without a measure are presented in Table 5.8 on page 46. An elaboration on the results is given below.
Looking at Table 5.8, it becomes clear that a separation of streams:

- spreads the crowd over various entrances;
- creates more high density locations in the station hall;
- spreads the crowd over various buffer sections;
- substantially increases peak densities before the check-in gates;
- substantially increases peak densities at the platforms, and
- has mixed effects on travel time based on peak crowd flow.

From the perspective of the Dutch Railways, the separation of streams is not an effective measure. It results to a more dense crowd in the station, both in the station hall as on the platforms, which can result in serious safety issues.
With regards to the passenger perspective, the reduced travel times in a very extreme situation might be comfortable. However, the increased densities at both the check-in gates and platform will not be considered an improvement, as this will also interfere with the safety perception of a passenger.
The first goal, to spread the inflow over the various inflow sections, will inherently be achieved as pedestrians will not have other options to enter the station. The second goal will also have its inherent effects, as conflicting flows will be less due to the separation. However, the fact that there are increased densities is an unexpected consequence of the measure that can have serious impacts on the safety of the crowd.
In general, while it has considerable down sides, the separation of streams might still serve a useful purpose in a very specific situation. Disentangling the flows based on their destination can be useful when conflicting flows are a potential crowding issue or when an upstream bottleneck causes safety issues. Nonetheless, important to note in a station environment where this measure is applied to, is that downstream of the separation location, there are minor to no bottlenecks (like the check-in gates in the case study) and there is a near infinite discharge capacity.

5.3.6 Behavioural influencing

The results of the behavioural influencing measure when reflected to the situation without a measure are presented in Table 5.9 on page 49. An elaboration on the results is given below.
Looking at Table 5.9, it becomes clear that behavioural influencing has some unexpected outcomes. While the inflow pattern shows effects that are not necessarily strange, issues occur when analysing the densities. There seems to be a weird kink for all scenarios for the first buffer section at about 22:25 and the extreme triple has a very high and long peak. Visual inspection of

model runs led to the presumption that this has to do with the crowding considering the routing aspect northwest of the station hall, that has already been discussed in Section 5.2.6.
Moreover, the barely and none decreasing density in front of the check-in gates of track 8 in the extreme triple scenario is likely caused by incorporating runs where local non-solving deadlocks occur. While there has been explicitly filtered for deadlocks in front of the check-in gates of tracks 6 & 7, it can be stated that this does not mean that all (non-solving) deadlocks are discarded. Moreover, the densities in front of the check-in gates of tracks 4 & 5 in the regular and 20% increase scenarios do not show a decreasing pattern, but this does not seem to propagate to the same extend as for track 8 in the extreme triple scenario. It is unclear how these non-decreasing densities at the check-in gates of tracks 4 & 5 occurs.
Also with regards to the travel times, the results do not seem to go down to the original level. The fact that the travel times do not return to the original level does seem to be a logical consequence of the enlarged areas covered by congestion as visible on the density plots, meaning that people will encounter congestion over a larger area and therefore will encounter congestion for a longer time span. Why the travel times do not seem to decrease in the case of the extreme triple scenario is however unclear.
Nonetheless, behavioural influencing seems to:

- spread inflow over the entrances, but decrease total inflow;
- larger crowded areas with increased densities all around the station;
- increase peak densities at the buffer sections;
- increase peak densities at the check-in gates;
- have varying effects on platform density, and
- significantly increase travel times.

From the perspective of the Dutch Railways, behavioural influencing through the presented way is not an effective measure as it almost only results in worse KPI values. The only positive aspect is that it might decrease density at some platforms. though as the implementation itself can be discussed, these effects might turn out completely differently in a real-life situation.
With regards to the passenger perspective, the same can be concluded: almost all of the KPIs turn out in a worse way.
The goal to have a lower inflow is achieved to some extend, as the peak of the summed station inflow is lower in all scenarios, but this inflow is not necessarily smoother: while the crowd seems to spread out over larger areas, severely increased densities occur in the buffer sections.
In general, it is difficult to present a situation where the behavioural influencing would be relevant. However, as the way implementation of the measure in the model is discussable, it should also not be disregarded as a hopeless option. Behaviour is a complex subject and real-life effects might be different than modelled in this research. Therefore, more interest into the topic can be beneficial.

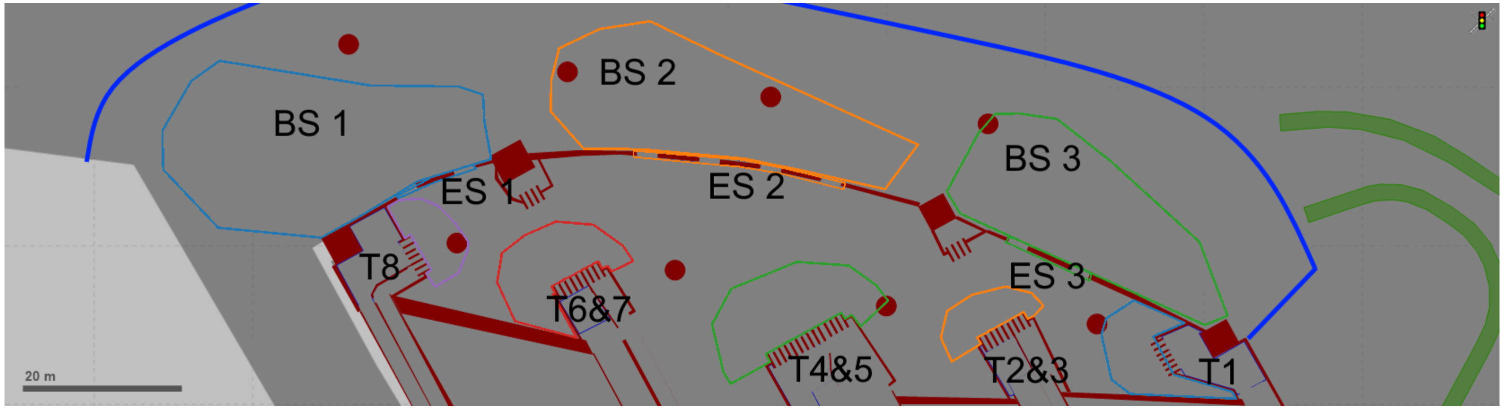


Figure 5.20: Altered copy of Figure 5.17 with text labels as mentioned in Table 5.4 and colours based on the graphs in Tables 5.7 to 5.6.

Table 5.4: Reading guide for Tables 5.5 to 5.6. Note that the relative effects are regarding the peak KPI values.

KPI	***Scenario name***				***Visualisation in Figure 5.20***
Flow through entrance sections	*Figure showing the inflow over time through the various entrance sections including the summed inflow through all sections*				Entrance sections labelled with ‘ES’
	Rel. eff.[1] on entrance section 1	Rel. eff. on entrance section 2	Rel. eff. on entrance section 3	Rel. eff. on summed inflow	
	Short elaboration on relative effects of the measure on flow through entrance sections.				
Density plot station hall	*Figure showing the density in the station hall and its direct environment at the moment with the highest overall density of a representative model run.*				
	Short elaboration on visible effects in density plot.				
Density in buffer section	*Figure showing the density over time in the various buffer sections*				Buffer sections labelled with ‘BS’
	Rel. eff. on buffer section 1	Rel. eff. on buffer section 2	Rel. eff. on buffer section 3		
	Short elaboration on relative effects of the measure on density in buffer sections.				

Table 5.4 continues on the next page.

[1]Relative effect

Continuation of Table 5.4		
KPI	***Scenario name***	***Visualisation in Figure 5.20***
Density before check-in gates	*Figure showing the density over time before the various check-in gates* Rel. eff. on check-in gates of track 1 | Rel. eff. on check-in gates of tracks 2 & 3 | Rel. eff. on check-in gates of tracks 4 & 5 | Rel. eff. on check-in gates of tracks 6 & 7 | Rel. eff. on check-in gates of track 8 Short elaboration on relative effects of the measure on density before check-in gates sections.	Tracks labelled with 'T'
Density on platform	*Figure showing the density over time on the various platforms* Rel. eff. on the platf. of track 1 | Rel. eff. on the platf. of tracks 2 & 3 | Rel. eff. on the platf. of tracks 4 & 5 | Rel. eff. on the platf. of tracks 6 & 7 | Rel. eff. on the platf. of track 8 Short elaboration on relative effects of the measure on density on the platforms.	Not visible in Figure 5.20, but tracks labelled with 'T'
Travel time to platform	*Figure showing the travel time over time to the various platforms* Rel. eff. on the route to platf. of track 1 | Rel. eff. on the route to platf. of tracks 2 & 3 | Rel. eff. on the route to platf. of tracks 4 & 5 | Rel. eff. on the route to platf. of tracks 6 & 7 | Rel. eff. on the route to platf. of track 8 Short elaboration on relative effects of the measure on travel times to various platforms.	Start line of travel time count in dark blue, tracks labelled with 'T'

Table 5.5: Density plots for the ***no measure*** situation. For a legend see Figure 5.18.

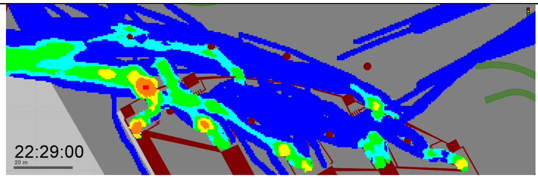
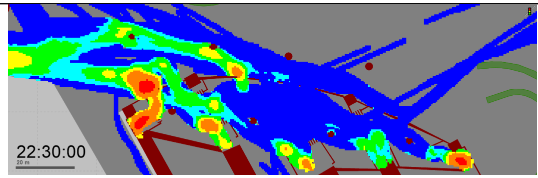
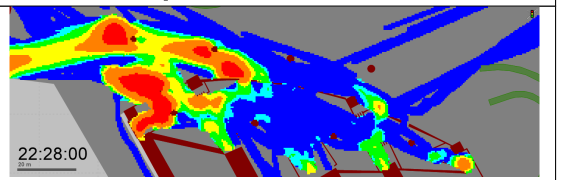
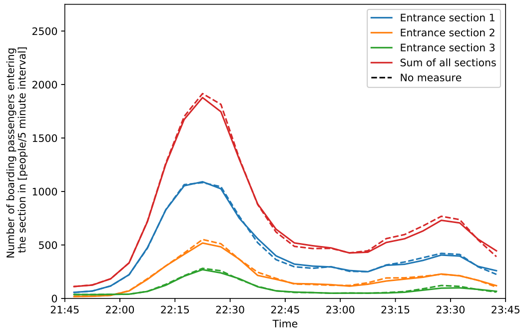
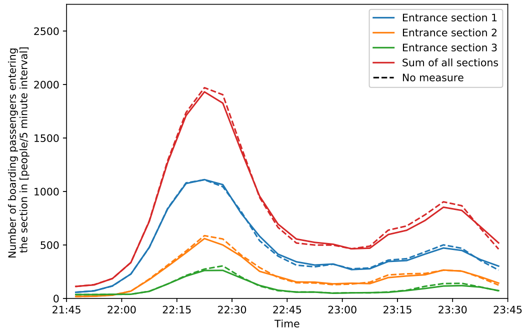
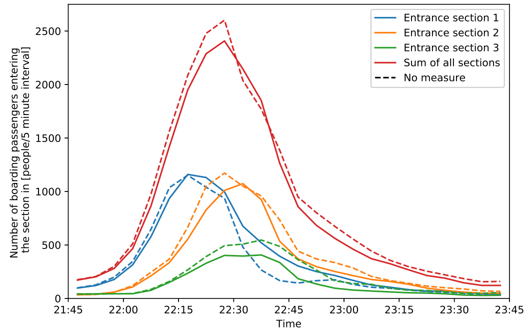
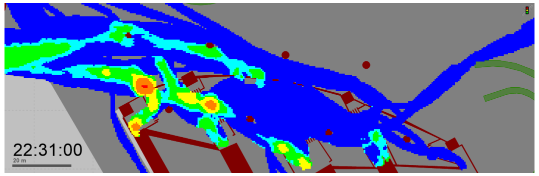
KPI	**Regular triple**	**20% increase**	**Extreme triple**
Density plot station hall	 Main density issues in buffer section 1 and before check-in gates of platforms 6 to 8.	 Similar to regular triple, but more extreme, also before other check-in gates.	 Extreme increase in crowd waiting in BS1. Increase in use of ES 2 visible.

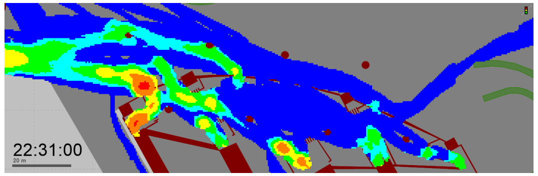
Table 5.6: Results of the modelling study per KPI for the ***spreading of peak flow*** measure. Statistically significant results are underlined. Note the different y-axes for the travel time analysis. For a legend of the density plots, see Figure 5.18.

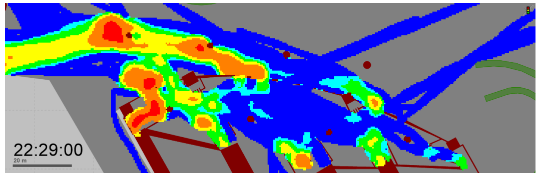
<table>
<tr><th>KPI</th><th>Regular triple</th><th>20% increase</th><th>Extreme triple</th></tr>
<tr><td>Flow through entrance sections</td><td>

+0.8% | -6% | -4% | -2%
Only *minor effects* on peak inflows.</td><td>

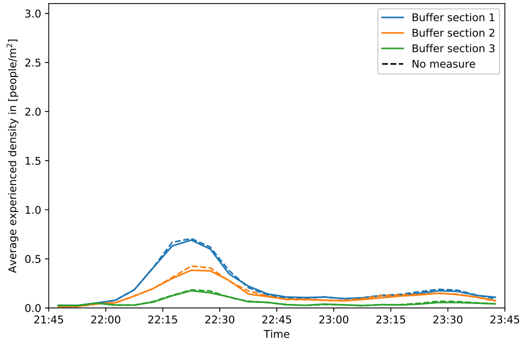
+0.2% | -5% | -14% | -2%
Little more substantial decreases of peak inflows than regular triple, though still minor.</td><td>

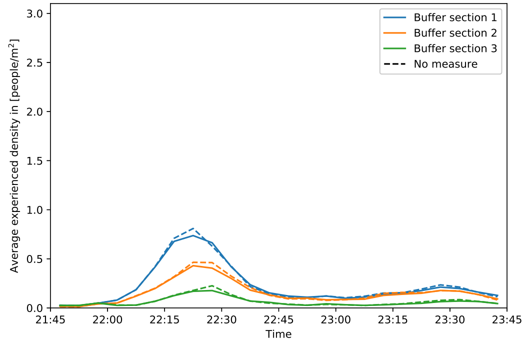
+0.6% | -8% | -26% | –7%
Little more substantial decreases of peak inflows than 20% increase, specifically for section 3.</td></tr>
<tr><td>Density plot station hall</td><td>

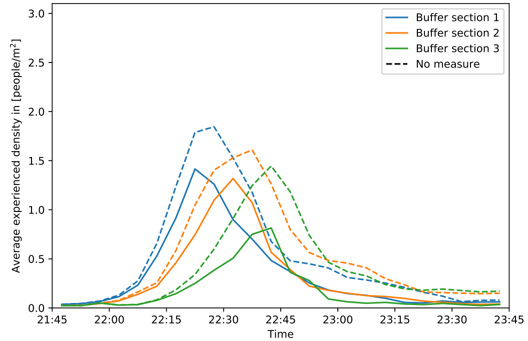
Relatively *similar pattern as in no measure* situation.</td><td>

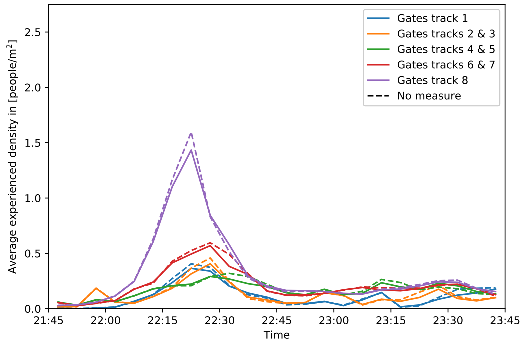
similar to no measure situation, though *crowding areas seem smaller*.</td><td>

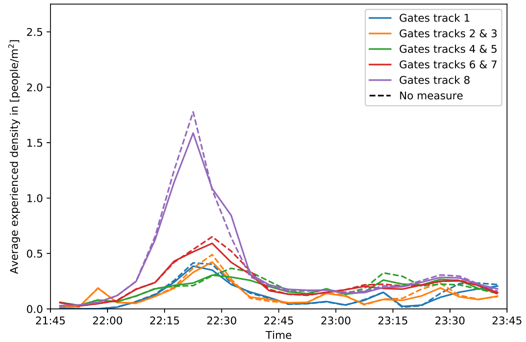
Densities lower and areas covered by crowd seem smaller.</td></tr>
<tr><td colspan="4">Table 5.6 continues on the next page.</td></tr>
</table>

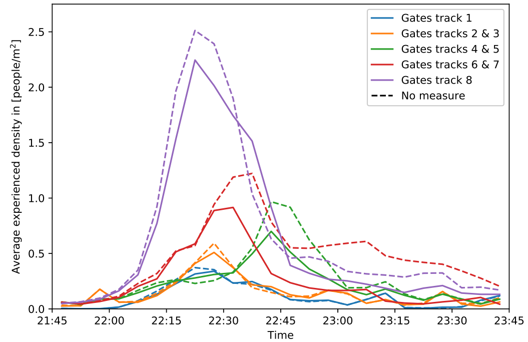
<table>
<tr><th colspan="4">Continuation of Table 5.6</th></tr>
<tr><th>KPI</th><th>Regular triple</th><th>20% increase</th><th>Extreme triple</th></tr>
<tr>
<td>Density in buffer section</td>
<td>

<table><tr><td>-2%</td><td>-10%</td><td>-4%</td></tr></table>
Only measure with (slight) decreases in peak density for all buffer sections.</td>
<td>

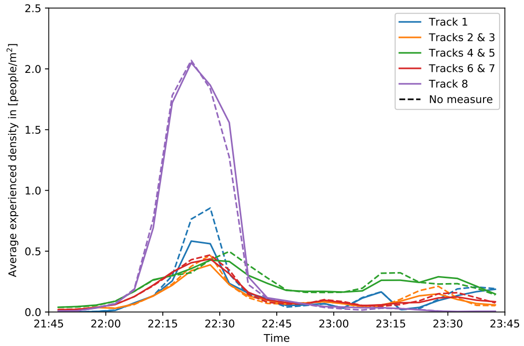
<table><tr><td>-9%</td><td>-7%</td><td>-22%</td></tr></table>
Similar to regular triple.</td>
<td>

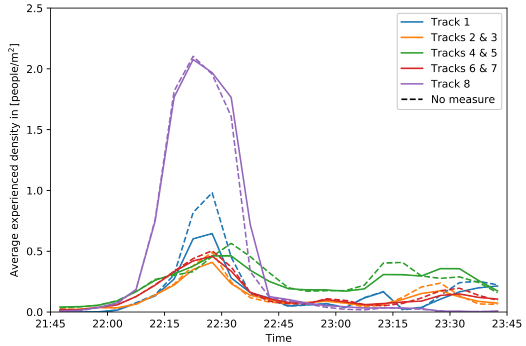
<table><tr><td>-23%</td><td>-18%</td><td>-44%</td></tr></table>
Similar to regular triple, but with more substantial effects.</td>
</tr>
<tr>
<td>Density before check-in gates</td>
<td>

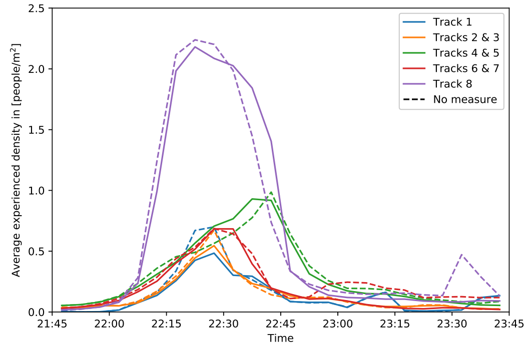
<table><tr><td>-10%</td><td>-11%</td><td>-9%</td><td>-4%</td><td>-10%</td></tr></table>
Clear decreases in peak density for all sections.</td>
<td>

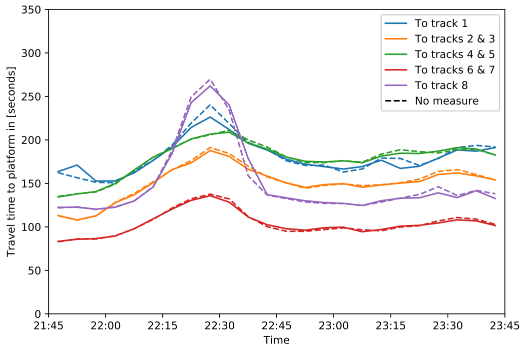
<table><tr><td>-7%</td><td>-14%</td><td>-17%</td><td>-9%</td><td>-11%</td></tr></table>
Similar to regular triple.</td>
<td>

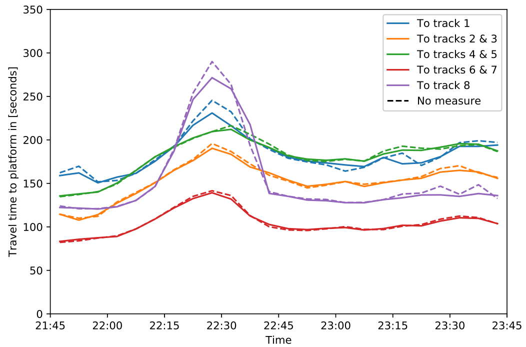
<table><tr><td>-9%</td><td>-14%</td><td>-28%</td><td>-25%</td><td>-11%</td></tr></table>
Similar to regular triple, though a bit more substantial decreases.</td>
</tr>
<tr><td colspan="4">Table 5.6 continues on the next page.</td></tr>
</table>

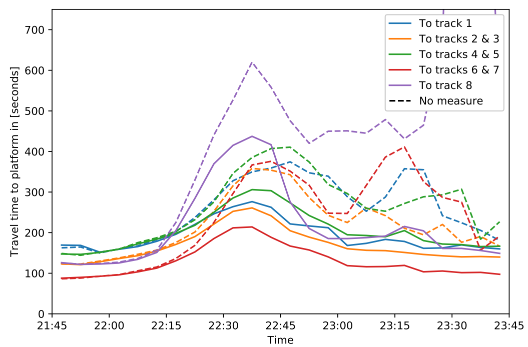
<table>
<tr><th colspan="4">Continuation of Table 5.6</th></tr>
<tr><th>KPI</th><th>Regular triple</th><th>20% increase</th><th>Extreme triple</th></tr>
<tr>
<td>Density on platform</td>
<td>

-32% | -17% | -14% | -7% | -1%
Decreases in peak density for all platforms, though for the platform of track 1 clearly more substantial than for the platform of track 8.</td>
<td>

-34% | -17% | -18% | -9% | -1%
Very similar to regular triple.</td>
<td>

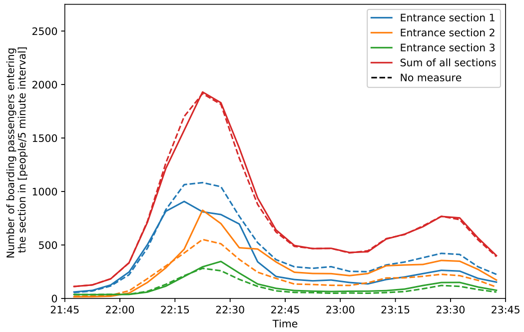
-31% | -19% | -6% | -0.4% | -3%
Very similar to regular triple.</td>
</tr>
<tr>
<td>Travel time to platform</td>
<td>

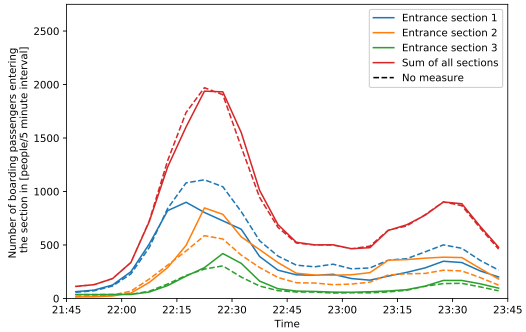
-6% | -2% | -1% | -1% | -2%
Only minor effects on peak travel time for all routes.</td>
<td>

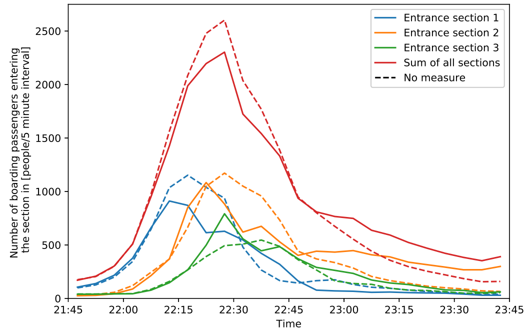
-6% | -3% | -2% | -2% | -6%
Similar to regular triple</td>
<td>

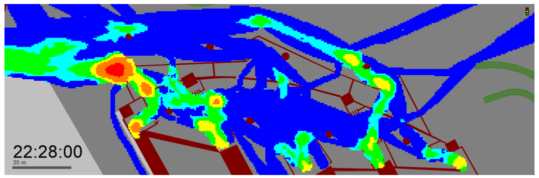
-26% | -27% | -25% | -48% | -78%
Substantial decreases in peak travel time for all routes.</td>
</tr>
</table>

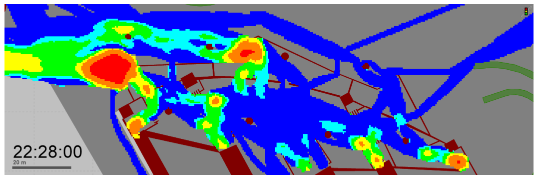
Table 5.7: Results of the modelling study per KPI for the ***barriers*** measure. Statistically significant results are underlined. Note the different y-axes for the travel time analysis. For a legend of the density plots, see Figure 5.18.

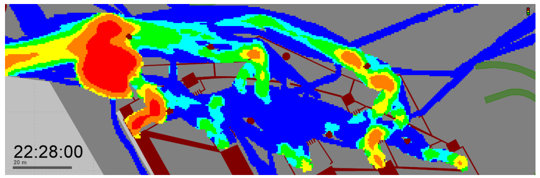
<table>
<tr><th>KPI</th><th>Regular triple</th><th>20% increase</th><th>Extreme triple</th></tr>
<tr><td>Flow through entrance sections</td>
<td>

<table><tr><td>-16%</td><td>+50%</td><td>+23%</td><td>+0.8%</td></tr></table>
Better spread of peak flow over various entrance sections, overall flow not altered very much.</td>
<td>

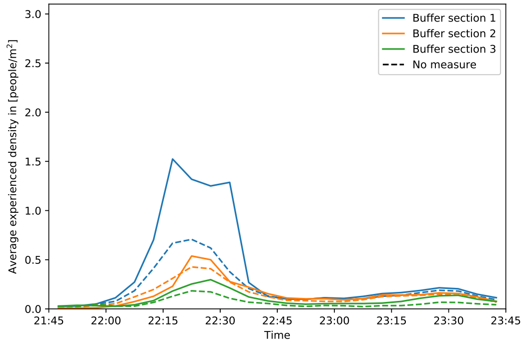
<table><tr><td>-19%</td><td>+44%</td><td>+38%</td><td>-2%</td></tr></table>
Similar to regular triple.</td>
<td>

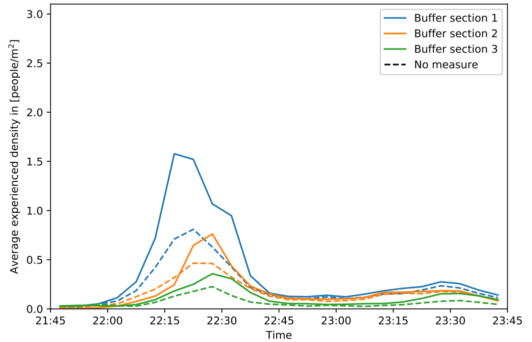
<table><tr><td>-21%</td><td>-8%</td><td>+45%</td><td>-12%</td></tr></table>
Effect for entrance section 1 and 3 similar to regular triple, though decreases for section 2 and overall flow.</td></tr>
<tr><td>Density plot station hall</td>
<td>

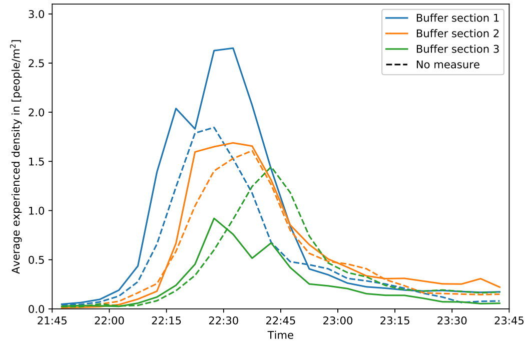
Location with highest density moved outside the station hall.</td>
<td>

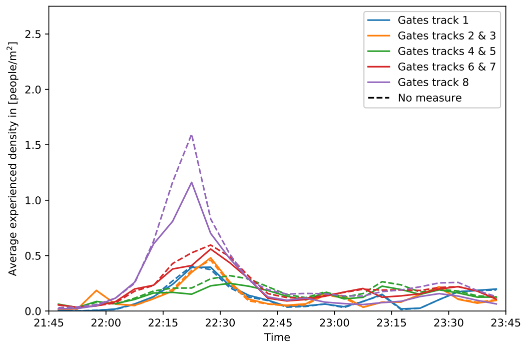
Similar to regular triple.</td>
<td>

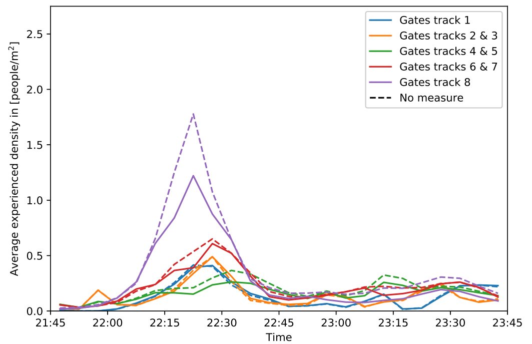
Seemingly better spread of crowd over the entrance sections as crowding occurs at entrance section 3 as well.</td></tr>
<tr><td colspan="4">Table 5.7 continues on the next page.</td></tr>
</table>

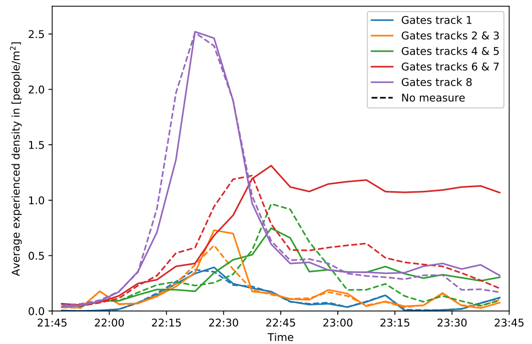
<table>
<tr><td colspan="4">Continuation of Table 5.7</td></tr>
<tr><th>KPI</th><th>Regular triple</th><th>20% increase</th><th>Extreme triple</th></tr>
<tr><td>Density in buffer section</td>
<td>

<table><tr><td>+116%</td><td>+26%</td><td>+62%</td></tr></table>
Substantial increase of peak densities as the buffer bottleneck is smaller than in other measures.</td>
<td>

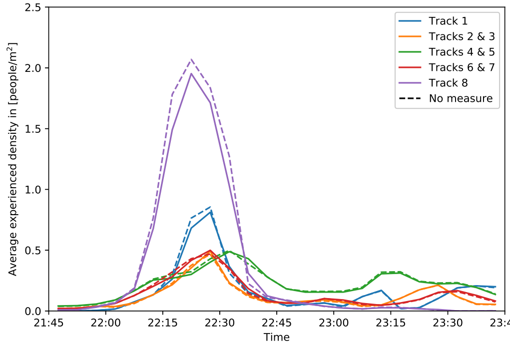
<table><tr><td>+95%</td><td>+64%</td><td>+58%</td></tr></table>
Similar to regular triple, but more substantial increase in section 2.</td>
<td>

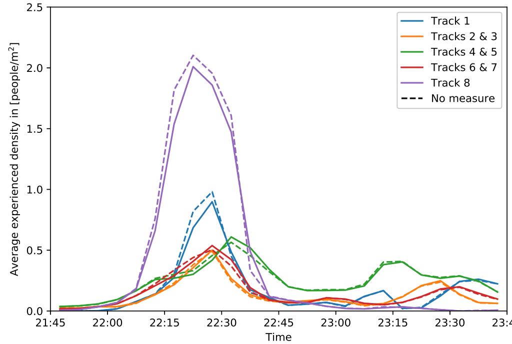
<table><tr><td>+44%</td><td>+5%</td><td>+36%</td></tr></table>
Similar to regular triple, though impact smaller.</td></tr>
<tr><td>Density before check-in gates</td>
<td>

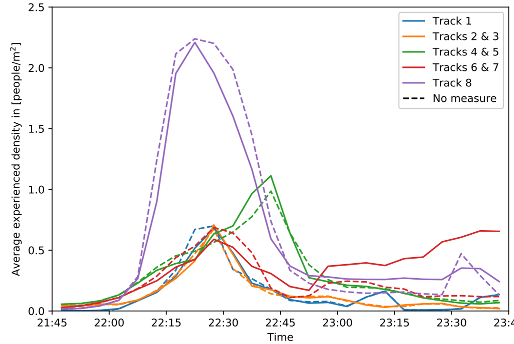
<table><tr><td>-2%</td><td>+5%</td><td>-22%</td><td>-6%</td><td>-27%</td></tr></table>
Few effects on peak densities for the first two gates sections, decreasing effects for sections 3 to 5.</td>
<td>

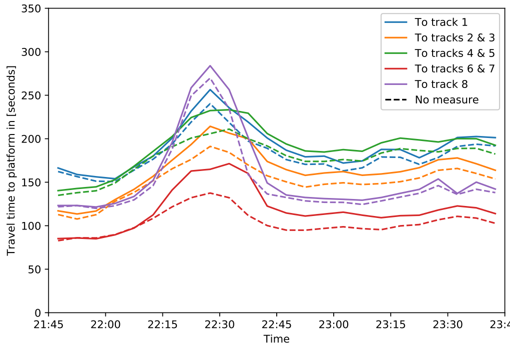
<table><tr><td>-1%</td><td>+0.0%</td><td>-28%</td><td>-6%</td><td>-31%</td></tr></table>
Similar to regular triple.</td>
<td>

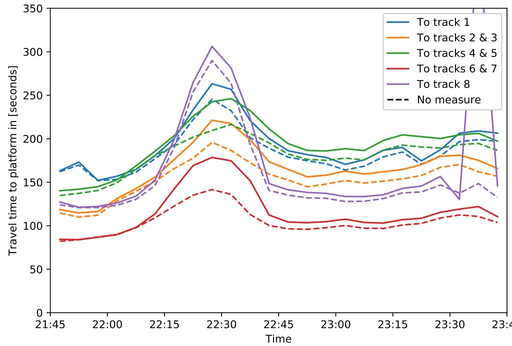
<table><tr><td>+5%</td><td>+23%</td><td>-23%</td><td>+7%</td><td>+0.3%</td></tr></table>
Diverse effects for the various sections. Backing-up of crowd at gates of track 8.</td></tr>
<tr><td colspan="4">Table 5.7 continues on the next page.</td></tr>
</table>

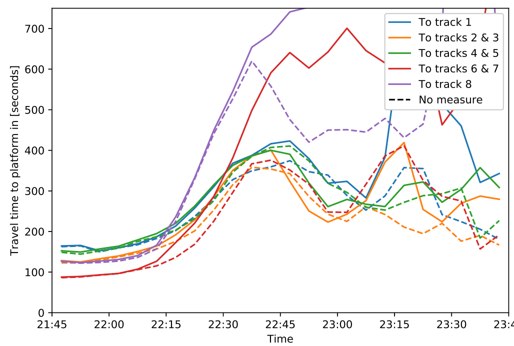
<table>
<tr><th colspan="4">Continuation of Table 5.7</th></tr>
<tr><th>KPI</th><th>Regular triple</th><th>20% increase</th><th>Extreme triple</th></tr>
<tr><td>Density on platform</td>
<td>

<table><tr><td>-5%</td><td>+5%</td><td>-2%</td><td>+6%</td><td>+6%</td></tr></table>
Slight effects on all peak platform densities.</td>
<td>

<table><tr><td>-8%</td><td>+2%</td><td>+8%</td><td>+7%</td><td>-4%</td></tr></table>
Similar to regular triple.</td>
<td>

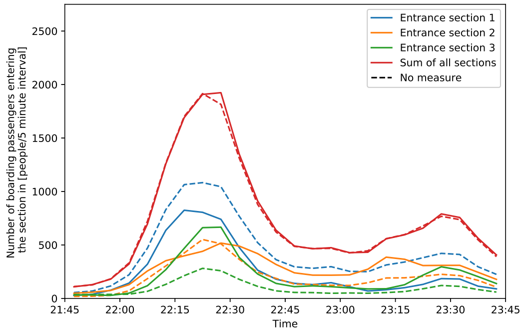
<table><tr><td>+3%</td><td>+5%</td><td>+13%</td><td>-4%</td><td>-1%</td></tr></table>
Many not significant effects, though a potential more substantial increase at the platform of tracks 4 & 5.</td></tr>
<tr><td>Travel time to platform</td>
<td>

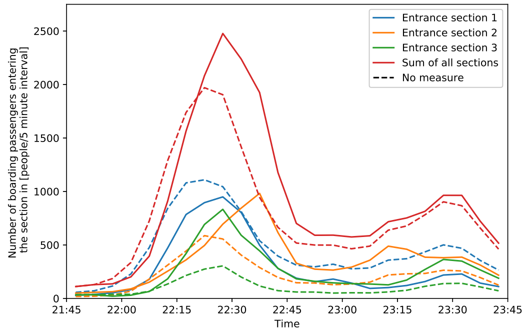
<table><tr><td>+7%</td><td>+12%</td><td>+11%</td><td>+25%</td><td>+5%</td></tr></table>
Clear increase for peak travel time on all routes.</td>
<td>

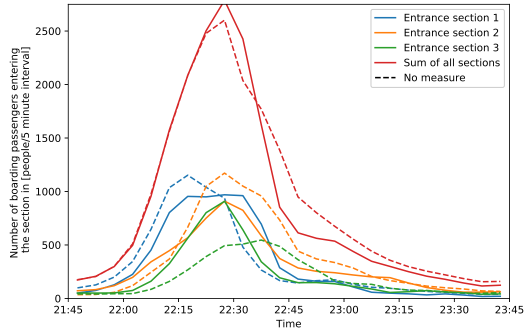
<table><tr><td>+7%</td><td>+13%</td><td>+4%</td><td>+26%</td><td>+47%</td></tr></table>
Similar for regular triple. Weird peak for route to platform of track 8 around 23:40 (+47%, not significant) likely caused by model issue.</td>
<td>

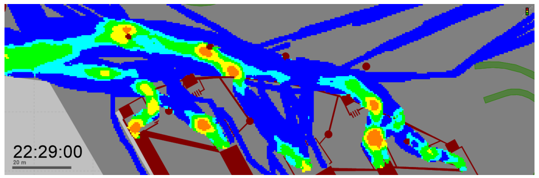
<table><tr><td>+95%</td><td>+17%</td><td>+3%</td><td>+131%</td><td>+33%</td></tr></table>
Substantial increases, though very erratic patterns and not many significant results. Effect on routes to platforms of tracks 1, 6 & 7 and 8 likely subject to model issue.</td></tr>
</table>

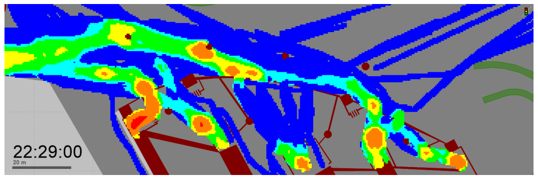
Table 5.8: Results of the modelling study per KPI for the ***stream separation*** measure. Statistically significant results are underlined. Note the different y-axes for the travel time analysis. For a legend of the density plots, see Figure 5.18.

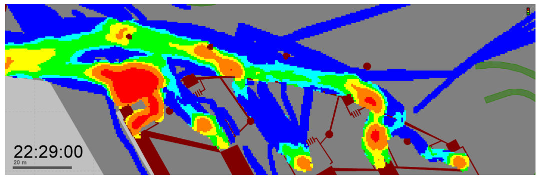
<table>
<tr><th>KPI</th><th>Regular triple</th><th>20% increase</th><th>Extreme triple</th></tr>
<tr><td>Flow through entrance sections</td>
<td>

| -24% | -6% | +137% | +0.5% |
Extreme increase in peak inflow at section 3 due to spatial spreading. Total inflow not altered much.</td>
<td>

| -14% | +67% | +174% | +26% |
Peak inflow also *substantially increased for section 2 and total inflow*.</td>
<td>

| -21% | -8% | +66% | +7% |
Only substantial increase in peak flow in section 3. Overall peak inflow slightly increased.</td></tr>
<tr><td>Density plot station hall</td>
<td>

Decreased density in buffer section 1 but *increased density at other buffer sections. Increased densities at most check-in gates*.</td>
<td>

Similar to regular triple.</td>
<td>

Few changes for buffer section 1. *Increased densities before check-in gates.*</td></tr>
<tr><td colspan="4">Table 5.8 continues on the next page.</td></tr>
</table>

Continuation of Table 5.8

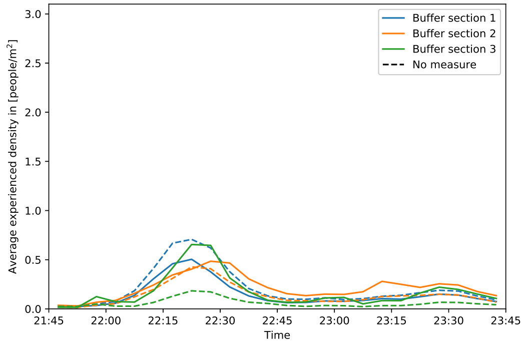
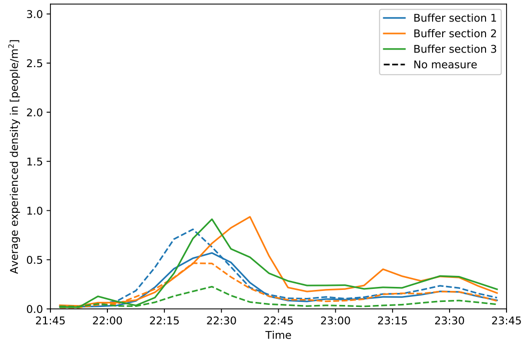
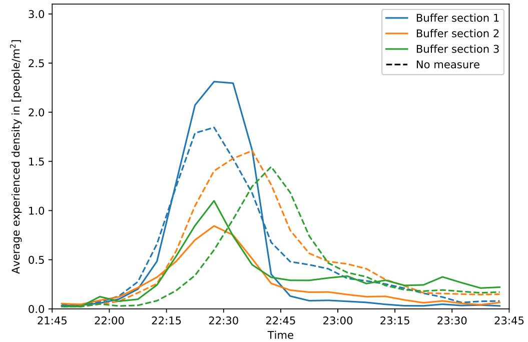
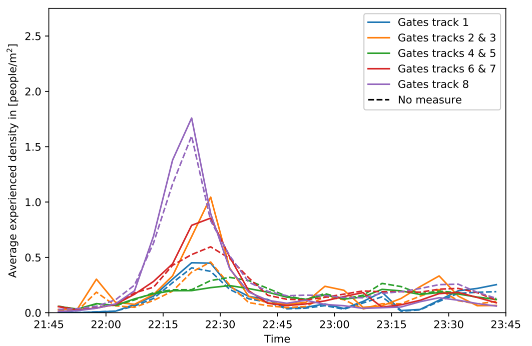
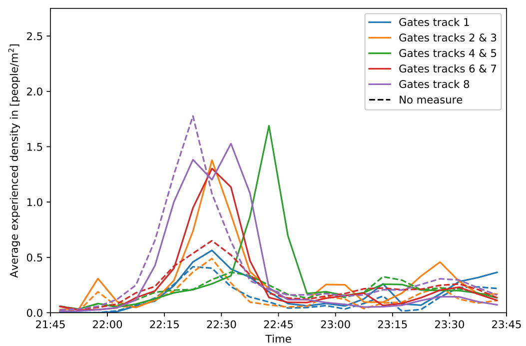
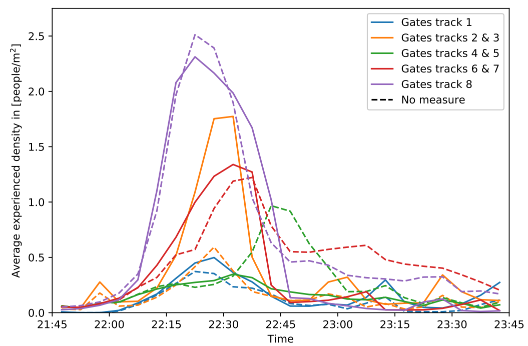
KPI	Regular triple	20% increase	Extreme triple
Density in buffer section	 -29% +14% +257% *Spatial spreading* of crowd over the various buffer sections clearly visible.	 -30% +101% +304% Similar to regular triple for sections 1 and 3, but *more extreme increase in section 2*.	 +25% -48% +24% Interestingly, potential increase of peak density in section 1, decrease in section 2 and relatively small increase in section 3 compared to other scenarios.
Density before check-in gates	 +11% +128% -23% +44% +10% *Increased peak densities for most check-in gates sections* except for the gates of the platform leading to tracks 4 & 5.	 +37% +182% +362% +100% -14% *Extreme increases* in peak density most check-in gates sections. Peak for tracks 4 & 5 interestingly at a later moment in time.	 +34% +199% -64% +10% -8% Relatively similar to regular triple .

Table 5.8 continues on the next page.

Continuation of Table 5.8

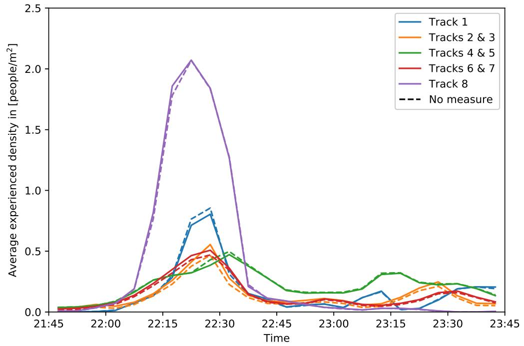
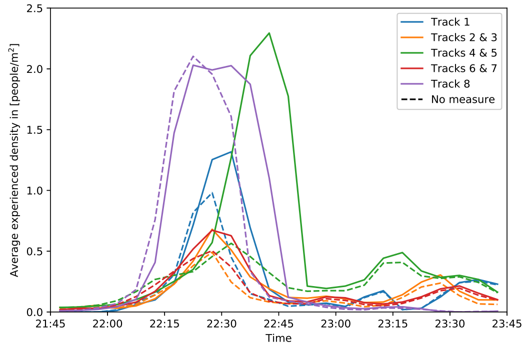
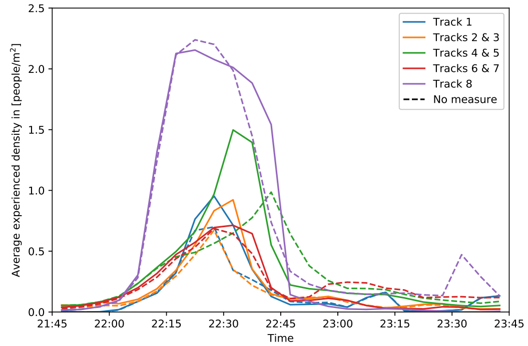
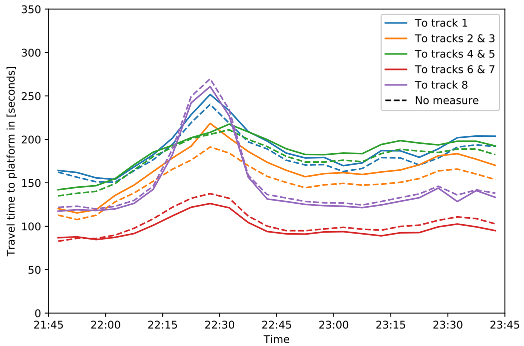
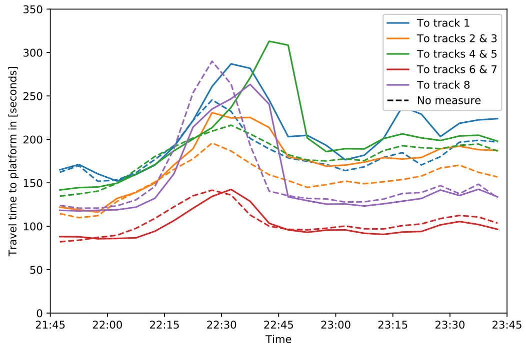
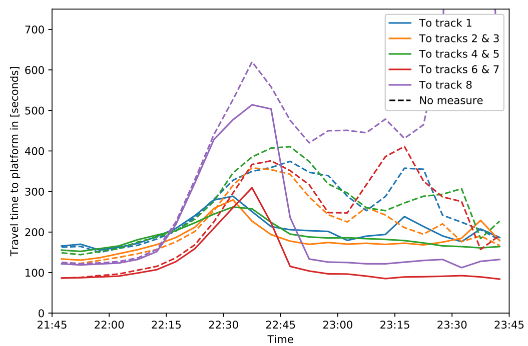
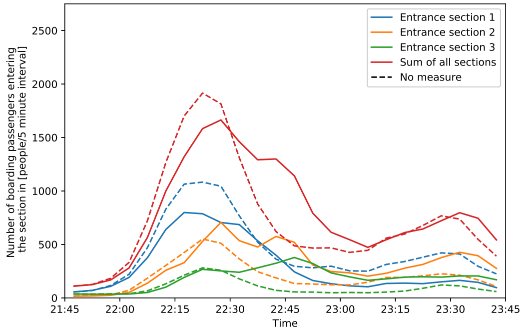
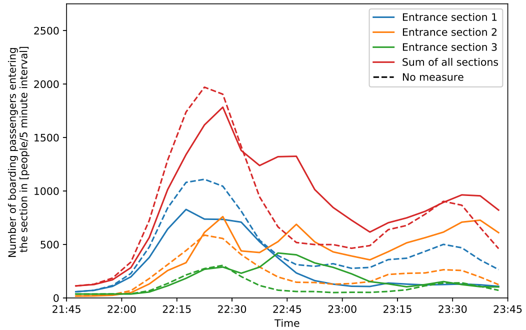
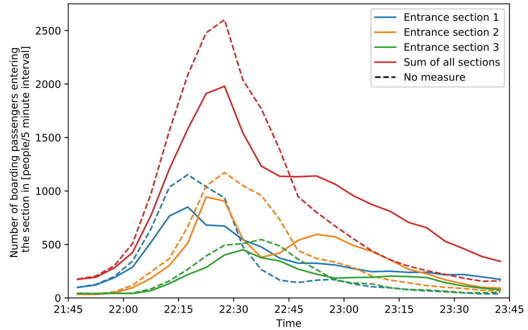
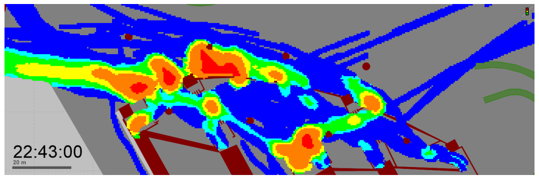
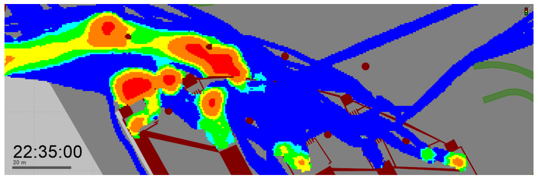
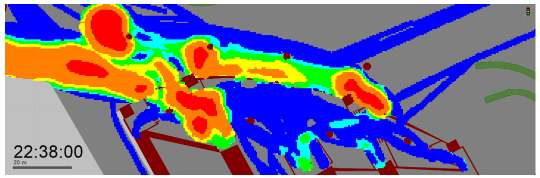
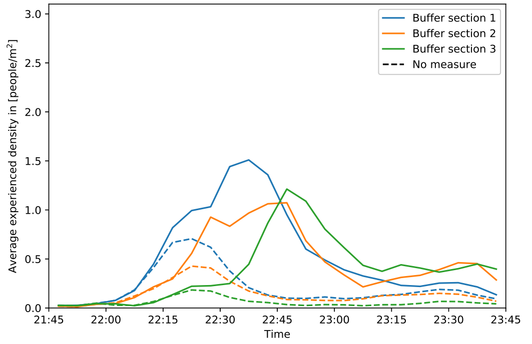
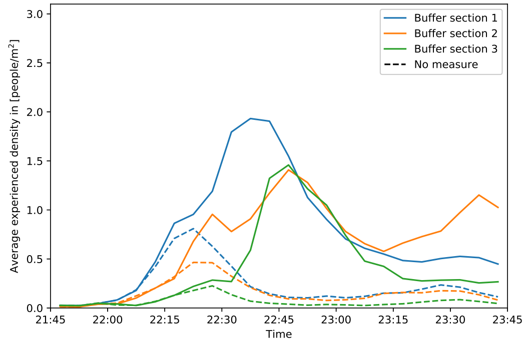
KPI	Regular triple	20% increase	Extreme triple
Density on platform	 -6% | +19% | -5% | +8% | +0.1% *Minor effects*, except for increased peak density on the platform of tracks 2 & 3.	 +34% | +38% | +306% | +33% | -3% *Substantial to extreme increases in peak density*, except for the platform of track 8.	 +36% | +37% | +52% | +4% | -4% Relatively similar to 20% increase.
Travel time to platform	 +5% | +14% | +3% | -8% | -3% *Increased peak travel time* for the platforms of tracks 1 to 5 due to the fact that that they have to make a detour.	 +17% | +18% | +45% | +0.6% | -9% Similar to regular triple, but more substantial effects.	 -23% | -22% | -36% | -25% | -74% *(Potential) decrease in travel time to all platforms*, due to that the crowd is better spread over station and does not try to enter through the same entrance section.

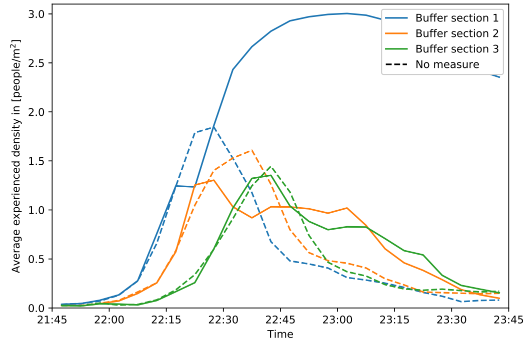
Table 5.9: Results of the modelling study per KPI for the ***behavioural influencing*** measure. Statistically significant results are underlined. Note the different y-axes for the travel time analysis. For a legend of the density plots, see Figure 5.18.

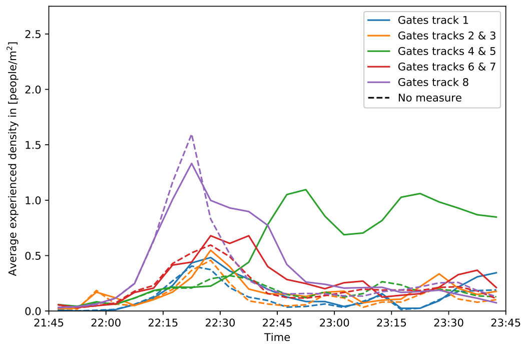
<table>
<tr><th>KPI</th><th>Regular triple</th><th>20% increase</th><th>Extreme triple</th></tr>
<tr><td>Flow through entrance sections</td>
<td>
-26% | +28% | +34% | -13%
Seemingly spatial spreading of the crowd over the various entrances. Overall a decrease in inflow.</td>
<td>
-25% | +30% | +38% | -9%
Very similar to regular triple</td>
<td>
-26% | -19% | -18% | -24%
Clear decrease in inflow for all sections.</td></tr>
<tr><td>Density plot station hall</td>
<td>
Worst moment is later in time. Increased densities at all locations.</td>
<td>
Increased densities, mainly in buffer sections 1 and 2.</td>
<td>
High densities in all buffer sections and increasing densities in the station hall.</td></tr>
<tr><td colspan="4">Table 5.9 continues on the next page.</td></tr>
</table>

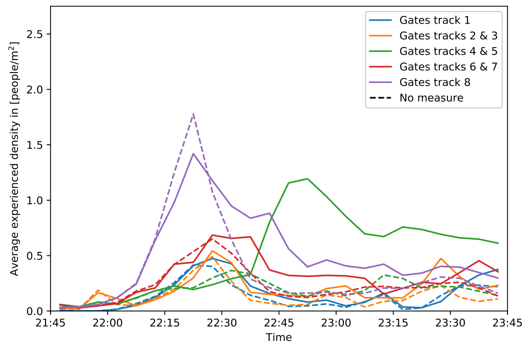
Continuation of Table 5.9

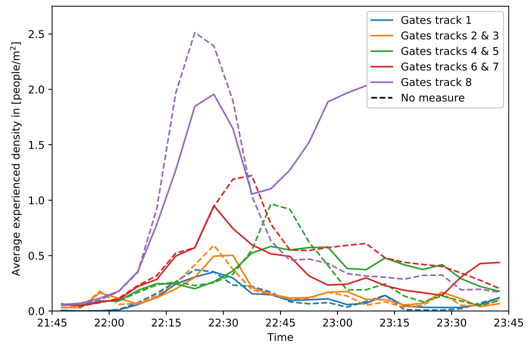
<table>
<tr><th>KPI</th><th>Regular triple</th><th>20% increase</th><th>Extreme triple</th></tr>
<tr><td>Density in buffer section</td>
<td>

+114% | +151% | +561%
Extreme increases in peak densities, though probable modelling data collection issues as discussed in Section 5.4.</td>
<td>

+139% | +203% | +546%
Similar as regular triple.</td>
<td>

+63% | -19% | -6%
Probable modelling issue leading effect of buffer section 1. Interestingly extreme effects of other scenarios not visible for other sections.</td></tr>
<tr><td>Density before check-in gates</td>
<td>

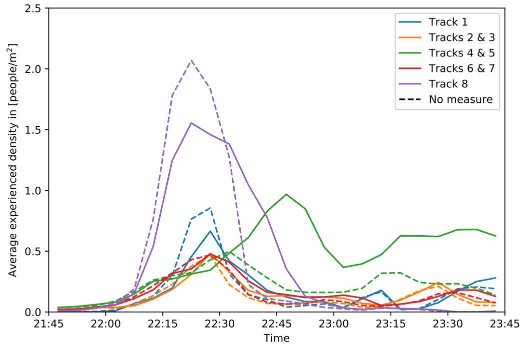
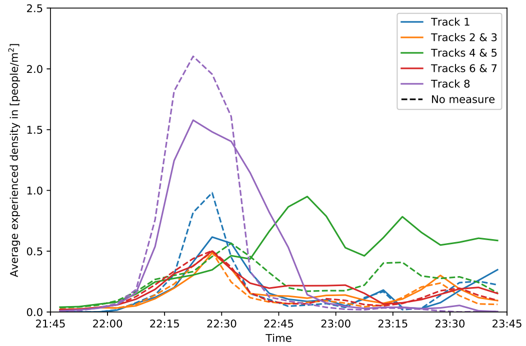
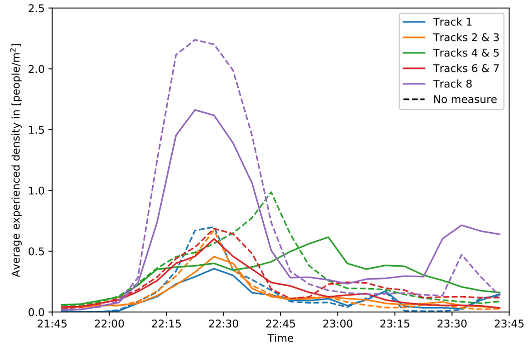
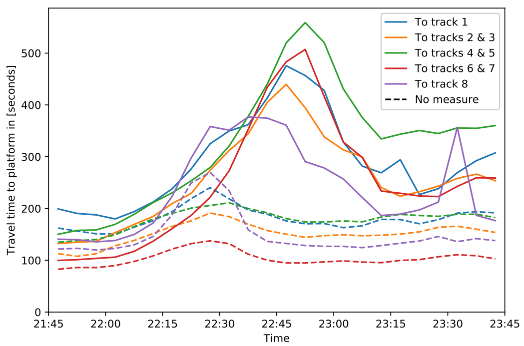
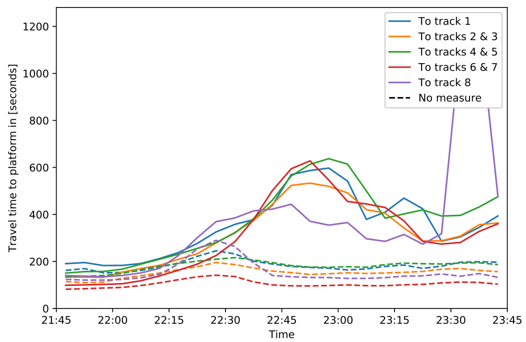
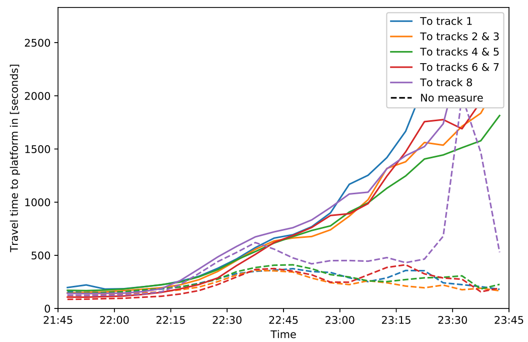
+19% | +20% | +243% | +14% | -17%
Substantial to extreme increase in peak density for most check-in gates sections, except for the (non-significant) decrease for track 8.</td>
<td>

-14% | +11% | +226% | +5% | -20%
Similar pattern as for regular triple, except that the section of the platform of track 1 sees a decrease in peak density.</td>
<td>

-5% | -15% | -40% | -22% | -12%
Non-significant results for all sections, though there is a probable decrease in peak density. Possible modelling issue for track 8.</td></tr>
</table>

Table 5.9 continues on the next page.

Continuation of Table 5.9

KPI	**Regular triple**	**20% increase**	**Extreme triple**
Density on platform			
	-22% · +3% · +95% · +2% · -25%	-37% · -1% · +68% · -0.4% · -25%	-49% · -32% · -38% · -12% · -26%
	Various effects on the peak density of the different platforms, though *extreme increase* most striking for tracks 4 & 5.	Relatively similar to regular triple	Quite *substantial decreases* for all platforms, though not all significant.
Travel time to platform			
	+98% · +130% · +165% · +269% · +40%	+143% · +172% · +195% · +344% · +53%	+536% · +500% · +342% · +401% · +321%
	Extreme increases for all routes. Increase for route to the platform of track 8 seems to be not as extreme, but this is a result of a modelling issue.	Similar to regular triple.	Continuously growing travel time, likely caused by modelling issue.

5.4 Discussion

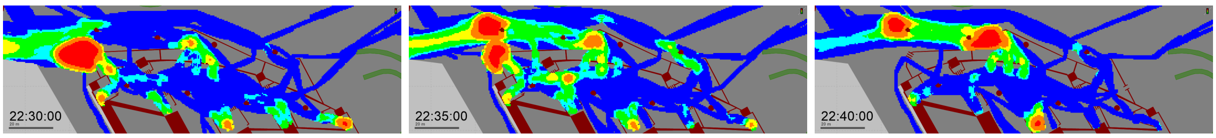
Modelling studies inherently have points of discussion as a result of modelling simplifications or assumption that underly the model. This modelling study is no different.

5.4.1 Data input of model

First of all, the number of dates that are used to create the normalised flow profiles that are visible in Figure 5.5 is limited. If at one of the days that served as input for any of the profiles, an unincorporated event took place, ranging from a (small) disruption in the train service, to weather related events like rain or public disturbances in the Bijlmer ArenA area, such events might have a relatively high impact on the normalised flow profile, influencing the calibration. Moreover, the types of events in the venues can also play a role for the profile: a rap concert attracts a different crowd than a pop concert, leading to different crowd behaviours and possibly flow profiles. Though the events selected for the normalisation are deemed to attract a somewhat similar crowd, it is also important to keep in mind that these profiles can be different for a different type of events in the same venue.

5.4.2 Calibration of routing method

Secondly, the calibration did not necessarily result in a properly calibrated model. The resulting RSMNE value of 0.69 is deemed rather high. This gives its questions on whether the model can give reliable results. It has been mentioned that a part of this low calibration value has to do with the fact that station inflow counts are delayed based on the model input and model lay-out. When accounting for this, the RSMNE is better, but still has a value of 0.52. This can possibly be attributed to the routing method, where only the travel time of the various possible routes is incorporated, while also incorporating aspects like density on a route are likely to yield better results. This was however not possible to incorporate in the modelling software, as elaborated upon in Appendix C.4.
An important consequence of only incorporating (historic) travel times in routing choices became clear when analysing density plots of individual runs for some 20% increase and extreme triple scenarios. Initially, the crowd chooses to use the first entrance section (see Figure 5.21(a)). The travel time on this route rises, so people start to use the other entry sections (see Figure 5.21(b)). At some moment, however, almost all people want to use these other routes, as in the 'memory' of the model people using the route through entrance section 1 still have a long travel time, while barely any new people are using entrance section 1 (see Figure 5.21(c)). This is unrealistic, as in a real-life situation the crowd waiting in front of entrance section 2 is likely to re-route back to entrance section 1 if entrance section 1 has no waiting crowd. Therefore, it is important to keep in mind that the credibility of the model remains a key point of discussion in this research.



(a) 22:30 (b) 22:35 (c) 22:40

Figure 5.21: Change of density over time for a single run of the barriers measure in the 20% increase scenario.

5.4.3 Routing structure of pedestrians

Thirdly, another aspect related to the routing has already been discussed in Section 5.2.6: the extensive use of routing points. A simple model structure is often better, as it requires less substantiation on why structural choices are made. The used model has a relatively complex model structure, to e.g. let pedestrians walk round a waiting crowd to use a different entrance section (as discussed in Section 5.2.6) or pass an obstacle with a wider curve to combat unrealistic deadlocks. This structure will however effect the results of the model because travel times (that are also important for route choice) might be longer. This aspect with regards to routing might be solved using the 'dynamic potential' routing method. This method calculates the quickest route for pedestrians in near real (simulation) time, but this has severe consequences for the computational speed. Therefore, it had been decided to not incorporate the dynamic potential in this modelling study, while it might yield more realistic results.

5.4.4 Travel times in extreme triple scenario

Fourthly, the extreme triple scenario lead to some interesting results that deserve some special discussion. The fact that the travel times do not seem to go down that much after the peak for multiple measures (e.g. see *travel time to platform* in Table 5.7) is very strange, specifically as most of the other KPIs do not show this behaviour in their profiles. It might simply be that the station is not able to properly handle the extreme peak flow of pedestrians, leading to extreme crowding and in turn long travel times. However, since the densities in the buffer sections do seem to go down after the peak, it is more likely that there is another cause. E.g. the crowding outside the station, as discussed in Section 5.2.6, can be important in this, as this crowding severely impacts the travel times, but does not necessarily influence many other KPIs. This gives less credibility to the model as a whole. As also visible in the density plots, this crowding northwest of the station is most severe during the extreme triple scenario, leading to a reduction of the degree of credibility of the model in these extreme situations.

5.4.5 Behavioural measure

Finally, the implementation of the behavioural measure can be subject to elaborate discussion. First is the fact that the research of Zeng et al. [2019], where the measure is based on, only analyses pedestrian flows in one dimension. The effects on two-dimensional crowds might be completely different. Second, the impact of the measure is implemented to the same extend at every location in the model. This can be disputable because of aspects like background noise of the station or other sources interfering with music, likely making the background music less effective regarding behavioural influence than in the study of Zeng et al. [2019]. Finally, and possibly most importantly, the calibration to recreate the relative effects has been done in a rather simple manner. The altered social forces model parameters are altered in a counter-intuitive way (see Appendix C.5.4), indicating the complexity of this behavioural model. Moreover, the idea to recreate the *relative* effects in the first place is disputable, as the effects of behavioural influencing might not be linearly proportional regarding crowd flow characteristics.

5.5 Conclusion

Conclusions are drawn for the modelling study based on the effects of each measure on the various KPIs. An overview of the various advantages and disadvantages of the various measures is presented in Table 5.10 on page 55.
When analysing Table 5.10 it becomes clear that it is possible to determine effects of the various measures, as each of the measures has its distinct effects regarding advantages and disadvantages. Based on these (dis-)advantages it is possible to analyse the applicability of a measure

to a generalised station environment. The spreading of the peak flow seems to have significant potential to have a positive impact for all KPIs, but a genuine implementation to achieve the effects of the modelled measure is not analysed, making it relevant to further look into methods that can achieve the exact spreading effect. Moreover, whereas the barrier and separation measures have conflicting effects, this means that they can be used in opposite situations: the barrier measure moves high density locations out of the station hall to an upstream location, while the separation measure increases the densities further downstream.

An important outlier regarding the measures is the behavioural influencing measure. While for the other measures effects are seen that resemble the goals/expectations of the measure, this is not necessarily the case for the behavioural influencing. Rather strange outputs appear from the model, and the outputs also do not necessarily show desirable effects. While the latter aspect is something that can be an important conclusion, the former aspect indicates that the model itself might have its issues. Therefore, it would be very useful to investigate behavioural influencing and the implementation of such measures into the modelling software further, before final conclusions are drawn regarding such measures.

Besides the behavioural influencing measure, the model itself also has its points of attention, as indicated in the discussion in Section 5.4. The most prominent aspect in this regard concerns the fact that the calibration outcome is not necessarily good, which is expected to have its origin in the routing method. Moreover, the routing structure might also play a role in undesired crowding aspects. There might be a solution for increasing the ‘realism’ of the model for both these aspects by using the dynamic potential routing method, but this has significant impacts on the computational speed and has therefore not been used in this research. Nonetheless, since the general aspects of the crowd flow is captured, the model is deemed good enough that the overall effects of the measures can be identified.

All in all, it can be concluded that while the model has its issues regarding credibility, it is possible to use it to determine effects of various measures since most of the effects are in line with the expected outcomes. While the measures each have their advantages, they also have some (unexpected) disadvantages, as visible in Table 5.10. Based on these (dis-)advantages, it is identified to which possible crowd management situation in a station environment the measures would be applicable. Important to note in this translation to other station environments is that the degree of the effect as resulting from the case study will be different as local crowd and infrastructural characteristics will play an important role in this, but the overall effects for the measures are expected to be similar.

Table 5.10: Overview of the (dis-)advantages of the analysed measures and the situations to which they would be applicable.

Measure	Advantages	Disadvantages	Applicability of measure
Spreading of peak flow	• Reduces size of crowded areas • Decreases peak densities • Can greatly reduce travel times	• Not investigated how the spreading effect can be achieved.	Applicable in a situation where a specific audience can be targeted and convinced to postpone their departure from an event. Moreover very relevant to improve the situation for an extreme triple scenario.
Barriers	• Moves high density locations out of the station hall • Spreads flow over entrances	• Not really applicable in a short-term time-span • Increases travel time	Applicable if there is enough buffer space available outside of the station and you want to decrease densities inside the station and want.
Separation of streams	• Spreads flow over entrances • Reduces conflicting streams in the station hall	• Increases densities in front of check-in gates • Increases densities on platforms	Applicable if conflicting streams are a potential safety issue, there are no bottlenecks in the station hall and there is a (near) infinite discharge capacity.
Behavioural influencing	• Seems to spread waiting crowd over a larger area	• Unclear whether modelled effects will be present in real life • Seems to increase densities at all locations • Significantly increases travel times	Since it is debated whether the implementation of the measure into the model is correct, effects (and therefore applicability) are unclear. More interest into the topic needed for proper analysis.

6 DISCUSSION

The two individual parts of this research have seen their discussions in Sections 4.3 and 5.4 respectively. There are however also interfaces between the parts that deserve discussion, mainly concerning the implementation of the analysed measures. Moreover, an overview of the limitations of the research is presented.

6.1 Interfaces between literature and modelling study

First, the spreading of peak flow is something where various stakeholders in crowd management can and likely have to play a role. Convincing people to delay their departure can be hard to do, and therefore collaboration between various parties is key. This relevance of collaboration between parties is something that came up during almost all interviews. It was noted that this should be improved to have a better crowd management process in general, and given that the results of this research show that a spreading of the peak can have very promising effects, this can be stated to be of key relevance.

Secondly, the implementation of the separation of streams. The basic idea behind this measure is to place regular crowd barriers in the station to create such a situation. This was also discussed during some of the interviews, where the interviewees indicated that they did not expect that regular crowd barriers would be sturdy enough. Crowds exert large forces, while crowd barriers can only withstand very small loads. Therefore, while crowd barriers can function greatly with respect to guiding small crowds, application to large crowds might be difficult. Similarly, if one wants to implement the barriers measure in a short-term notice, this can only be deemed to be achievable with ‘regular’ crowd barriers instead of Mojo barriers, leading to similar aforementioned issues.
Accompanying the separation of streams is the fact that this measure also need explicit signage and/or communication to the crowd regarding the measures. As mentioned by interviewees, people are likely to simply use the first entrance of the station they see, and therefore it should be made clear to the pedestrians that certain entrances will only give access to specific platforms. Still, it remains likely that people will enter the station through an incorrect entrance as a result of habit meaning that either people will have to leave the station again or people will jump over the barriers, causing other safety and crowd issues.
A final aspect with specific regards to the separation of streams is that there are shops present in the station hall that were mentioned to attract quite some visitors after events. This has also been seen during a visitation to the station during an event on 19-10-2021. Placement of barriers in the station will hinder people from going to a shop before going to the platform, potentially resulting in similar crowd issues as mentioned above. Moreover, a more practical issue regarding hindering people to go to a shop before going to the platform is that the shop owners are also likely to not be very happy about losing potential revenue as people might simply skip the shop.

Finally, the behavioural measure with regards to the effect of background music was discussed during the interviews, where interviewees expressed their doubts concerning effectiveness. In the current model the effects are implemented to all pedestrians and at every location in the model. This is likely not achievable in real life, even if the effects of the measure on individual pedestrians will be identical as modelled. Moreover, the extend to which the measure has its effect is similar for all pedestrians, which is not entirely realistic. These uncertainties should also be kept in mind besides the problems with the modelling of behavioural influencing in the first place, indicating the relevance of further research into this topic.

6.2 Key limitations

As also indicated in the discussion of the two individual parts of this research, the research does have its limitations. This part of the discussion gives an overview of the most important limitations of the research.

6.2.1 Overall model quality

The most important limitation of the research concerns the quality of the model used for the simulation experiments. As the calibration of the model did not yield a very satisfactory result, the outcomes of the modelling study should not be considered as completely reliable.
In order to improve the quality of the model and its outcomes, the model should ideally be improved based on the main limiting factor, which in this case is considered to be the routing method. A potential solution for the quality issue is brought forward, but it is not investigated, limiting the insights into the actual outputs of the model.

6.2.2 Behavioural measures

A second key limitation concerns the behavioural influencing of a crowd. The measure analysed in this research is currently based on a single study into the matter and its implementation is based on a rather coarse calibration. In order to get reliable insights into such a measure, it is important to have a broad scientific background where can be relied upon, as it is not as straightforward as an infrastructural measure.
A single study does not necessarily provide such a basis, as for behavioural influencing aspects like culture and environment might play an important role that are not considered in this research. Moreover, when implementing such a measure into modelling software, it should be done properly and extensively as behaviour is a complex matter and the modelling of behaviour is no different. As both the scientific background and implementation of the measure have their deficiencies in this research, these are a relevant limitation regarding any behavioural measure.

6.2.3 Translating effects to other environments

A final key limitation concerns translating the effects of measures to other infrastructural environments. This aspect has been investigated by bringing it up during the interviews and subsequently analysing the effects of an individual measure from a more abstract point of view. During the interviews, the main response given was that the effect of measures is always dependent on the infrastructural environment. This was kept in mind during the generalisation of the measure effects.
However, as still only a single case study is used, it is unclear whether the generalised effects will be present to any similar extend in other environments. It is expected that this will be the case, but there is no evidence for this, especially since the crowd managers explicitly mentioned that the infrastructural environment plays a key role, leading to a limitation of the translatability of the results. Ideally, more cases are analysed to see whether similar effects occur, so that a more robust conclusion can be made for the generalised outcomes of the research.

7 CONCLUSION

The two individual parts of this research have seen their conclusions in Sections 4.4 and 5.5 respectively. Using those, it is possible to answer the research questions and reflect on the research goal. Moreover, recommendations for future research are presented.

7.1 Answering of research questions

The research questions are answered bottom-up, starting at the sub-questions, in order to work towards the answering of the central research question.

7.1.1 Monitoring insights

Sub-question 1 was stated as:
What monitoring insights are desired by crowd managers concerning (short-term) crowd management?
Through the literature analysis and interviews, it became clear that the most important insights are based around spatio-temporal characteristics as crowd density and crowd flow. Crowd density is specifically relevant to monitor at locations where people are waiting, in case of a station environment this is on the platforms and in front of the check in gates. Crowd flow is specifically relevant at locations where people usually move, e.g. in a station hall.
Besides spatio-temporal aspects, more and more attention is given to human factors in crowd management. Aspects like age structure and crowd atmosphere are deemed relevant to incorporate, as it influences the available options for potential measures. As examples, a younger crowd is more likely to get notified by a text message or push notification than an older crowd and a happy crowd is often more willing to cooperate regarding the (sudden) implementation of a measure than an upset crowd. Real-time monitoring of these aspects through tools and dashboards is not often executed as currently e.g. social media monitoring is rather expensive and often there is relied on information of stewards in the field. Nonetheless, the topic is seeing growing interest in the field of crowd monitoring.
In order to make predictions about crowd flows, proper data is needed. Relevant information that can serve as input for making such predictions is data about:

- pedestrian flows during/after events;
- the infrastructural environment of the station environment;
- the event(s) that is(/are) organised, and
- the public transport time table in the station environment.

These data combined ideally lead to a complete origin/destination matrix regarding the flow profile, as it allows for detailed analysis of the flows on a microscopic level. Depending on the exact level of detail, such an analysis can analyse the effects of possible measures.

All in all it can be said that the desired monitoring aspects mainly concern spatio-temporal aspects. Regarding active monitoring, crowd density and flow characteristics are most important, while for making predictions flow details are also needed to create a suitable insight in origins and destinations. A human factor approach desires more insights into crowd characteristics, but these are currently difficult to measure and incorporate in large-scale crowd monitoring.

7.1.2 Potential measures

Sub-question 2 was stated as:
What (potential) measures are available to influence crowds in station environments within 3 hours?
During the interviews it was brought up that it is possible to analyse crowd management measures from the same perspective as vehicular management. This means that the same types of measures can be used: informing, limiting flow, separating flows and increasing capacity. From the perspective of crowd management this would result in implementations like informing and advising the crowd, limiting the station inflow through barriers, separating the crowd flows in the station through barriers and increase discharge capacity in the form of implementing extra trains in the timetable. Whether all these measures are implementable in a 3-hour time span is discussable, specifically for the extra trains measure, as time tabling is a precise and time-consuming procedure in the first place.
It has also been found that as a result of the growing interest in the aforementioned human factor approaches, there is growing interest in measures that focus on influencing the behaviour of crowd members. An interesting research in this sense has been found concerning the effect of background music on an moving crowd. As such a measure does not require infrastructural or time table changes, it is deemed relevant to specifically analyse such a measure from the short-term perspective.
The translatability of measures between various environments is expected to be largely dependent on the infrastructural environment: most measures require a certain type of environment to have the expected and desired effect. This does not necessarily mean that a specific measure cannot be implemented in a specific environment. It does mean that the exact effect of the measure depends on the environment.
All in all it can be concluded that four types of measures might be implemented in a 3 hour time span: advising the crowd, limiting crowd flow, separating crowd flows and behavioural influencing. The exact effects of each of the measures are likely to be different in different environments, but it is expected that a general similar trend can be seen independent of the environment.

7.1.3 Effect of measures

Sub-question 3 was stated as:
Can the effects of crowd management measures in station environments be modelled and forecast for different scenarios using micro-simulation?
In order to analyse the effects of various measures in the case study, various scenarios have been established that incorporate different degrees of crowding. Most importantly, it is relevant to look into a relatively common high intensity scenario and an a worst-case scenario. With respect to the case study, the former is stated to be a ‘regular triple’ situation (where three events occur on the same evening, but have different end times), while the latter is stated to be an ‘extreme triple’ situation (where three events occur on the same evening with the same end time). As the worst-case scenario might be a very extreme situation, a relatively uncommon busy situation might also be relevant. To incorporate this in the case study, a scenario has been established similar to the regular triple, but with a 20% increase in crowd size. Based on

these various scenarios, it is possible to analyse the effect of measures in different crowding situations.
Based on the measures types mentioned above, four measures have been set up to see whether their effects can be identified: spreading peak flow, placing barriers outside the station, separating streams inside the station and behavioural influencing by means of background music. Details on how these measures are exactly modelled can be found in Appendix C.5. As followed from the modelling study, each of the measures have their own respective effects, as summarised in Table 5.10. Nonetheless, it should be noted that the calibration of the model had its issues, making it difficult to confidently state that the used model is able to capture the effect of measures perfectly. Most effect shown by the various measures showed effects that could be expected from the respective measures. Though important to note is that the modelling of behavioural measures deserves specific attention.
A behavioural measure can mainly be implemented through altering the parameters of the social forces model that describes the behaviour of the pedestrians in the modelling software. The focus on the social forces model in this research turned out to be smaller than initially expected when setting up the research. Nonetheless, the parameters of the social forces model have been altered in such a way that it has been tried to implement the the behavioural measure concerning the playback of background music. The exact calibration of the model to account for such a measure and alter the behaviour of pedestrians in a realistic way is however a sensitive task and therefore the results in this research concerning the behavioural measure have their points of discussion.
All in all, the effects of various measures can be analysed using the modelling software and the established scenarios. As most of the analysed measures have effects that are in line with the expectations, the used model is deemed to be capable to forecast overall effects. However, as there are issues with the calibration of the model and the implementation of the behavioural measure, the exact results should not be seen as 100% mirroring reality.

7.1.4 Development of a crowd measurement tool

Based on the aforementioned aspects, it is possible to draw an overall conclusion for the main research question of this research, which was stated as:
Is it possible to develop a tool that can forecast future crowd states and assess the effectiveness of short-term crowd management interventions in order to optimise crowd flows in station environments?
It for sure is possible to develop a tool that can forecast crowd states and assess effects of measures, however the reliability of the exact outcomes remain a point of discussion. The used model is deemed sufficiently capable of modelling various measures, as for most measures the effects where as hypothesised by the goal of the measure before analysis. Whether the identified effects are representative for all situations can however be discussed given the calibration of the model. The aspect that is expected to be key in the calibration outcome is the routing method, meaning that there likely is a possibility that the model quality can be enhanced when a more in-depth routing method is used. Nonetheless, using a tool based on the used modelling software, it is possible to analyse the effect of a measure before implementation.
Nonetheless, important to note is the timing with regards to the computational time of the model. While the modelling tool can forecast effects of measures, short-term or real-time analysis of multiple measures will be difficult. The run time of a single model run is substantial (about 30 [minutes]), making a short-term analysis difficult. Therefore, such a tool will be useful to analyse potential measure beforehand, to have a toolbox of measures available when the crowd situation asks for intervention to keep the situation safe.

7.2 Reflection to research goal

The goal stated at the start of the research was:
Design a method that can forecast effects of crowd flow interventions in station environments.
This research unfortunately does not explicitly present a full-fledged method that forecasts the effects of crowd flow interventions in station environments as a result. Through the course of the research, more attention has been given to the explicit analysis of effects of different measures on crowd flows rather research into the development of a method. Nonetheless, as various measures have been analysed in a structured and documented way, there has been an implicit development of such a method, that in short can be described through:

1. Identify crowd flows of historic events and normalise them to create a generalised insight into the crowd flow;
2. Use the (expected) number of event visitors to create the crowd flow profile for the model;
3. Calibrate the model with respect to the route choice to capture the reference situation as good as possible;
4. Identify the measure you want to analyse and the way this measure will be implemented;
    - Infrastructural measure? Implement infrastructural elements;
    - Behavioural measure?
        - Routing/departure choice? Analyse crowd flow and/or routing aspects;
        - Movement behaviour? Analyse parameter values of the social forces model;
5. Analyse the results of the model given the calibration and measure implementation quality of the model.

All in all, while the goal as stated before the start of the research is not completely reached, it is possible to say that the goal is implicitly achieved to a considerable extend through the analysis of the effects of measures.

7.3 Recommendations for future research

Based on the outcomes of this research, it is also possible to recommend relevant subjects of research that can be considered relevant for crowd management.
First of all, it would be interesting to investigate whether the model quality can be enhanced as the calibration did not necessarily lead to a very good result. A better model will result in a more realistic analysis of the effects of the measures. Aspects like implementation of more variables in the route choice and the use of dynamic potential for routing itself can be of key importance to create a more realistic model.
Secondly, regarding the implementation of the behavioural measure: research into the exact effect of various behavioural measures is of importance. Different researches showed potential measures, but very few actually presented the exact effects of the measure, leading to difficulties regarding the implementation of them in a modelling environment. Moreover, such measures should not only be evaluated in purely experimental situations, but also be applied to large(r) scale real-life implementations to see its effects in practice.
Thirdly, accompanying the interest that should be given to behavioural measures: the exact implementation of behavioural measures into modelling software deserves attention. The social forces model is able to catch a wide range of behavioural aspects, but is very delicate, complex and not intuitive concerning its calibration. Therefore, in order to capture behavioural measures

in a realistic way, dedicated researches into the implementation of behavioural measures into modelling software are relevant.
Fourthly, it would be relevant to see to what extend the case study environment leads to the identified effects or whether such effects are also to be expected in different environments. The interviewed crowd managers often stated that effect of measures is dependent on the infrastructural environment. If similar effects as identified in this research are found in other (station) environments, there is a broader scientific support for the general effects of the measures.
Fifthly and finally, since the peak spreading shows very promising results, more attention should be paid to how such aspects can be achieved. This can probably be seen as an extension of the aforementioned attention that should be given to behavioural measures. However, also proper collaboration between various involved parties in crowd management should be investigated on a practical level as such collaboration can be key in aspects like timing the exact end time of events, organising side events or providing information that might be able to spread the crowd. Improvement in cooperation between parties might also increase safety for and comfort of the crowd, which in the end is key in proper crowd management.

Bibliography

AFAS Live. AFAS Live events on Facebook, 2021. URL `https://www.facebook.com/AFASLiveOfficial/events`.

AFC Ajax. AFC Ajax (@AFCAjax) on Twitter, 11 2021. URL `https://twitter.com/afcajax`.

Mohammed S Ahmed and Allen R Cook. Analysis of freeway traffic time-series data by using Box-Jenkins techniques. *Transportation Research Record*, 722:1–9, 1979.

Ali M. Al-Shaery, Shroug S. Alshehri, Norah S. Farooqi, and Mohamed O. Khozium. In-Depth Survey to Detect, Monitor and Manage Crowd. *IEEE Access*, 8:209008–209019, 2020. ISSN 21693536. doi: 10.1109/ACCESS.2020.3038334.

Constantinos Antoniou, Jaume Barcelo, Mark Brackstone, Vincenzo Punzo, Bilmi Berk Celikoglu, Biagio Ciuffo, Pete Sykes, Tomer Toledo, Peter Vortisch, and Peter Wagner. Traffic Simulation: Case for guidelines. Technical report, European Commission Institute for Energy and Transport, Luxembourg, 2014. URL `https://www.researchgate.net/publication/260211100`.

Cecile Appert-Rolland. Modeling of Pedestrians. In *Traffic and Granular Flow '13*, Jülich, 2015. Springer International Publishing. ISBN 9783319106298. doi: 10.1007/978-3-319-10629-8.

Ali Arian, Alireza Ermagun, Xiaoyu Zhu, and Yi Chang Chiu. An Empirical Investigation of the Reward Incentive and Trip Purposes on Departure Time Behavior Change. In *Advances in Transport Policy and Planning*, volume 1, pages 145–167. Elsevier B.V., 1 2018. ISBN 9780128152942. doi: 10.1016/bs.atpp.2018.07.001.

Richard Arnott, Andre de Palma, and Robin Lindsey. Does providing information to drivers reduce traffic congestion? *Transportation Research Part A: Genera*, 25(5):309–318, 1991. ISSN 0191-2607. doi: 10.1016/0191-2607(91)90146-H.

Bouchra Aylaj, Nicola Bellomo, Livio Gibelli, and Alessandro Reali. A unified multiscale vision of behavioral crowds. *Mathematical Models and Methods in Applied Sciences*, 30(1):1–22, 1 2020. ISSN 02182025. doi: 10.1142/S0218202520500013.

Muhammad Baqui and Rainald Löhner. PedPIV: Pedestrian Velocity Extraction from Particle Image Velocimetry. *IEEE Transactions on Intelligent Transportation Systems*, 21(2):580–589, 2 2020. ISSN 15580016. doi: 10.1109/TITS.2019.2899072.

Dietmar Bauer, Stefan Seer, and Norbert Brändle. Macroscopic Pedestrian Flow Simulation for Designing Crowd Control Measures in Public Transport after Special Events. In *Proceedings of the 2007 Summer Computer Simulation Conference*, pages 1035–1042, San Diego, CA, 2007. Society for Computer Simulation International. ISBN 1565553160.

Nicola Bellomo and Christian Dogbe. On the modeling of traffic and crowds: A survey of models, speculations, and perspectives. *SIAM Review*, 53(3):409–463, 2011. ISSN 00361445. doi: 10.1137/090746677.

Eran Ben-Elia and Dick Ettema. Rewarding rush-hour avoidance: A study of commuters' travel behavior. *Transportation Research Part A: Policy and Practice*, 45(7):567–582, 2011. ISSN 09658564. doi: 10.1016/j.tra.2011.03.003.

Michel Bierlaire, Riccardo Scarinci, Marija Nikolić, Yuki Oyama, Nicholas Molyneaux, and Zhengchao Wang. Methodologies for understanding and improving pedestrian mobility. In Ole B. Jensen, Claus Lassen, Vincent Kaufmann, Malene Freudendal-Pedersen, and Ida Sofie Gøtzsche Lange, editors, *Handbook of Urban Mobilities*, chapter 10, pages 97–106. Routledge, London, 2020. ISBN 978-1-138-48219-7.

Daniel Boto-Giralda, Francisco J. Díaz-Pernas, David González-Ortega, José F. Díez-Higuera, Míriam Antón-Rodríguez, Mario Martínez-Zarzuela, and Isabel Torre-Díez. Wavelet-based denoising for traffic volume time series forecasting with self-organizing neural networks. *Computer-Aided Civil and Infrastructure Engineering*, 25(7):530–545, 2010. ISSN 10939687. doi: 10.1111/j.1467-8667.2010.00668.x.

Vinícius J Cassol, Cláudio Rosito Jung, Muhammad Usman, Petros Faloutsos, Glen Berseth, Mubbasir Kapadia, Norman I Badler, and Soraia Raupp Musse. Evaluating and Optimizing Evacuation Plans for Crowd Egress. *IEEE Computer Graphics and Applications*, 37(4):60–71, 2017.

Clayson Celes, Azzedine Boukerche, and Antonio A.F. Loureiro. Crowd management: A new challenge for urban big data analytics. *IEEE Communications Magazine*, 57(4):20–25, 2019. ISSN 15581896. doi: 10.1109/MCOM.2019.1800640.

Chenyi Chen, Yin Wang, Li Li, Jianming Hu, and Zuo Zhang. The retrieval of intra-day trend and its influence on traffic prediction. *Transportation Research Part C: Emerging Technologies*, 22:103–118, 2012. ISSN 0968090X. doi: 10.1016/j.trc.2011.12.006.

Enhui Chen, Zhirui Ye, Chao Wang, and Mingtao Xu. Events Using Smart Card Data. *IEEE Transactions on Intelligent Transportation Systems*, 21(3):1109–1120, 2020.

Chih Yuan Chu. A computer model for selecting facility evacuation design using cellular automata. *Computer-Aided Civil and Infrastructure Engineering*, 24(8):608–622, 11 2009. ISSN 10939687. doi: 10.1111/j.1467-8667.2009.00619.x.

Emiliano Cristiani and Daniele Peri. Handling obstacles in pedestrian simulations: Models and optimization. *Applied Mathematical Modelling*, 45:285–302, 5 2017. ISSN 0307904X. doi: 10.1016/j.apm.2016.12.020.

Dorine C. Duives, Guangxing Wang, and Jiwon Kim. Forecasting pedestrian movements using recurrent neural networks: An application of crowd monitoring data. *Sensors (Switzerland)*, 19(2), 1 2019. ISSN 14248220. doi: 10.3390/s19020382.

Dorine C. Duives, Tim van Oijen, and Serge P. Hoogendoorn. Enhancing crowd monitoring system functionality through data fusion: Estimating flow rate from wi-fi traces and automated counting system data. *Sensors (Switzerland)*, 20(21):1–25, 11 2020. ISSN 14248220. doi: 10.3390/s20216032.

Zipei Fan, Xuan Song, Ryosuke Shibasaki, and Ryutaro Adachi. CityMomentum: An Online Approach for Crowd Behavior Prediction at a Citywide Level H.4 Information Systems Applications: Miscellaneous; H.2.8 Database Management: Database Applications-data mining, Spatial databases and GIS. *Proceedings of the 2015 ACM International Joint Conference on Pervasive and Ubiquitous Computing*, pages 559–569, 2015. URL `http://dx.doi.org/10.1145/2750858.2804277`.

Victoria Filingeri, Ken Eason, Patrick Waterson, and Roger Haslam. Factors influencing experience in crowds – The participant perspective. *Applied Ergonomics*, 59:431–441, 2017. ISSN 18729126. doi: 10.1016/j.apergo.2016.09.009. URL `http://dx.doi.org/10.1016/j.apergo.2016.09.009`.

John J Fruin. DESIGNING FOR PEDESTRIANS: A LEVEL-OF-SERVICE CONCEPT. In *50th Annual Meeting of the Highway Research Board*, pages 1–15, Washington D.C., United States, 1971. ISBN 0309019680.

David Garcia-Retuerta, Pablo Chamoso, Guillermo Hernández, Agustín San Román Guzmán, Tan Yigitcanlar, and Juan M. Corchado. An efficient management platform for developing smart cities: Solution for real-time and future crowd detection. *Electronics (Switzerland)*, 10 (7), 4 2021. ISSN 20799292. doi: 10.3390/electronics10070765.

V. X. Gong, J. Yang, W. Daamen, A. Bozzon, S. Hoogendoorn, and G. J. Houben. Using Social Media for Attendees Density Estimation in City-Scale Events. *IEEE Access*, 6:36325–36340, 6 2018. ISSN 21693536. doi: 10.1109/ACCESS.2018.2845339.

Josep Maria Salanova Grau, Evangelos Mitsakis, Panagiotis Tzenos, Iraklis Stamos, Luigi Selmi, and Georgia Aifadopoulou. Multisource Data Framework for Road Traffic State Estimation. *Journal of Advanced Transportation*, 2018, 2018. ISSN 20423195. doi: 10.1155/2018/9078547.

Jaap M Groenendijk. Haalbaarheidsonderzoek toepassing Praktijkproef Amsterdam (en 'slim reizen'). Technical report, Twynstra Gudde, Amsterdam, 2018.

Milad Haghani. Optimising crowd evacuations: Mathematical, architectural and behavioural approaches. *Safety Science*, 128(March):104745, 2020. ISSN 18791042. doi: 10.1016/j.ssci.2020.104745. URL `https://doi.org/10.1016/j.ssci.2020.104745`.

Dirk Helbing and Pratik Mukerji. Crowd disasters as systemic failures: Analysis of the love parade disaster. *EPJ Data Science*, 1(1):1–40, 2012. ISSN 21931127. doi: 10.1140/epjds7.

Ning Huan, Stephane Hess, Enjian Yao, and Wenting Liu. Time-dependent pricing strategies for metro lines considering peak avoidance behaviour of commuters. *Transportmetrica A: Transport Science*, 2021. ISSN 23249943. doi: 10.1080/23249935.2021.1946203.

Azhar Mohd Ibrahim, Ibrahim Venkat, K. G. Subramanian, Ahamad Tajudin Khader, and Philippe De Wilde. Intelligent evacuation management systems: A review. *ACM Transactions on Intelligent Systems and Technology*, 7(3), 2016. ISSN 21576912. doi: 10.1145/2842630.

Nicholas Jarvis, John Hata, Nicholas Wayne, Vaskar Raychoudhury, and Md Osman Gani. MiamiMapper: Crowd analysis using active and passive indoor localization through Wi-Fi probe monitoring. *Q2SWinet 2019 - Proceedings of the 15th ACM International Symposium on QoS and Security for Wireless and Mobile Networks*, pages 1–10, 2019. doi: 10.1145/3345837.3355959.

Johan Cruijff ArenA. Johan Cruijff ArenA events on Facebook, 2021. URL `https://www.facebook.com/johancruijffarena/events/`.

M. G. Karlaftis and E. I. Vlahogianni. Statistical methods versus neural networks in transportation research: Differences, similarities and some insights. *Transportation Research Part C: Emerging Technologies*, 19(3):387–399, 2011. ISSN 0968090X. doi: 10.1016/j.trc.2010.10.004. URL `http://dx.doi.org/10.1016/j.trc.2010.10.004`.

Joel A Kirkland and Anthony A Maciejewski. A Simulation of Attempts to Influence Crowd Dynamics. In *SMC'03 Conference Proceedings. 2003 IEEE International Conference on Systems, Man and Cybernetics. Conference Theme - System Security and Assurance (Cat. No.03CH37483)*, pages 4328–4333, 2003. doi: 10.1109/ICSMC.2003.1245665.

Tobias Kretz, Jochen Lohmiller, and Peter Sukennik. Some indications on how to calibrate the social force model of pedestrian dynamics. *Transportation Research Record*, 2672(20): 228–238, 7 2018. ISSN 21694052. doi: 10.1177/0361198118786641.

Avril M. Law. *Simulation Modeling and Analysis*. McGraw-Hill, New York, fifth edition, 2015. ISBN 978-1-259-01071-2.

Yiping Le, Saizo Aoyagi, Tetsuo Shimizu, and Kazuki Takahashi. Study on Departure Time Choice of Tourism Purpose Trips with the Perception of Predicted Near-future Traffic Condition-An Experiment Using a Mobile Application. In *2020 IEEE 5th International Conference on Intelligent Transportation Engineering, ICITE 2020*, pages 141–145. Institute of Electrical and Electronics Engineers Inc., 9 2020. ISBN 9781728194097. doi: 10.1109/ICITE50838.2020.9231518.

Kai Li, Chau Yuen, Salii S. Kanhere, Kun Hu, Wei Zhang, Fan Jiang, and Xiang Liu. Understanding crowd density with a smartphone sensing system. In *IEEE World Forum on Internet of Things, WF-IoT 2018 - Proceedings*, volume 2018-January, pages 517–522. Institute of Electrical and Electronics Engineers Inc., 5 2018. ISBN 9781467399449. doi: 10.1109/WF-IoT.2018.8355126.

Kai Li, Chau Yuen, Salil S. Kanhere, Kun Hu, Wei Zhang, Fan Jiang, and Xiang Liu. An Experimental Study for Tracking Crowd in Smart Cities. *IEEE Systems Journal*, 13(3):2966–2977, 9 2019. ISSN 19379234. doi: 10.1109/JSYST.2018.2880028.

Yang Li, Xudong Wang, Shuo Sun, Xiaolei Ma, and Guangquan Lu. Forecasting short-term subway passenger flow under special events scenarios using multiscale radial basis function networks. *Transportation Research Part C: Emerging Technologies*, 77:306–328, 2017. ISSN 0968090X. doi: 10.1016/j.trc.2017.02.005. URL `http://dx.doi.org/10.1016/j.trc.2017.02.005`.

Gioele Luchetti, Adriano Mancini, Mirco Sturari, Emanuele Frontoni, and Primo Zingaretti. Whistland: An augmented reality crowd-mapping system for civil protection and emergency management. *ISPRS International Journal of Geo-Information*, 6(2), 2 2017. ISSN 22209964. doi: 10.3390/ijgi6020041.

Sharmila Majumdar, Moeez M. Subhani, Benjamin Roullier, Ashiq Anjum, and Rongbo Zhu. Congestion prediction for smart sustainable cities using IoT and machine learning approaches. *Sustainable Cities and Society*, 64(March 2020):102500, 2021. ISSN 22106707. doi: 10.1016/j.scs.2020.102500. URL `https://doi.org/10.1016/j.scs.2020.102500`.

A.N. Marana, S.A. Velastin, L.F. Costa, and R.A. Lotufo. Estimation of crowd density using image processing. In *IEE Colloquium on Image Processing for Security Applications*, pages 1–8, London, 1997. doi: 10.1049/ic:19970387.

C. Martella, J. Li, C. Conrado, and A. Vermeeren. On current crowd management practices and the need for increased situation awareness, prediction, and intervention. *Safety Science*, 91: 381–393, 2017. ISSN 18791042. doi: 10.1016/j.ssci.2016.09.006.

Martijn Mes. SIMULATION, Data analysis, warm-up period & comparing models, 2019.

Nicholas Molyneaux, Riccardo Scarinci, and Michel Bierlaire. Pedestrian management strategies for improving flow dynamics in transportation hubs. In *STRC 17th Swiss Transport Research Conference*, Monte Verità / Ascona, 2017.

Nicholas Molyneaux, Riccardo Scarinci, Monte Verità, / Ascona, and Michel Bierlaire. Two management strategies for improving pas-senger transfer experience in train stations STRC 18th Swiss Transport Research Conference Two management strategies for improving passenger transfer experience in train stations Two management strategies for improving passenger trans-fer experience in train stations. In *18th Swiss Transport Research Conference*, Ascona, 2018. Ecole Polytechnique Fédérale de Lausanne.

Nicholas Molyneaux, Riccardo Scarinci, and Michel Bierlaire. Design and analysis of control strategies for pedestrian flows. *Transportation*, 48(4):1767–1807, 8 2021. ISSN 15729435. doi: 10.1007/s11116-020-10111-1.

Mehdi Moussaïd, Dirk Helbing, and Guy Theraulaz. How simple rules determine pedestrian behavior and crowd disasters. *Proceedings of the National Academy of Sciences of the United States of America*, 108(17):6884–6888, 2011. ISSN 00278424. doi: 10.1073/pnas.1016507108.

Nidal Nasser, Muhammad Anan, Mohammad Faiz Chikh Awad, Hesham Bin-Abbas, , and Lutful Karim. An expert crowd monitoring and management framework for Hajj. In *2017 International Conference on Wireless Networks and Mobile Communications (WINCOM)*, pages 1–8, 2017. doi: 10.1109/WINCOM.2017.8238202.

NIBRA. Dance Valley 2001, een evaluatie van de gebeurtenissen. Technical report, Nederlands Instituut voor Brandweer en Rampenbestrijding, Arnhem, 2001.

Cheol Oh, Stephen G Ritchie, and Jun-seok Oh. Exploring the Relationship Between Data Aggregation and Predictability to Provide Better Predictive Traffic Information. *Journal of the Transportation Research Board*, 1935(1):28–36, 2005. doi: 10.1177/0361198105193500104.

OpenStreetMap. OpenStreetMap - Station Bijlmer ArenA. https://www.openstreetmap.org/#map=17/52.31349/4.94036, 6 2021. URL `https://www.openstreetmap.org/#map=17/52.31349/4.94036`.

Alexandros E. Papacharalampous, Oded Cats, Jan Willem Lankhaar, Winnie Daamen, and Hans Van Lint. Multimodal data fusion for big events. *Transportation Research Record*, 2594:118–126, 2016. ISSN 03611981. doi: 10.3141/2594-15.

PTV. *PTV VISSIM 2021 User Manual*. PTV, Karlsruhe, 2021.

Lorenz Schauer, Martin Werner, and Philipp Marcus. Estimating Crowd Densities and Pedestrian Flows Using Wi-Fi and Bluetooth. In *MobiQuitous 2014 - 11th International Conference on Mobile and Ubiquitous Systems: Computing, Networking and Services*, pages 171–177, 2014.

Xiaomeng Shi, Zhirui Ye, Nirajan Shiwakoti, Dounan Tang, and Junkai Lin. Examining effect of architectural adjustment on pedestrian crowd flow at bottleneck. *Physica A: Statistical Mechanics and its Applications*, 522:350–364, 5 2019. ISSN 03784371. doi: 10.1016/j.physa.2019.01.086.

Maaike Snelder and Simeon Calvert. Real-time reistijdvoorspellingen voor routekeuze- en vertrektijdstipadvies - een toepassing in de Praktijkproef Amsterdam. In *Colloquium Vervoersplanologisch Speurwerk 2015*, Antwerpen, 2015. Colloquium Vervoersplanologisch Speurwerk.

Xiao Song, Zenghui Zhang, Gongzhuang Peng, and Guoqiang Shi. Effect of authority figures for pedestrian evacuation at metro stations. *Physica A: Statistical Mechanics and its Applications*, 465:599–612, 1 2017. ISSN 03784371. doi: 10.1016/j.physa.2016.08.015.

Hang Su, Jun Zhu, Yinpeng Dong, and Bo Zhang. Forecast the plausible paths in crowd scenes. *IJCAI International Joint Conference on Artificial Intelligence*, 0:2772–2778, 2017. ISSN 10450823. doi: 10.24963/ijcai.2017/386.

Shuming Sun, Juan Chen, and Jian Sun. Traffic congestion prediction based on GPS trajectory data. *International Journal of Distributed Sensor Networks*, 15(5), 2019. ISSN 15501477. doi: 10.1177/1550147719847440.

Yuxing Sun, Biao Leng, and Wei Guan. A novel wavelet-SVM short-time passenger flow prediction in Beijing subway system. *Neurocomputing*, 166:109–121, 2015. ISSN 18728286. doi: 10.1016/j.neucom.2015.03.085. URL `http://dx.doi.org/10.1016/j.neucom.2015.03.085`.

Qing Tang and Xianbiao Hu. Triggering behavior changes with information and incentives: An active traffic and demand management-oriented review. In *Advances in Transport Policy and Planning*, volume 3, pages 209–250. Elsevier B.V., 1 2019. ISBN 9780128162132. doi: 10.1016/bs.atpp.2019.05.002.

Martin Treiber and Arne Kesting. *Traffic flow dynamics: Data, models and simulation*. Springer Berlin Heidelberg, Berlin, first edition, 1 2013. ISBN 9783642324604. doi: 10.1007/978-3-642-32460-4.

Treinposities.nl. Vertrekstaat station Amsterdam Bijlmer ArenA, 2021. URL `https://treinposities.nl/vertrekstaat/amsterdam-bijlmer-arena/`.

Gaurav Tripathi, Kuldeep Singh, and Dinesh Kumar Vishwakarma. Crowd emotion analysis using 2D ConvNets. In *Proceedings of the 3rd International Conference on Smart Systems and Inventive Technology, ICSSIT 2020*, pages 969–974. Institute of Electrical and Electronics Engineers Inc., 8 2020. ISBN 9781728158211. doi: 10.1109/ICSSIT48917.2020.9214208.

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*, Jülich, 2015. Springer International Publishing. ISBN 9783319106298. doi: 10.1007/978-3-319-10629-8.

Eleni I. Vlahogianni, Matthew G. Karlaftis, and John C. Golias. Short-term traffic forecasting: Where we are and where we're going. *Transportation Research Part C: Emerging Technologies*, 43:3–19, 2014. ISSN 0968090X. doi: 10.1016/j.trc.2014.01.005. URL `http://dx.doi.org/10.1016/j.trc.2014.01.005`.

Michael Wagner, Henriette Cornet, David Eckhoff, Philipp Andelfinger, Wentong Cai, and Alois Knoll. Evaluation of Guidance Systems at Dynamic Public Transport Hubs Using Crowd Simulation. In *Proceedings - Winter Simulation Conference*, volume 2020-December, pages 123–134. Institute of Electrical and Electronics Engineers Inc., 12 2020. ISBN 9781728194998. doi: 10.1109/WSC48552.2020.9383949.

Guo Yuan Wang, Fan Yu Wu, You Liang Si, Qin Zeng, and Peng Lin. The Study of the Impact of Obstacle on the Efficiency of Evacuation under Different Competitive Conditions. In *Procedia Engineering*, volume 211, pages 699–708. Elsevier Ltd, 2018. doi: 10.1016/j.proeng.2017.12.066.

Jinghong Wang, Bowei Jin, Jia Li, Fanghao Chen, Zhirong Wang, and Jinhua Sun. Method for guiding crowd evacuation at exit: The buffer zone. *Safety Science*, 118:88–95, 10 2019. ISSN 18791042. doi: 10.1016/j.ssci.2019.05.014.

Yu Wei and Mu Chen Chen. Forecasting the short-term metro passenger flow with empirical mode decomposition and neural networks. *Transportation Research Part C: Emerging Technologies*, 21(1):148–162, 2012. ISSN 0968090X. doi: 10.1016/j.trc.2011.06.009. URL `http://dx.doi.org/10.1016/j.trc.2011.06.009`.

Nanda Wijermans, Claudine Conrado, Maarten van Steen, Claudio Martella, and Jie Li. A landscape of crowd-management support: An integrative approach, 7 2016. ISSN 18791042.

Martin Wirz, Tobias Franke, Daniel Roggen, Eve Mitleton-Kelly, Paul Lukowicz, and Gerhard Tröster. Probing crowd density through smartphones in city-scale mass gatherings. *EPJ Data Science*, 2(1):1–24, 2013. ISSN 21931127. doi: 10.1140/epjds17.

Daichi Yanagisawa, Ayako Kimura, Akiyasu Tomoeda, Ryosuke Nishi, Yushi Suma, Kazumichi Ohtsuka, and Katsuhiro Nishinari. Introduction of frictional and turning function for pedestrian outflow with an obstacle. *Physical Review E - Statistical, Nonlinear, and Soft Matter Physics*, 80(3), 9 2009. ISSN 15393755. doi: 10.1103/PhysRevE.80.036110.

Yufei Yuan, Winnie Daamen, Dorine Duives, and Serge Hoogendoorn. Comparison of three algorithms for real-Time pedestrian state estimation - Supporting a monitoring dashboard for large-scale events. In *IEEE Conference on Intelligent Transportation Systems, Proceedings, ITSC*, pages 2601–2606. Institute of Electrical and Electronics Engineers Inc., 12 2016. ISBN 9781509018895. doi: 10.1109/ITSC.2016.7795974.

Guang Zeng, Andreas Schadschneider, Jun Zhang, Shibo Wei, Weiguo Song, and Rui Ba. Experimental study on the effect of background music on pedestrian movement at high density, 3 2019. ISSN 03759601.

Xianlong Zhao, Kexin Yang, Qimei Chen, Duo Peng, Hao Jiang, Xianze Xu, and Xinzhuo Shuang. Deep learning based mobile data offloading in mobile edge computing systems. *Future Generation Computer Systems*, 99:346–355, 2019. ISSN 0167739X. doi: 10.1016/j.future.2019.04.039. URL `https://doi.org/10.1016/j.future.2019.04.039`.

Yongxiang Zhao, Tuantuan Lu, Libi Fu, Peng Wu, and Meifang Li. Experimental verification of escape efficiency enhancement by the presence of obstacles. *Safety Science*, 122, 2 2020. ISSN 18791042. doi: 10.1016/j.ssci.2019.104517.

Min Zhou, Hairong Dong, Petros A. Ioannou, Yanbo Zhao, and Fei Yue Wang. Guided crowd evacuation: Approaches and challenges, 9 2019. ISSN 23299274.

Ziggo Dome. Ziggo Dome events on Facebook, 2021. URL `https://www.facebook.com/ziggodome/events/`.

Nan Zou, Jianwei Wang, Gang Len Chang, and Jawad Paracha. Application of advanced traffic information systems: Field test of a travel-time prediction system with widely spaced detectors. *Transportation Research Record*, 2129:62–72, 2009. ISSN 03611981. doi: 10.3141/2129-08.

A LITERATURE SEARCH QUERIES

This appendix presents the search queries used to find the literature cited in the research, and the hits per the search term. These search queries are mainly used for the determining the research context in Chapter 2 and the literature review in Chapter 4, however some search queries concern the implementation of measures as elaborated upon in Chapter 5 and Appendix C.
As this overview was made in retrospect of the search for literature, it was not possible to indicate which search queries led to the finding of specific references. Moreover, it might be that other sources and search queries were used for the research as well. E.g., an important other source is the meta-study of Haghani [2020]. Nonetheless, it is expected that Table A.1 gives insights in the most important search queries used for the research.

Table A.1: Details of search for literature queries used in the research.

Index	Search query	Hits	Database
1	transport AND ”short term forecasting”	74	Scopus
2	”arrival pattern” AND visitors	7	
3	”arrival pattern”	993	
4	Cited by: Multimodal data fusion for big events, Papacharalampous et al. [2016]	2	
5	events AND visitor AND departure	17	
6	events AND visitor AND arrival	74	
7	events AND ”arrival pattern”	88	
8	event AND ”arrival pattern”	88	
9	events AND arrival AND pattern	1,290	
10	”departure pattern” AND event	8	
11	”arrival pattern” AND concert	0	
12	”arrival event” AND concert	0	
13	”arrival profile” AND event	3	
14	”arrival pattern” AND event	88	
15	”arrival prediction”	139	
16	event AND ”departure curve”	1	
17	”departure curve”	59	
18	modelling AND ”event departure”	0	
19	modelling AND ”departure profile”	8	
20	modelling AND ”festival outflow”	0	
21	modelling AND pedestrian AND circuit	88	
22	modelling AND pedestrian AND festival	14	
23	modelling AND pedestrian AND events	334	
24	”love parade”	35	
25	love AND parade	68	
26	”passenger arrival”	318	

Table A.1 continues on the next page.

Continuation of Table A.1			
Index	**Search query**	**Hits**	**Database**
27	Cited by: On current crowd management practices and the need for increased situation awareness, prediction, and intervention, Martella et al. [2017]	28	Scopus
28	”crowd management” AND vehicle	40	
29	event AND departure	3,743	
30	event AND departure AND crowd	15	
31	crowd AND departure	91	
32	”departure of crowd”	0	
33	”crowd departure”	0	
34	”event departure”	6	
35	”event departure” AND crowd	0	
36	influencing AND crowd AND departure	0	
37	Cited by: A simulation of attempts to influence crowd dynamics, Kirkland and Maciejewski [2003]	30	
38	”influence crowds”	18	
39	”influencing crowds”	7	
40	”influencing crowd behaviour”	0	
41	”kinetic model” AND pedestrian	18	
42	”Modeling of Pedestrians”	155	
43	”crowd monitoring”	245	
44	”crowd monitoring” AND gps	12	
45	short AND term AND traffic AND forecasting	2,890	
46	”short-term” AND traffic AND forecasting	2,778	
47	praktijkproef AND amsterdam	2	
48	crowd AND management AND event AND departure	6	
49	influencing AND pedestrian AND behaviour	204	
50	pedestrian AND behaviour	8,511	
51	”crowd management” AND arrival	5	
52	”crowd management” AND departure	5	
53	event AND ”visitor departure”	0	
54	event AND ”visitor arrival”	14	
55	”event arrival”	176	
56	event AND ”arrival pattern”	88	
57	effect AND information AND departure AND time	516	
58	spread AND peak AND traffic AND inform	2	
59	Cited by: Does providing information to drivers reduce traffic congestion?, Arnott et al. [1991]	244	
60	methodologies AND for AND understanding AND improving AND pedestrian AND mobility	4	
61	Exploring the Effect of Crowd Management Measures on Passengers’ Behaviour at Metro Stations	1	
62	kirchhoff route choice	15,600	Google Scholar
63	kirchhoff route choice pedestrian	445	
64	logit route choice pedestrian	8,660	
65	Route Choice Modeling: Past, Present and Future Research Directions	1	
66	event arrival pattern	849,000	
67	event departure pattern	677,000	

Table A.1 continues on the next page.

Continuation of Table A.1			
Index	**Search query**	**Hits**	**Database**
68	lowering traffic peaks	28,800	Google Scholar
69	informing drivers	215,000	
70	informing drivers spread peak	46,600	

B INTERVIEW DETAILS

This appendix presents the details of the interviews that were part of this research. Section B.1 presents the structure and questions used for the interviews. Exact questions posed to the interviewee and the order in which questions are posed might differ per interviewee and therefore differ slightly with regards to the reporting of the interviews. Sections B.2 and onward concern the reporting of the individual interviews in chronological order in which the interviews were conducted.
Note that the interview structure was originally written in Dutch and the interviews were conducted likewise. This appendix presents a translated report of the structure and outcomes.

B.1 Interview structure

The interview structure shown below served as a guideline for all the conducted interviews. This means that not all questions are specifically asked to each interviewee, as the plan was to have a semi-structured interview to see what aspects were of specific interest to the interviewee. Moreover, the core of some answers to the written questions were given in the response to elaborations to other questions.

B.1.1 Introduction

Before the interview starts, an introduction about this research is given to the interviewee. It is explained what the research is about and what the underlying idea of the interview is. Also, the specific idea of *short-term* measures is introduced as measures that can be implemented during an event or within a time span of maximum 3 hours. Moreover, consent is asked concerning recording of the interviews for the purpose of reporting (which all interviewees agreed to) and it is mentioned that the interview report will be send to the interviewee to make sure the reporting is correct. After this introductory part, the interviews followed the structure as indicated by the subsections below.

B.1.2 Background interviewee

In order to be able to place your responses in the right context with regards to the other interviewees, it is relevant to know some aspects with regards to you (educational) background and experiences in the field of crowd management. Could you elaborate on this?

- In what phases with regards to the entire crowd management process are you involved?
- What (type of) projects/events have you been involved in?
- What role did you have during these projects/events?

B.1.3 Crowd monitoring & dashboarding

Before an event takes place, preparations will be made in order to make sure that (at least when everything goes as planned) the crowd flows are safe. Are different events approached differently? Are different types of event visitors approached differently?
During an event, it is important to keep track of the status of the crowd. What metrics are important to keep an eye on? Accompanying this aspect is the fact that dashboards are used to keep insights. Are you familiar with the use of dashboards to keep track of a crowd? If so, what are important aspects that should be visible there in order to gain quick insights into the crowd status?
Literature showed great interest in spatio-temporal aspects like 'crowd flow' and 'crowd density':

- To what extend are those relevant in your opinion?
- Is the relevance of these metrics dependent on different locations?
- Are there other aspects that you want to keep an eye on besides spatio-temporal aspects?

Besides spatio-temporal aspects, there is growing interest in actively incorporating 'crowd characteristics' in real-time. Besides aspects like age composition and visitor profiles based on event types, this also incorporates the 'atmosphere of the crowd':

- Is this something that you have incorporated im- or explicitly?
- If so:
  - What impact does incorporating such aspects make on your crowd management planning?
  - How do you measure such aspects?
  - Is the analysis of social media something to look into in this regards?
- If not:
  - Do you think it has added value to incorporate such aspects?

B.1.4 Scenarios

The use of scenarios is of course important with regards to being prepared for the occurrence of specific situations:

- What types of scenarios and what differences are important to take into account during the preparation of a crowd management plan?
- What are scenarios/aspects to incorporate in scenarios that you deem specifically relevant for the Bijlmer ArenA station area?

Is the homo-/heterogeneity of a crowd something to incorporate in scenarios

B.1.5 Measures

It is likely that for every scenario a different measures will be more suitable to take than others:

- What would be a relevant measures for the various previously discussed scenarios?
- Would it be possible to implement a measure within a short-term in order to combat negative aspects of a scenarios?

- Do you see the opportunity to implement measures that are more focusing on influencing the behaviour of the crowd rather than the physical environment?

To what extent would a specific measure be translatable to a different (geographic) environment? Or is it that certain prerequisites with regard to the environment or the crowd need to be met in order to make a measure work?
I have found various measures in literature that sound interesting with regards to implementation:

- There are many different studies that go into the evacuation of people from a building. To what extent can evacuation studies be applied to crowd management in your opinion?
- The use of stewards and push notifications is something that is mentioned as possible measures to supply the crowd with information:
  - Have such personal informing strategies been implemented at events that you were involved in?
  - To what extend does such informing strategy have its intended effect on the 'stubborn Dutch people'?
  - Are there clear differences between effectiveness with respect to crowd characteristics (e.g., younger versus older crowds or crowds familiar with the environment versus crowds less aware of their environment)?
- It is quite well-known that music can influence the feelings and behaviour of people.
  - A study showed that background music can also influence moving crowds. Is this something that you believe can be applied?
  - The study showed that crowd members slowed down and more stop-and-go waves occurred in the crowd. Is this something that can be positive to combat *over*crowding?
- Separation of streams can enhance the flows of people going to specific destinations. Is this something that can be achieved in a station environment?

Different possible measures have been discussed. Which do you deem to be achievable to implement on a short notice?

B.1.6 Closure

As a closure of the interview, the interviewee is thanked for his/her participation in the interview. A final content-wise question is posed on whether the interviewee wants to elaborate on any remaining thoughts with respect to the research and the subject of crowd management (be it specifically in the Bijlmer ArenA area or not).

B.2 Marion Vos

The interview with Marion Vos took place on 29 September 2021 at 16:00 via Microsoft Teams.

B.2.1 Background interviewee

Marion Vos is a self-employed crowd management and mobility professional involved in different (types of) events, ranging from music events like the Bevrijdingsfestival Zwolle and the Zwarte Cross to more general safety planning projects like crowd management for the inner city of Zwolle and venues that are part of the Libema leasure concern. She started working at the Bevrijdingsfestival Zwolle as an intern when event safety became a relevant issue for event organisers, though she has no specific background in (event) safety. Most knowledge she has with specific regards to safety of crowds is based on experience. With respect to the Zwarte Cross, she is more involved with mobility than crowd management.

B.2.2 Crowd monitoring & dashboarding

With regards to preparations, there are already quite some differences with the different project's Marion has worked on. For example, the Zwarte Cross has a limited number of tickets for sale, whereas the Bevrijdingsfestival has free entrance. This inherently means that for the Bevrijdingsfestival there are way more unknown variables, and the crowd management challenges are extensive there. Therefore, monitoring is key as well. Based on information provided by the police and the NS, the stream of people going to the event location is monitored. The exact counts are not of real importance, more important is the growth/decrease of the flow towards the location. On the event site, the crowd situation is monitored through cameras and observers in the field. With respect to the on-terrain monitoring, often a close watch is kept at the schedule of the event. It might be that there are moments during the day that it might seem that it will become too crowded (e.g., shortly before dinnertime), but through experience it is known that due to the schedule the crowdedness is highly likely to start to decrease within a short term.
At the Zwarte Cross, many cameras are placed all around the venue. The problems over there are often not related to possible over-crowded of for example the entrance or the overall number of people on the venue, but more related to the movement of people over the entire event terrain. From that perspective, it is key to have a schedule suitable for your event venue as well. While the available space is not necessarily the problem at the Zwarte Cross, the movement of people from one stage to the other might lead to bottleneck crowding. The main stage of the Bevrijdingsfestival has a clearly larger capacity than any other stage on the venue, so when the next act on the main stage attracts a completely different crowd than the previous act, it is just asking for trouble.
For dashboarding and real-time monitoring, cameras are applied at the different events that are used to count passing crowd members, though the extent of this is mainly related to budget constraints of the event organiser. In the context of inner-city crowd management, different (counting) sensors are being applied to gain insights into the crowd status, though privacy issues are relevant concerning widespread implementation of the sensors. Nonetheless, there are already many sensors rolled out that might be useful for crowd monitoring as well, e.g., induction loops for traffic data can give relevant insights for crowdedness in a city centre.
Crowd characteristics are mostly incorporated into the ex-ante risk analyses of events. During the event itself, not too much is actively done with it, though it might be that such aspects are incorporated implicitly. Influencing the crowd through social media is on the rise in order to gain insights into the atmosphere in the crowd and in order to serve as a real-time online help desk. The exact placement of cameras and sensors is also often based on the risk analysis. Through such an analysis it is often identified what regions of an event venue require special attention with respect to crowd management. Accordingly, such areas are often equipped with some

type of sensors for proper situational monitoring. As an example, the crowd density close to the podium is not of very special importance, as the density will be high there in any case (though a camera might still be relevant for monitoring public order). However, if the density towards the back of the crowd is high as well, it might indicate that there are potential crowd problems looming. Similarly, routes between stages are relevant in that sense as well. All in all, it is dependent on the outcomes of the risk analysis whether the installation of specific sensors is relevant or possibly even necessary.
The heterogeneity of a crowd is not necessarily tackled explicitly. It is mostly incorporated in the risk analysis, though it does not necessarily lead to different measures for different crowds. People that are part of a crowd are limited by their options of behaviour due to the crowd, though they still will want to make individual decisions. Therefore, a group will inherently be heterogenic, but also will always have homogenic characteristics. All in all, you have to prepare for different types of people: people who are self-sufficient, people who are not self-sufficient, children, elderly, non-Dutch speakers, visually and/or audibly handicapped.

B.2.3 Scenarios

Overcrowding is always a very relevant scenario, specifically for the Bevrijdingsfestival. Overcrowding can take place on both local scale (i.e., at a specific stage or route between stages) or at a venue-wide level. In preparation for the event, it is useful to define a best-case, worst-case, and realistic-case scenario in order to be prepared for various situations. At the Zwarte Cross, venue-wide overcrowding is less of an issue due to the limited available tickets, though local overcrowding at specific event sites might still be relevant. By already describing the scenarios, you already try to incorporate measures to counteract the possible negative effects. You are always limited by the physical environment of your event, which is key in the starting principles of the various scenarios.
With regards to station Bijlmer ArenA, it might be relevant to investigate disruptions of the train timetable. Moreover, simultaneous outflow of different events in the area around the station is relevant as this might lead to serious overcrowding issues at and around the station. Also, the accessibility by the emergency services during crowding might be something to investigate.

B.2.4 Crowd management measures

There are different types of crowd management measures, of which the pre-prepared measures are maybe the most often discussed and applied. These range from rather straightforward aspects like layout of the venue and placement of barriers to (static) signage. However, possibly the most important though not the first measure one thinks of is the schedule of an event, as this also allows for “scheduling” visitor flows.
On a more flexible, short-term level, security and service stewards can allow for direct contacts with a crowd. When also considering both a broader monitoring aspect as a broader target audience for a steward, the importance of height (e.g., through stilts or horses) should not be neglected as height allows for seeing and communicating with multiple people, standing further away. Moreover, sound installations allow for large-scale direct one-way communication towards a crowd. Besides the fixed sound installations at stages during an event, a mobile sound installation placed on a vehicle can be used for similar communication on other locations. LED screens placed at different locations allow for the display of messages to the crowd. The publication of social media messages is also a relevant way to contact the crowd, which can also be done through the development of an own app. What however should be noted with regards to social media and apps is that people might not respond to a message immediately as they might not be aware of potential dangers in the first place and also do not look at their phone a lot when at a festival. The effectiveness of such messages and apps might mainly be relevant for people checking their phones when traveling to the festivals. In this respect, it is also of importance that

messages are not conflicting with one another as this might cause confusion among visitors and lead to undesirable effects. Therefore, most messages are prepared beforehand to be send out in specific circumstances.

For the effectiveness of the messages (both textual and audible), it is key to not only state the problem, but also go into tips to let people avoid or solve the problem. Also think of the exact (sub)crowds that you can reach with your measures. As an example of the Bevrijdingsfestival, there is one stage on an island which is accessible by a narrow, fixed bridge and a wider pontoon bridge. While for evacuation purposes it seems logical to make the narrow bridge one-way for outflowing crowds, it is used as a one-way inflow point for the island, as on the island you can better reach the crowd to move away from the island using the wider bridge. People will inherently try to use an available corridor like the narrow bridge as an entry point, and as the stage is located on the island, one cannot easily reach the people on the mainland side of the bridge to inform them that the narrow bridge would only be used for outflow, potentially leading to crowd issues due to conflicting flows and high densities. On the other hand, people on the island can be reached with the audio installation on the stage to inform them that the pontoon bridge is used as an exit.

Important to remember is that measures should not be implemented in isolation: for convenience and reaching the crowd, it is better to focus on multiple measures at the same time.

With regards to the study that involved playing background music, it was mentioned that something similarly has been tried at the Bevrijdingsfestival through making the atmosphere somewhat less enjoyable at a specific stage. By lowering the volume and brightening the lights at the stage, it was tried to lure people away from the specific stage. Nonetheless, this is a very delicate measures, as it can potentially also lead to unrest in the crowd if done too much.

B.3 Rik Schakenbos

The interview with Rik Schakenbos took place on 30 September 2021 at 9:00 via Microsoft Teams.

B.3.1 Background interviewee

Rik Schakenbos is a researcher for NS Stations within the field of crowd control, specifically oriented toward crowd flows on and around train stations. This on one hand concerns event crowd control (e.g., Bijlmer ArenA and Zandvoort) and on the other structural crowd control at platforms and stations that are infamous for overcrowding (e.g., Amsterdam Zuid and Schiphol Airport). Subjects of such research range from checking whether (new) station designs are suitable for the expected crowd flow or whether the time tabling is suitable for the crowdedness of platforms. Concerning Bijlmer ArenA he was involved in the set-up of the currently implemented measures during events and has been involved in the first few events after the first implementation. Currently, however, other colleagues are more concerned with the operational aspects within the OMC (Operationeel MobiliteitsCentrum).

B.3.2 Crowd monitoring & dashboarding

For the preparations of events at Bijlmer ArenA, the differences in events also concern preparations for different types of event visitors. A first important difference to take into account is the modal split: some crowds are more likely to rely on cars, other are more based on public transport. Similarly, crowd characteristics differ per event. As an example, a match of the Dutch national football team often attracts more 'fathers with sons' than an Ajax match, which usually attracts more young adults. The identification of these characteristics are mostly based on similar historic events.
With respect to dashboards used by NS Stations, the presentation is based on data gathered within the station. During the first trials with active monitoring, many different graphs were available, but it became clear that only two are of main importance: inflow and outflow of people aggregated over a set time period. Together with the total number of people entering and leaving the station up to specific moments, relevant insights can be gained into the to-be-expected crowd situation at the end of an event. At the Bijlmer ArenA station the rule-of-thumb is used that if the inflow of the station reaches about 400 to 450 people per minute, issues are likely to occur, so the measures need to make sure the inflow stays below that.
The dashboard that was shown during the interview indicated that only few people used the station entry doors located the furthest away from the event venues while the accompanying ascending points were used by over a quarter of the people. This indicates that the people did not use the accompanying station entry but walked to the ascending points within the station hall after entering the station through one of the other doors. This is not ideal but given the relatively low number of people in the first place (about 13.000) it was not a problem for this event. In cases that more people make use of the station, more emphasis is put on making sure people queue at the right doors outside of the station, as crossflows within the station are great limiting factors of the pedestrian flow capacity in the station. The key for dashboarding is to keep it as simple as possible. This allows for the best interpretation, especially during the busiest 30 minutes after the event(s), where the entire situation can become quite hectic. Only the most key information is relevant in those cases. An addition to the presented dashboard might be to get some information about the people waiting outside of the station. Concerning Bijlmer ArenA, the municipality an ProRail are currently busy with some aspects in that regard.
Concerning the crowd characteristics, different aspects are taken into account in the risk analyses of events. The atmosphere within the crowd is not directly 'measured', but also mostly incorporated into the risk analysis scenarios. Within the OMC, signals concerning atmosphere

within the crowd are often recognised beforehand by policemen or stewards and preparations can be made accordingly. Social media are not used by NS Stations as a measure of atmosphere, also because this entire aspect is more part of the OMC in general. Therefore, it is more relevant to ask about this topic there.

B.3.3 Scenarios

Some weeks before the event itself it will already be determined what pre-defined scenarios are needed to take into account. This already has a close link with potential measures, as it also concerns the deployment of (extra) personnel and extra trains.
During the event itself, various possible scenarios may become relevant. With regards to a football match, overtime might be relevant, meaning that the crowd will exit the stadium at a later time than initially anticipated, which might specifically be difficult with respect to extra train deployment. Also, the share of visitors making use of public transport might be larger than expected is a scenario to take into account. A worst-case scenario would be that there is a disruption in the train and/or metro services.
Important to keep in mind with regards to the scenarios is that the event venues are allowed to independently set the timing for the events that they organise. This might mean that three events might start and end at around the same time, leading to an enormous crowd that wants to make use of the station at the same moment. However, similarly, it might seem to become a busy night when three events are organised, but if the end times of the events are distributed enough through time, there might be barely any real crowdedness at the station.

B.3.4 Crowd management measures

For the possible measures, it is most important that the safety of the crowd is secured. Only when the safety is secured, the crowd flow is of importance. Therefore, in order to secure the safety, the flow is sometimes hindered. At Amsterdam Bijlmer ArenA this is done through the placement of 'Mojo barriers' before the station entrance. These barriers have gates which can be used to regulate the inflow of passengers into the station. Once it becomes too crowded at the platforms or in the station in general, these gates will be closed to secure safety. Though, it should also be noted that a constant crowd flow can also increase safety. Therefore, the barriers are used to make sure that people only wait at one specific location in order to maintain a high flow at e.g. ascending points. Moreover, the people are already being sorted by destination as part of the waiting zone, leading to less conflicting flows in the station itself.
Methods of persuasion in order to have a more spread-out peak should mainly be taken at the venues themselves already. As the distance between the venues and the station is relatively small, it does not necessarily make sense to focus on persuasion methods on the boulevard that connects the venues to the station, as people that enter the boulevard simply already want to go to the station.
Some of the mentioned scenarios already have some clear possible measures. Overtime of a football match is difficult to apply a suitable measure for, as it is not doable to change the timetable at such short notice. The one thing that is currently tried is to have a 'sweep train' available that only starts its journey when it is sure that it can contribute to reducing crowdedness at Bijlmer ArenA station, though this is still very difficult to implement, mainly as a result of network effects on the nation-wide timetable. Concerning a larger number of visitors making use of public transport, it is possible to guide a specific part of the visitors to a different nearby (metro)station. This has been applied to (international) Ajax matches, where specifically the visiting fans were guided towards the Strandvliet metro station, which also was partly to make sure that the Ajax and visiting fans would not clash. A disruption in the train or metro services is also not easily solvable, though if it only concerns the services towards Amsterdam Centraal

of one of the two modes, the other is able to fill in the gap with help of further crowd control. In the case that there is an overall disruption, there are possibilities to inform the visitors of events that something is wrong, though this is something that the OMC knows more about. Though the key in the process is a) getting informed about the problem and b) informing the crowd about the issue.
Besides the currently common measure of placing barriers and gates at the entrance of the station, stewards are also present on the platforms to spread out the crowd. The stewards know the size of the next train and try to spread the crowd over the platform in such a manner that the train boarding process will happen as quickly as possible. Accompanying the spreading of the passengers, the stewards also inform the crowd managers at the station entrance about the degree of occupation of the platform.
The stewards at the station entrance and square are mostly busy with guiding passengers to stand in front of the right gate/station entrance. This is done in various ways as different people receive information best in different ways.
In general, the 4 principles of the measures that Rik has tried and implement stem from vehicular traffic. Ramp metering becomes gating. DRIP-messages become LED boarding. Separation of local and through traffic becomes separation of pedestrian streams based on destination platform. The implementation of a rush-hour lane becomes the implementation of extra trains. The separation of destinations is implemented through using the different entry doors to the station. However, this is not a strict enforcement, as passengers can still switch to a different platform than intended with the different gates after entering the station hall. It is impossible to separate the flows 100% correctly, there will always be some people who queue correctly. A bit of conflicting flows is not an issue, as long as the majority of the flows are separated.
The application of (background) music has not been thought of as a measure for crowd management at Bijlmer ArenA. Nonetheless it might have potential to create a spread in the arrival of people.
NS has thought of different measures, and most have been tried or moulded into the currently implemented measures. In order to have a more robust solution, they are currently thinking of redesigning the station as a whole, but as this concerns permanent infrastructural adaptions, this aspect is out of scope of this research.

B.4 Dave van Schaick

The interview with Dave van Schaick took place on 30 September 2021 at 13:00 via Microsoft Teams.

B.4.1 Background interviewee

Dave van Schaick originally has a background in the road construction sector as a contractor (NL: uitvoerder) and therefore got into traffic management from that perspective. He started his own company back in 2008 that specialised in road construction traffic management aspects. Current clients include governments, contractors, event organisers and engineering firms. Experiences with events and genuine crowd management started in 2015 with Sail Amsterdam. Currently he and his company are involved with mobility planning for the Lowlands and Down the Rabbit Hole festivals and concerts at the Goffertpark in Nijmegen and Malieveld in The Hague. Besides mobility planning, they also guide the execution of these plans during the events. This only concerns mobility outside of the event terrain.
When comparing traffic management during road construction and crowd management during events, he noticed that traffic management is more 'mature' by carrying out extensive risk analyses, while for events the idea is more about it being it a once-per-year event, so the impact on the environment will be minimal. Therefore such aspects are sometimes neglected by event organisers.

B.4.2 Crowd monitoring & dashboarding

With respect to different types of crowds, historical data of similar events is key in making a modal split in order to determine how to plan the mobility of an event. Also experience of the crowds can be key. A recurring festival like Lowlands often attracts recurring visitors, while an event like the Dutch GP or a concert at the Goffertpark attracts people to that location for possibly the one and only time someone will visit the location. This has implications for the 'expectation' of visitors during their trip to the event venue. This is maybe not real crowd management, as is involves a wider mobility aspect besides walking crowds, but still incorporates issues like people wanting to pass a specific bottleneck with their vehicle. Moreover, more older crowds also often require more signage to an event than younger crowds, which is key in mobility planning.
Important aspects to consider in crowd management planning are therefore: how many people will visit the event, what is the expected time of arrival of those people, what is the type of mobility of those people, are we able to handle this expected flow at specific locations? Most of these aspects are based on historic data. A relevant aspect is that the bottleneck identification through the analysis of expected flows at specific location is sometimes forgotten about, especially on the interface of responsibilities of different parties.
Dashboards are implemented at different events, but these are most often combined with the observations from the field to get the best insights. A lot of expert judgement by police and/or stewards takes place in order to gain insights into crowds in real time, regarding both flow-aspects as atmosphere-aspects.

B.4.3 Scenarios

Changing weather is of great relevance for events taking place outside.
With respect to mobility, and specifically public transport, a disruption of the train service can have major implications for the outflow of event visitors. This happened for an event at the Goffertpark, where it was key to inform people about the issue through the LED screens, but also in the shuttle busses that where available to transport people to the train station. As in this

case there were shuttle buses available, it was also brought forwards that maybe these buses could play a role in mitigating effects from the train disruption.
Evacuation scenarios where incidents happen at the event location are also relevant to consider, as this leads to an immediate outflow of a panicking crowd.
All in all, it can be stated that for every party and location involved in the event something can be different than expected, which can be incorporated in a possible scenario. The degree of resilience with respect to a scenario is dependent on the coordination of responsibilities between and available resources of the different parties. These different responsibilities and available resources of the various parties should also be known to each other in order to be able to deal with prepared scenarios but also with unprepared situations.

B.4.4 Crowd management measures

The basis of most possible measures is based on logical thinking. For example, the separation of different pedestrian streams is very logical if you want people to have a more structured pedestrian flow. This might be achievable through proper routing and signing, as at Sail 2015 problems occurred where this was not done properly.
Clear communication (through e.g. the aforementioned signage but also through verbal messaging) also supports this, as a situation was also brought up with regards to the Malieveld in the Hague where the riot police had to prevent people from using a closed route. Verbal communication has been widely applied to the Dutch GP, where ‘stewards' were placed on lifeguard chairs for visibility and audibility purposes, which was deemed very effective.
Push messages to the mobile phones of crowd members are seen as an option with a high potential and are currently investigated as an option for a project related to the Lowlands festival. In this sense not only push-messages are of relevance, but also pre-sent messages concerning a personal routing strategy can be an interesting option as it allows for steering individual visitors and possibly updating their advised routes in real time if situations change. This does not only concern vehicular traffic but can also be of relevance for pedestrians. What should not be forgotten in this sense is that people should be convinced that making use of such an option has a ‘reward' for them, otherwise people might not use such an option.
A proliferation of tooling is not beneficial for applications such as personalised routing as it confuses an event visitor about what is of relevance and whether it is beneficial or even necessary in the first place. Nonetheless, such digital and dynamic messaging should be seen as an addition to physical and static signing, as you will never reach the entire audience with applications or social media messages and in emergency situations people will not immediately reach for their phones but will initially rely on signage.
Important to keep in mind with all measures, specifically for waiting crowds, is that an action perspective should be provided. Especially when circumstances are different than the crowd expects (e.g., when the outflow-route is different than the inflow-route) people should be informed about what is happening, why it is happening and what is/can be done to mitigate problems.
Three key principles are present for possible measures: informing, steering, and simply accepting. Key in this aspect is to keep the overview of the situation in order to implement the right measures at the right time, and tooling might be able to help with that. Sometimes very simple steering methods, like (re)placing a fence or placing extra LED screens, can already have the desired effects.
Something that might be relevant for future development is a central, national database/platform that can be used for steering crowds during events. There might be issues with regards to privacy and commercial interests, but nonetheless this is likely to significantly help in crowd management as long as it is reliable and widely implementable.
Safeguarding of the data with regards to event safety (e.g., data gathered from an aforementioned central platform for crowd steering) is key in order to learn from past trials with errors

and successes as this can be used for future events. Therefore, it might be relevant for governments, this can be on local or national level, to ask involved parties to supply their data to them as part of the evaluation of an event. Not that data is the only key to optimising crowd flows at events, but the data can also provide insights into the human factor that is also of great relevance.

B.5 Daniël Pardijs

The interview with Daniël Pardijs took place on 4 October 2021 at 10:00 via Microsoft Teams.

B.5.1 Background interviewee

Daniël Pardijs has an educational background in Safety & Security Management (NL: Integrale Veiligheidskunde), and is currently involved in event safety at Mojo, the largest event organizer in the Netherlands. These events range from festivals to stadium concerts to open air concerts. He is part of the permits and security department of Mojo, that is involved in the development of safety and mobility planning. Besides the planning, they are also actively involved in the executing the safety plans, where they are 'safety coordinators': the central contact person for anything safety related for the event.

B.5.2 Crowd monitoring & dashboarding

Crowd management already starts once the initial idea of an event comes up. Starting that very moment, aspects like event venue, target audience, origin of the audience are already up for discussion. The audience aspects are mostly based on historical data from similar events.
The risk analysis is key in the preparations of an event. Every risk is analysed based on experience for its relevance and potential degree of severity. Even aspects like the importance of counting event visitors at specific locations are considered with respect to certain risks, which is different for every event. In this sense there already is a large difference between festivals and concerts. For festivals the arrival pattern can be as long as 12 hours and the departure pattern as long as 7 hours, whereas for a concert people arrive within the 3 hours before an event and everyone departs within 1 hour after the event, while both events can have the same number of visitors. The short departure pattern for concerts leads to a very high pressure on the environment and available resources for crowd management. As festivals are often organised every year at the same location and often attract the same audience as the year before, the preparations are way more about tweaking the spatial situation compared to the years before as the situation is way more predictable than for concerts.
The use and application of dashboards is rising. This has become more relevant as the mobility operations (crowd management outside of the event venue) and the safety operations (crowd management at the event venue) is becoming more integrated as data from both operations are combined to create insights. The best way to integrate the data is by using a central control room where for example parking or public transport data can be combined with ticket scan data to get insights about the inflow. Currently the presentations that show such data have quite some makeshift solutions but are not necessarily coherent and neatly designed dashboards. The current status and challenge are to filter what data is most relevant to create the best insights into the crowd status without having redundancy.
The sharing of data that can serve as input for dashboards between the different involved parties is key in getting the most interesting insights. A good relationship between the data gathering parties (which often are government-related) is therefore necessary. These data-sharing aspects might also lead to discussions about who is responsible for what crowd aspect, which is a key topic of discussion as well.
The monitoring of the atmosphere in the crowd is mostly done based on the 'classical way' by using people in the field that monitor the crowd. Nonetheless, preparations are made beforehand to deal which such aspects based on the crowd characteristics, though these might not necessarily play out the way intended. It is known that camera software can also be used to monitor the crowd for atmosphere related aspects, but this is currently not actively put in practice. This is mainly due to the fact that it is a constant trade-off about whether or not the

implementation of a certain innovation yields the desired insights. Similarly, trials with social media have been carried out and are of interest for future developments.

B.5.3 Scenarios

The basis of scenarios that are mostly taken into account when planning events are bad weather scenario's (for outside events), public disturbances and overcrowding. Nonetheless, also some generally fewer common aspects like thread of terroristic attacks or (as currently relevant) spread of infectious diseases can be incorporated as well. There is a standard list of about 20 risks that are relevant to incorporate with respect to scenarios which are mostly related to the aforementioned subjects. This list is not static, but changes over time with respect to public demand for analyses of specific risks. In general, the various scenarios are established to comply to positive imaging towards and demands from society, to assess financial investments and to identify business risks.

B.5.4 Crowd management measures

With respect to Bijlmer ArenA, the division of responsibilities can be enhanced, which also plays a role in the various scenarios. Mojo is not the venue manager of the ArenA and therefore has less responsibilities there. At the Goffertpark for example, Mojo is the venue manager and therefore has the possibility to have better integration of all crowd management processes. In order to make sure everyone is aware of everyone's capabilities and responsibilities, it would overall be beneficial to see improvement at an inter-organisational level. Besides, while schooling with respect to crowd management is beneficial for the quality of crowd management in general, it is best to have field experience, as only that gives practical insights into the matter.
The application of hard measures at Bijlmer ArenA, such as the barriers that are currently used, might not be completely necessary if more responsibilities are tuned with one another. A relevant point of attention is the crowd waiting in front of the station. In general, the NS does have a great sense of what must be done, but as they make use of public space as buffer space, it becomes more difficult who is responsible for the crowd there. Moreover, mass-psychology starts to have a relevant impact here: how do people behave, how do they feel, how do we give them an action perspective? If a gate to the station is closed, a literal pressure will be exerted on the barrier. Even more relevant is the re-opening of the gate, which will lead to all people wanting to pass through the gate simultaneously. In order to make this manageable, informing the crowd of what is happening is key to make sure incidents do not occur. And for proper informing of the crowd, the collaboration of all involved parties is of utmost importance, even though this is also a difficult aspect in the entire crowd management process.
When looking at exchangeability of measures, it is also key to look at the capacity and various methods of sensors so that those can form a basis for timely identifying certain statuses of the crowd. Accompanying measures can be implemented in a similar way dependent on e.g. a physical environment. A great innovation is the implementation of sensors in the Bijlmer ArenA station, extension of such a system to other stations would be beneficial as often data coming from the NS is often limited. For crowd managers it is important to know what methods (for measurement and measure implementation) are available and in what situation can he/she use those methods for the best application of crowd management.
With ever increasing (societal) interest in sustainability and the fact that e.g. less parking space is available at event venues, an issue that is becoming more and more relevant for Mojo is the steering of event visitors with regards to their choice of travel mode. Currently, few is done with active influencing of people on this topic and only prognoses are made on a passive level. However, active influencing beforehand to steer people to use a specific mode can be relevant to create a better expectation of how people will travel to an event. This in turn will hopefully

lead to less crowd management stress with regards to real-time monitoring and intervening with the crowd, and will lead to a more sustainable way of visiting events.

In general, the ArenA area is top-of-the-league with respect to suitability of events: there is no other location in the Netherlands that is able to cope with 120.000 event visitors that visit using cars, public transport, mopeds and bicycles on a potential daily basis. So, while issues are raised, in general the practice is not entirely bad. Nonetheless, there might still be things that can be optimised.

In crowded situations, the hectic environment is not always pleasant for people in the crowd. Spatial awareness of the crowd is key in crowd management, therefore some simple aspects like tarped fencing versus see-through fencing can already make a difference in the feeling and behaviour of the crowd, dependent on the exact situation. In most cases it is beneficial for the experience of the crowd and therefore for crowd management in general to be transparent about the measures taken so that people are aware of what is happening. People are then more willing to accept that they are part of a (waiting) crowd, as long as they see that there is a plan in action and they have an action perspective themselves.

B.6 Nnuss van der Veer & Rob van Beek

The interview with Nnuss van der Veer and Rob van Beek took place on 4 October 2021 at 15:00 via Microsoft Teams.

B.6.1 Background interviewees

Nnuss van der Veer works for the V&OR (Verkeer & Openbare Ruimte, EN: Traffic and Public Space) department of the municipality of Amsterdam where she is involved with crowd management at events. Moreover, she is involved in 'Regie Zuidoost', which is the municipal department responsible for stimulating and coordinating cooperation between various parties during (road) works in the Amsterdam Zuidoost city district, and the OMC (Operationeel MobiliteitsCentrum, EN: Operational Mobility Centre).

Rob van Beek is involved with traffic management in the municipality of Amsterdam. Currently he is busy with 'spatial advice', i.e., planning (road) works. For the past time he was also the director for event mobility in the Amsterdam Zuidoost. Moreover, he is one of the chairmen of the OMC.

Important to note with their overall background as employees of the municipality is that the municipality is responsible for what happens at the public spaces, not what happens inside of the venues or buildings like stations. Therefore, the notions made and experiences shared in this interview are relevant in the context of public spaces like roads, parks and pedestrian areas.

B.6.2 Crowd monitoring & dashboarding

In the basis, the approach to different types of event visitors is not very different for different events. Nonetheless, they are aware that different types of crowds are attracted at different events. Experienced visitors like Ajax-fans have a very fixed pattern of arrival and departure, while for irregular events this can differ quite substantially. Similarly, Ajax-fans are difficult to steer as they are well aware of the environment and have their own personal habits with regards to mobility, while visitors of other events can be influenced better as they are often less familiar with the environment. Nonetheless most events are approached similarly, except for K-pop concerts, as that audience largely arrives by public transport but gets picked up by car after the concert.

For the municipality, active real-time counting of crowd members is not really of interest. There are no counting sensors placed in the public space around the ArenA. There are some cameras installed, though they are used for safety monitoring rather than visitor counting. This means that there is no active counting of the number of people waiting in front of the barriers as installed by the NS. Nonetheless, it is well-known that the entire ArenA can be empty within 10 minutes after an event ended, potentially even faster, meaning that this is likely to lead to an immediate peak of people wanting to exit the area. It is difficult to spread this peak.

The OMC is not very much involved with the atmosphere of the crowd. Some aspects are discussed, especially based on own experiences during the trip to the ArenA area, but there is no fixed plan on incorporating the atmosphere of the crowd. The only explicit incorporation of 'atmosphere' has to do with high-risk matches where the visiting fans are kept in the stadium longer in order to avoid potential disturbances, though this is not something decided upon by the OMC. What is mentioned however is that emotions and atmosphere of the crowd have not really played a significant role in the difficulties that have been present in the past few years.

Social media are monitored by LiveCrowd to gain insights into the crowd. This has specifically been used by the ZiggoDome to monitor but also to interact with the crowd. This interaction can be at a 1-on-1 level by replying to individual messages, but also on a 1-to-many level by posting relevant information or advice about routes to take. It is a very interesting development that has a lot of potential, but due to costs it is not yet implemented that often.

During EURO 2020, the public spaces were equipped with some sensors, but as the situation was far from crowded due to the COVID-19 restrictions, few conclusions could be draw. Nonetheless, the idea is to implement similar trails again in the future, but how and when this can be implemented is currently still unsure.

B.6.3 Scenarios

Each OMC starts with an analysis of which of a set of about 30 pre-described scenarios is most relevant at that moment. These scenarios mainly concern the steering of vehicular traffic by using DRIPs and similar messaging signs. If specific vehicular crowding is identified which is more suitable for a different scenario, the scenario is changed and the messaging changes accordingly. For the (vehicular) outflow, there are no clear scenarios, but there are traffic light scripts that involve increases of green time and red time and the deployment of traffic controllers to steer the vehicle fleet in such a way that the least moments of conflict are present in the system.

Scenarios with respect to public transport are the responsibility of the public transport providers. It is acknowledged that the NS is ahead of the rest of the OMC members when it comes to crowd management. They have a clear view on data gathering, steward deployment and physical measures.

Special scenarios, and special OMCs, are relevant when there are events at all three venues: the so-called triple A events involves all three event venues besides the 'regular' OMC members. In the case of relevant road works in the area around the ArenA it might be that Rijkswaterstaat joins the OMC.

B.6.4 Crowd management measures

At the ArenA it has been tried to spread out the entry and exit peak by using 5-minute time slots, specifically during EURO 2020. It worked well for the inflow, but people mostly neglected this with regards to the outflow. For the inflow, it is possible to have some 'hard' measures like that people simply cannot enter the venue before their time slot as their ticket will simply not be accepted, but for the outflow that measure is not executable. Nnuss thinks that it might be possible that the outflow out of the stadium will be blocked by police order if there is a worst-case scenario with respect to rioting and fighting at the Boulevard, but as this has never happened it is not known if this would actually be the case. Nonetheless, Rob expects that once an outflow of the stadium has started, it will be very difficult to stop the flow even if you wanted to.

The implementation of a side-event has not been tried at the ArenA, mostly as this is not cost-effective. This would mean that the ArenA must employ its personnel for longer, meaning higher costs for few to no extra income. It has been tried to keep the bars in the stadium open for some extra time, but the effectiveness of that is not specifically analysed.

The barriers that are placed around the Bijlmer ArenA station are not a measure that is solely taken by the NS but is done in cooperation with the other parties involved in the OMC. NS implements the measure rather frequently, as they see that an overcrowding station simply leads to serious safety issues. However, those barriers are not really last-minute solutions, as it can take quite some time to place such obstacles. Also, such infrastructural aspects are also not always available on-demand as while they are deployed rather frequently, it is not that frequently that they can be used at every desired instance.

The Mojo barriers are applied with a reason: they are way more robust than regular crowd barriers. Trials have been held with regular crowd barriers, but the pressure which the large waiting crowd exerts on these barriers is simply too large to provide an efficient physical blocking structure. On the enormous available space that is the ArenA boulevard, a row of crowd barriers will not make a significant contribution to crowd management. Moreover, guiding with physical

elements like barriers is not always the right way to go as they inherently cause bottlenecks. Moreover, obstacles that can literally succumb under the pressure of the crowd might even lead to injuries.
Steering a crowd with music and also lights is only done when there are podia located in public spaces. Police even wants to know what artists are playing at such events, so that they can adapt their strategy based on the expected atmosphere based on the music genre. Also, with regards to outflow of those events, music is used sometimes, but importantly this is not (yet) done at the ArenA Boulevard. This is party due to the fact that the boulevard is very close to the ArenA itself and the fan-zones directly around the ArenA produce sound as well, and the boulevard itself is rather large so music might not be heard by the crowd over their own bustling.
A measure that has been applied at the Wallen, is the deployment of stewards/hosts who initiate a certain walking speed at locations where crowding is likely to occur. Since people are likely to follow behaviour of others, this is a simple but effective measure to make sure the crowd keeps moving in the narrow alleyways.
All in all, crowd management is more than just physical environment lay-out and sensoring. It is also relevant to incorporate behaviour, crowd characteristics, tidiness, feeling of safety and many other aspects. However, as the ArenA area does not have very large crowd management issues, not all of these aspects are incorporated in the crowd management approach there. Nevertheless, the area is open for improvement and innovation, as the residents, the visitors, the event organisers and all other relevant parties simply want to have a pleasant, safe and comfortable environment. Therefore, from a cost-efficiency perspective, it is important to analyse the effect of individual measures through trials before permanent implementations are done. Finally, while data gathering and monitoring is important, it is impossible to have proper crowd management without incorporating the human dimension.

B.7 Sherman Bonofacio

The interview with Sherman Bonofacio took place on 6 October 2021 at 11:00 via Microsoft Teams.

B.7.1 Background interviewee

Sherman Bonofacio has been busy with (crowd) safety for over 30 years. Originally, he has a background in the military. After he left the military, he followed education with regards to Security Management. He is experienced as both a security steward in the field and as a security manager. As a security manager, he has been employed at various different companies, ranging from PostNL to Rotterdam Ahoy. Currently he is working for TSC as a senior consultant with respect to crowd management and safety & security.

B.7.2 Crowd monitoring & dashboarding

Every event has a different event profile and accompanying visitor profile, which is identified in the risk analysis. Based on those profiles the deployment of manpower and resources is decided upon. As an example, for a Britney Spears concert where people will already show up to queue in the days before the concert, a different approach will be taken towards aspects like barrier placement and first aid deployment. Visitors of a Pavarotti concert are completely different, as they will e.g. go to the venue's restaurant first, so that has to be properly prepared for the crowd.
As part of a crowd management plan, 5 stages are defined for preparation purposes. As indicated, every stage has its own challenges:

1. Arrival – planning of how to handle the arrival of visitors with respect to mobility.
2. Inflow – planning on how to deal with the (spread of the) inflow peak of the visitors.
3. Event – planning of how to deal with the crowd during events, e.g. are the visitors seated or standing and what challenges does that bring.
4. Outflow – vice versa of inflow
5. Departure – vice versa of arrival

For crowd monitoring, both monitoring through stewards and sensors is of key relevance. Sensors do not only concern cameras, but also digital aspects like 'tags' can be of use in identifying crowdedness. Such sensors can be of use in monitoring the crowd density. If the density becomes larger than 6 people per square metre, problems are inevitable. Besides density, the overall number of people is of importance to know with respect to emergency exits. As a combination of both, the identification of clusters is important.
Atmosphere is also something that is incorporated into the visitor profile. This would not only concern expected atmosphere as part of a specific event, but also possible emotional statuses. E.g., the emotional experience of a football fan is very different compared to a visitor of the North Sea Jazz festival. It is important to base your style of messaging on the emotional status of your crowd in order to get the desired effects. During an event, 'stand by teams' are present to 'measure' and if needed act accordingly if the atmosphere takes a more negative turn than expected. Social media are also monitored during an event (especially larger festivals) as part of the tasks done by the central control room. In this central control room, parties like first aid, police, traffic management, CCTV operator and crowd management are together to discuss the relevant crowd issues at hand.

B.7.3 Scenarios

During the entire phasing of an event, it is necessary to check whether the crowd behaves as planned and whether adjustments are needed. For the various possible deviations of crowd behaviour, scenarios should be made that allow for quick responses based on the deviations. The scenarios largely serve as scripts for when deviations are noticed during monitoring.
For outside events, a bad weather scenario is always relevant.
For a 'hot-and-happeing' artist, especially when popular among youngsters, a scenario should be prepared that people will come to the event venue possibly even days before the event itself. As illustrated with the aforementioned Britney Spears concert, this leads to making the necessary precautionary measures.
Again, it is stressed that the event and visitors profile are key in determining which scenarios are relevant for an event. All event profiles have their own set of scenarios, independent of location and moment. Of course, it is possible that some are removed or added based on the environment or temporary aspects. With respect to the ArenA area, the statements with regards to event and visitors profile are relevant as well.

B.7.4 Crowd management measures

Overall, it is best to tackle or at least acknowledge all potential issues beforehand. If this for some reason is not doable or is simply not done, it is key to identify potential issues in a timely manner. If there are bottleneck locations, it should have been incorporated in the crowd management plan with accompanying measures to mitigate the possible bottleneck effects as good as possible.
However, if issues still occur at the bottleneck, it is key to inform the crowd about potential detour routes. This informing can be done through either the deployment of stewards (mostly only for indoor locations) or the use of LED screens (main communication form for outdoor locations through text vehicles, but also applicable for screens at indoor locations). The messages displayed at the screens are often pre-programmed.
Social media and push messages are used for communication with event visitors. This might concern messages about issues regarding the event but also with respect to unexpected mobility issues, like an accident on one of the main roads to the venue. An interesting example was the most recent edition of North Sea Jazz, where it was communicated to the crowd that the timetable of tram and metro services were extended.
The effectiveness of social media and push notifications are highly fluctuant. As a broad rule of thumb (specifically for an older visitor profile), it can be stated that 65-70% ignore messages that are sent. Interestingly, older people are more reluctant to follow-up on sent messages, while younger generations are more docile with respect to received messages.

B.8 Daniël van Motman

The interview with Daniël van Motman took place on 7 October 2021 at 9:00 via Microsoft Teams.

B.8.1 Background interviewee

Daniël van Motman works for the V&OR (Verkeer & Openbare Ruimte, EN: Traffic and Public Space) department of the municipality of Amsterdam where he is part of the traffic management group. At first, he was employed at the traffic policy department but later switched to the traffic management group in order to have a more practical touch with the matter. He specialised himself within large events in the urban space, like the inauguration of Willem-Alexander as King of the Netherlands in 2013. After Sail 2015 he was involved in bringing crowd management aspects from the police to the responsibility of the municipality. He has been the director for event mobility in the Amsterdam Zuidoost for multiple years.

The past year has been mostly dedicated to implementing measures to let people keep 1,5 metre distance throughout the city as a result of the COVID-19 pandemic. Through the implementation of counting sensors throughout the city, it has been monitored if specific areas were becoming too crowded. This data is (partially) publicly available in real-time through druktebeeld.amsterdam.nl and moreover weekly and monthly topsheets are created to give overview of crowdedness. In this respect, Daniël is currently involved in creating an overview of the data in order to create data driven insights into crowd management.

B.8.2 Crowd monitoring & dashboarding

Event management is tailored to the target audience of an event, as different events attract different audiences with different preferences with respect to mobility. Key in this approach is also that the inflow/ingress of an event does not necessarily correspond with the outflow/egress. The 'regiestructuur' (EN: management structure) Zuidoost is the collaboration of all involved parties with respect to mobility management during an event in the ArenAPoort area. By having a strategic, tactical, and operational analysis (of which the latter is done by the OMC), it is tried to predict and manage the entire mobility system concerning an event in the most optimal way. The most relevant aspects for real-time measurement are densities and overall counting. It is important to know details of the crowd, not an individual within the crowd. By using threshold values, it is possible to be altered about looming dangers and potentially act based on the exceeded threshold.

People are sometimes guided by the crowd that they are not even aware of alternatives. Therefore, intentional stagnation of the crowd or actively informing the crowd about alternatives can already have a great influence in steering people.

Most crowd professionals work with the DIM-ICE risk analysis established by prof. Keith Still. DIM stands for the three primary influences of crowd behaviour: design, information, and management. ICE stands for three primary phases of crowd behaviour: ingress, circulation, and egress. Using such a risk analysis, an overview is created into the possible statuses of a crowd.

In essence, traffic management does not differ a lot from crowd management. The underlying ideas are often similar: regulating inflow, maximising outflow. However, for crowd management, safety is a way more prominent aspect. From that aspect, the threshold values for taking action for crowd management are relatively lower than for traffic management, as with traffic management the vehicle provides a better degree of safety.

In order to provide proper solutions for specific situation, it might be relevant to look into Fruin's service levels for pedestrian flows in metro stations. This approach uses flow and density details do assign a service level to a situation, which can also be applied to other spatial environments. What however should be noted in this sense is that other environments might need different

threshold values for the various service levels as the activities carried out at a specific location can lead to different dynamics with accompanying service levels.
With respect to atmosphere and the Bijlmer ArenA environment, crowd streams are separated when there is a high-risk Ajax match, in order to make sure there are no conflicts between fans. With respect to other events, the deployment of stewards at the right locations is key. Stewards are key in 'measuring' atmosphere and also have the potential to quickly respond to potential issues.
Social media is not very much incorporated into atmosphere/crowd monitoring at this moment but has a large potential. LiveCrowd, e.g., has the possibilities to actively scan social media with respect to the visitors of an event. In that sense they would be very useful to be involved within an OMC, but due to costs this is not widely implemented. However besides social media, other data like beer consumption might also give an indication about atmosphere of a crowd.
For events, especially football matches, with a "bad" atmosphere, e.g., when Ajax loses an important game, it is often seen that the outflow of visitors happens extremely quickly. People simply want to go home at such a moment and not wait around any longer. Interestingly, riots or fight are not happening very often at such moments.

B.8.3 Scenarios

Scenarios are different for the involved parties. Police often quite 'simply' thinks about placement of fences and other very concrete measures, whereas the OMC uses a network-wide approach to the mobility surrounding an event. This shows the principle that police and other forms of law enforcement are often more involved in crowd control, whereas crowd management as carried out by the 'regiestructuur' and OMC is more focussed informing and advising the crowd.
Currently, operations are carried out with monitoring and scenario identification on a green-orange-red level. Green means everything goes generally well. Orange means that there are some disruptions and crowdedness in the network. Red means that there should be active crowd control, i.e., closure of specific areas or even police deployment. Accompanying plans for when an orange situation occurs are already quite detailed and prepared. This can range from pre-prepared messages on screens or social media, or stewards/hosts that are pre-instructed to act accordingly to a plan. The goal of such scenarios is always to go back to the 'green' situation as quickly as possible.

B.8.4 Crowd management measures

Measures taken in the city centre can be very simple, e.g. implementing one-way traffic, though on-street manpower is important for the actual implementation. Another measure that has been tried during EURO 2020 was to assign people to entry and exit time slots. Unfortunately, due to the COVID-19 measures, a relative low amount of people was allowed to enter the stadium. Therefore, few can be said about the effectiveness. Nonetheless, Daniël strongly believes that such an approach will be efficient to spread out the peak. Moreover, as multiple other stations are located close to Bijlmer ArenA, like Strandvliet metro station and Duivendrecht train and metro station, motivating people to use these stations is likely to have a positive influence on crowding. Especially during Triple As (events at all three venues located at the ArenA Boulevard) the spread of people over the different stations is of importance. Even though it often does not have main crowding issues, inflow of an event is of importance here as well, as people often exit an area through the same way they entered an area.
Three main aspects are key in steering crowds to decrease a peak in the crowd: infrastructure, information and manpower.
Measures should be widened to also incorporate actions taken at the venues, so a more integral approach is applied. However, it is very important that all parties involved in the crowd

management processes are aware of each other's actions so that overview is kept. Moreover, pro-actively steering the crowd in a timely manner is important to make sure that genuine problems do not occur in the first place.
The application of background music has not yet been tried too often. Light as a steering element, so that might also be an interesting aspect. With respect to waiting crowds and application of music as a measures for crowd management, the Efteling is a perfect example of that sounds and music can play a role in managing a crowd.
Push notifications and social media messages are great in informing people, but it should be kept in mind that they simply are advices, people can still behave in another was if they choose to. Such messages are most effective for people who are not familiar with the area. People who are familiar with the area are more reliant on they (historical) experiences with the area. Effectiveness of push messages are also dependent on aspects like the content/formulation of the message and the urgency of the message. You want to give people some action perspective and potentially steer people towards a certain option, but also do not want to create panic among the crowd.
Hosts/stewards also only can give advices to steer a crowd, but they cannot enforce anything. If enforcement is needed to some extent, BOAs (EN: community service officers) are called to help with the situation. If the situation really grows out of hand, police will be the only party able to actually close off a specific area. Most often, it can be predicted in advance where and when extra assistance by BOAs and police is needed based on expertise.
The best approach for measures is an integral approach. While this might not give the effects of the implementation of a single measure, it does incorporate the complexity of the entire situation, which is especially relevant for the ArenA-area. Therefore there should not only be looked at the Bijlmer-ArenA station, but also looked to the venues and the surrounding stations for potential measures.
All in all, simple measures might already do the job, especially for common situations. However, for more complex situation it might be very interesting to look into innovations, research them and potentially carry out a trial with them. Attention should not only be paid to the innovations themselves, but also to the accompanying organisational and governance framework. The practice of OMCs are quite well known at this moment for the ArenAPoort area, but this principle can be translated to other events, both within the Amsterdam and outside of the Amsterdam area. Eventually, this will lead to an integral perspective where cooperation between all involved parties is key.

B.9 Henk Rovers

The interview with Henk Rovers took place on 12 October 2021 at 16:00 via Microsoft Teams.

B.9.1 Background interviewee

Henk Rovers works as a security inspector for NS and has been working for the railways for over 30 years. He is involved in the station and train security and crowd control during events in the greater Amsterdam area. From this perspective he has been involved with the Bijlmer ArenA station, but also with Zandvoort station and the former Almere Strand stop. He is part of the OMC of the ArenA.

B.9.2 Crowd monitoring & dashboarding

In the basis, NS approaches all events similarly. Based on the modal split and expected number of visitors/passengers, an analysis is made concerning train and station capacities. Using these logistical insights, together with historical insights about regular station and train occupancy, it is analysed whether crowd control measures are needed. Besides the logistical aspects, the deployment of stewards is analysed for the overall safety aspect with regards to the visitor profile of the event.

The preparations are already started at least 25 weeks ahead of the event to make sure that everything can be carried out logistically. Also train service disruptions (e.g., for railroad maintenance) need to be scheduled as well, so such aspects can also be incorporated in the preparations.

During the events, the central control room of the NS in Utrecht monitors the crowd through the cameras in the station and of course the Bijlmer ArenA station is also equipped with a large number of sensors. The OMC also has cameras outside of the station to monitor the crowd there.

For the inflow of the event, the atmosphere is often not the problem: people are excited to go to an event, independent of whether it is a concert or a football match. This has to do with the fact during the inflow, people are often only in small groups, so there are few sources for trouble. The train conductor serves as a very useful source of information for the moments when there is an atmosphere-related problem in the trains or at the station during the inflow.

For the outflow, it is already predicted how many people will be part of the (public transport) outflow based on the inflow. This outflow peak often happens within 15 minutes after the conclusion of the event. In order to keep a safe environment, the main attention with regards to monitoring is given to the station hall and the platforms. The most important indicators to steer on are the density and spread of people on the platform and the number of people entering the station. In the case of Bijlmer ArenA , if this number becomes larger than 500 people per minute, it is likely that the entry to the station will be closed for a short time. For Zandvoort and the Dutch Grand Prix the main issue lay with the fact that there was a counterflow of commuters during the outflow of the event, which has quite some impact on the entire system.

Regarding atmosphere monitoring in the crowd, social media is used to monitor the opinions of a waiting crowd, but stewards also play a key role in this, as a change in atmosphere is not necessarily noticeable on camera images. If such a change is noticed, the police are notified to be alerted to possibly take action.

B.9.3 Scenarios

For the ArenA area, there are three main scenarios: a regular Ajax match, a triple (events at all three venues in the ArenA area) and a disruption of train services. For the regular Ajax match, it is quite well known how many people will go to the ArenA by public transport and what direction these people are coming from. For triples, this is often more unclear, as it might be that visitors of the events visit the ArenA area for the first (and possibly only) time, so it is difficult to have a very confident prediction of the exact modal split and visitor flows. With a disruption of the train services, it simply is either the case that only a limited number of trains can ride in a specific direction, or even that no train rides at all.

B.9.4 Crowd management measures

For the regular Ajax match, there are generally some slight logistical (i.e., train service) measures implemented and extra safety personnel deployed in order to keep the situation safe. For triples, more robust measures are taken: (Mojo) barriers are placed at the entrance and more emphasis is put on routing and signage. With a disruption of train services, a wider perspective is needed to e.g. look into cooperation with the GVB and/or have a quite elaborate (re)routing plan.

As often the main plan is to keep the station hall and platforms safe with regards to overcrowding, the gates in the Mojo barriers at Bijlmer ArenA are closed to make sure the number of people at the aforementioned locations does not become too high. Similarly, the overall indicator that was monitored to keep the situation as safe as possible at Zandvoort was the crowd density at the platforms.

If there is an unexpected incident, it is key to inform the crowd as quickly and clearly as possible with a message that provides an action perspective. This can be done through information on the screens at a venue, but also through sending an SMS or using the services of LiveCrowd to send a geo-fenced (social media) message. This has been tried in the past, and about 85% of the visitors received the message.

Especially in the case of unexpected train service disruptions, people are not happy about it in the first place, but by informing them there will be acceptance which creates a larger degree of calmness among both the crowd and the stewards at the station. People will still try to see with their own eyes whether the disruption is real, but when informed beforehand they are more likely to accept new instructions.

In case of a disruption, it is possible to re-route people to Duivendrecht station, as this historically also was the main train station for the ArenA area before the Bijlmer ArenA station was redesigned. Nonetheless, it is important to keep in mind that with respect to the ArenA area, Duivendrecht is more suitable for trains going to Almere and Amersfoort rather than going to Amsterdam Centraal or Amsterdam Zuid, especially station capacity-wise.

With respect to trying to spread people out over time to create a lower peak, there have been some trials to motivate people to do so. However, as there is little to do for visitors once an event is finished, people want to leave the venue immediately. This also has to do with permits, especially in the case of (outside) concerts and festivals, as e.g. keeping the music on longer might infringe with the issued permit. Football fans also will leave once the match is over, as their source of entertainment has ended.

As preparation is key, short-term measures are likely to be more part of crisis management instead of crowd management. In that sense, it is likely that other parties need to be involved as well, as NS is not necessarily prepared to implement crowd control in crisis situations. The police and municipality are also very important here.

With respect to responsibilities, not only in crisis situations but also in regular situations, it might be useful that the municipality invests more in crowd control in the ArenA area, as they are responsible for the public space and issue permits for the events/event venues. The NS is responsible for guaranteeing safety at the stations, and for regular operations the station design should suffice in this. For the passenger flow at events however, it is the case that there can be a ‘hyper peak flow’ and extra measures in the form of barriers are needed to ensure the safety in the station. As in general most of these hyper peak flows occur around events, the best solution in Henk's opinion might be an overall plan, including the crowd management measures around the station, to ensure safety of this flow as part of the overarching mobility plan.

Hard separation of passenger streams through e.g. barriers would be very interesting and useful, though there are some issues with it. First of all, there are some shops in the station hall, and hard separation in the station hall would not be well received by those shops as people will not be able to access the shops that are not part of their queue. Moreover, people who enter the wrong queue will have to switch either while in the queue or in the station hall, which is not very user-friendly if this is blocked by obstacles. Also, in the case of a partial disruption where trains are re-located to another platform than originally planned, separation in the station hall causes problems. Nonetheless, more clear separation in front of the station might already give some more guidance and stream separation.

The application of background music is a nice idea, but its effects might be disputable. People simply want to go home after an event, and while it might be nice that e.g., people recognise the songs of the concert they went to, its effect on crowd behaviour might only be minor.

Measures might be translatable, as basic principles are mostly the same. Though the geographic environment dictates which principles are more prominent than others. Key will always remain to keep the passenger flow safe and stable. It is dependent on the (possible) logistical and crowd management measures what can be implemented and how safe and stable flow can be implemented. Also, the effect that measures have on other people that make use of the station (or simply pass by the station) but have nothing to do with the event is something to take into account.

All in all, the use of new technologies is interesting for crowd management. Accompanying this is the fact that making better predictions leads to better tuned measures to the actual situation.

B.10 Maurits van Hövell

The interview with Maurits van Hövell took place on 21 October 2021 at 15:30 via Microsoft Teams.

B.10.1 Background interviewee

Maurits van Hövell is the mobility and environment manager of the Johan Cruijff ArenA where he is involved with the accessibility of the stadium and public affairs regarding parties outside of the stadium, e.g. the public transport agencies and the municipality. With this background, he was involved in the development of various tools with regards to mobility aspects of the ArenA. Important to know with regards to crowd management in the ArenA, is the fact that the ArenA itself only facilitates an event. They are not necessarily involved in the direct visitor-contact, which is most often part of the tasks of the organiser of the event.

B.10.2 Crowd monitoring & dashboarding

Preparations for events start way before the event itself takes place, especially with regards to mobility. In principle all events are different. There are even differences between Eredivisie and European matches of Ajax. Important aspects that are incorporated here are the number of event visitors, the visitor profile, and the modal split.
For the preparations, there are different levels of consultation, which are structured based on strategic, tactical, and operational aspects. The strategic and tactical levels meet once every four weeks, operational meets every single week. The operational meetings evaluate the operations of the past week and looks ahead to event(s) in the coming week in order to be prepared for short term changes with regards to the mobility environment. For special events (mainly non-Ajax matches) preparations on the strategic and tactical level start four to eight weeks before the event itself.
During the inflow of an event, real time insights are available concerning the number of tickets scanned. Based on that data they can determine how many people are inside the stadium and how many they are still expecting to enter the stadium. For the outflow, such insights are not available since the gates are simply opened to let the people leave.
Within the stadium there is a wifi-network which can be used to actively scan for people's phones with their wifi turned on. This can give good indications about the degree of occupancy of the stadium but is not yet used extensively for monitoring. Moreover, there are of course cameras spread around the stadium, but these do not necessarily have the qualities to also be applied as counting sensors.
The 'atmosphere' is 'monitored' through a central logging system. This system is especially used for (negative) incidents such as fights. Social media is not necessarily monitored by the ArenA, but most often incorporated through the event organiser. Based on the event and potential incidents, the people involved with social media monitoring join the OMC to provide input. Transactions and insights into the (beer) consumption can be monitored in real time but are not necessarily inputs for atmosphere monitoring. The crowd monitoring system of the municipality that is present on the Boulevard is also important is crowd monitoring both with regards to flow and atmosphere monitoring.

B.10.3 Scenarios

There is a difference between concerts and football matches. Visitors of football matches are often reoccurring visitors who are first of all (more or less) familiar with the environment. After the match is over, they quite quickly leave the stadium within about 20 minutes. Away supporters are sometimes held longer in the stadium to avoid conflicts with the home supporters, and/or

are given ‘private’ metros from the Strandvliet metro station to avoid interaction between the two groups.
During concerts there are more walking routes throughout the stadium, as besides the grandstands the field is also used as a ‘stand’ for visitors. These routes might conflict with each other in a different way than during football matches, but this is of less relevance to the environment outside of the stadium. Besides this aspect, the capacity during concerts is as high as 70.000, which does have implications outside the stadium as well.
With regards to the division of people over the various entrances, the following inflow details are of relevance with respect to a football match:

Table B.1: Representative indication of the number of people using the various entrances of the Johan Cruijff ArenA for a footbal match.

Entrance	Visitors
A+B+C	19,500
D	1,000
E	5,000
F	1,100
G	6,500
H	5,200
J	6,400
K	2,100
M	8,000

B.10.4 Crowd management measures

Different trials have been held with regards to spreading the outflow of visitors. These trials include organising a quiz within the stadium but not on the grandstands. Moreover, the placement of a DJ on a similar location has been tried in combination with a longer opening the catering booths (which has also been tried as an individual measure). The pubs in the direct environment of the stadium are often jam packed with visitors after an event, so it is up for discussion concerning whether there are enough pub-like facilities present in the area. The social safety can be enhanced to create a more hospitable atmosphere to stay longer as currently the direct environment of the stadium and station has relatively bad lighting conditions and not a very welcoming lay-out to remain in the area some time longer. Also, the fact that the public transport services end relatively early does not help in encouraging people to remain in the ArenA area after an event. This is especially relevant since sustainable transport is becoming an ever more relevant issue for the municipalities and visitors, which means capacity should be increased in the first place.
The spreading of outflow peaks using time slots for inflow and outflow has also seen interest, specifically during EURO2020. During the inflow of matches this showed some successes, but due to COVID-19 measures, there was a very limited capacity of the entire stadium. It is deemed almost impossible to apply such an idea for when the entire stadium is filled with 55.000 visitors, especially during the outflow. It would likely result in safety issues and issues with regard to deployment of personnel. For a regular Ajax match, the entire stadium is empty in about 20 minutes, so very attractive entertainment or similar side-events are needed in order to convince people to stay within the stadium for longer to decrease the peak pressure on the mobility system. Accompanying this aspect is that consumptions are not the cheapest in the ArenA and most people do not consider a concrete structure like the stadium as an attractive atmosphere for staying longer, making people want to leave sooner rather than later.
The implementation of the barriers at the station as is currently done has its price tag, which

possibly can also be used for a type of entertainment within the stadium. This in turn can be a win-win situation as people staying longer is also likely to mean more income which can be used for the payment for more attractive entertainment.
Providing the crowd with useful information about their (mobility) perspectives is something deemed very useful. Presenting the right message is important in this, but it always remains disputable how large the effect of such information provision is on the entire outflow. This in turn is also dependent on the timing of the event: especially later during the evening, people simply want to go home.
The application of background music during outflow has not been analysed but can be interesting. U-Smile, a collaboration between, amongst others, VU of Amsterdam and TU Delft that goes into developing, testing and evaluating smart measures to affect (travel) behaviour. They did some research about keeping the visitors in the ArenA area for a longer time after an event.
Actively encouraging people to make use of the other stations around the ArenA is something that has been done during EURO2020 and this can be done structurally. This does not only concern the Strandvliet metro station but also the Duivendrecht station that has a proper walking route to the stadium. Currently few active encouragements are done in this sense. Also, since station Bijlmer ArenA has the name ArenA in it, most people, specifically people that do not visit the venue regularly, are more likely to make use of the Bijlmer ArenA station.
On a political and organisational level there is a lot to gain with regards to crowd management. Not in the management aspect itself, but for example the lay-out and redesigning of the station is something that has to be brought up politically. Therefore, local politics should be aware of the crowd management issues in the first place.
The barrier solution used by the NS is a proper solution to ensure safety in the current situation/environment, though not ideal on all aspects. More attention towards a timetable that continues later into the night is something that can be very valuable as well, as that already gives room for people to stay longer in the first place, especially since Ajax and the events in the ArenA attract visitors from all over the country. This might also be a political aspect since the encouragement of sustainable transport is something related to political influences.
The exchange of (public transport) data is something which can be of great relevance as well. Not only between the crowd managing parties, but also towards the crowd itself. An example with regards to information provision to the crowd could be a traffic light that indicates whether it is busy at the station when people leave the stadium. This can encourage people to stay a little longer, buy another drink or some food or go to a different station. It should be noted however that Ajax supporters are difficult to influence as they have their own habits with regards to visiting an Ajax match. This means that in order to influence them, a clear incentive should be given to them to let them change their behaviour in the first place.

C MODEL SET-UP DETAILS

This appendix presents the details of the model set up as is referred to in Section 3.3.

C.1 Available data

Counting data during 21 (non-)event dates are made available by Dutch Railways for this research. An overview of these dates is available in Table C.1.

Table C.1: Overview of the dates of which the Dutch Railways has shared pedestrian count data and the events organised at the various venues at these dates and their respective starting times.

Date	**Johan Cruijff ArenA**		**Ziggodome**		**AFAS Live**	
	Event	Start time	Event	Start time	Event	Start time
08-05-2019	Ajax - Tottenham	21:00	-		-	
16-05-2019	-		Gods of Rap	19:15	Anne-Marie	20:00
23-05-2019	-		Backstreet Boys	20:00	-	
31-05-2019	De Toppers	20:00	-		-	
09-06-2019	-		-		Eddy Vedder	19:30
11-06-2019	Metallica	21:00	-		The Smashing Pumpkins	20:00
16-06-2019	P!nk	20:00	-		-	
03-09-2019	-		-		Blue Man Group	20:00
06-09-2019	-		-		Blue Man Group	20:00
13-08-2019	Ajax - PAOK	20:30	-		-	
10-09-2019	*no events*					
17-09-2019	Ajax - Lille	21:00	-		-	
24-09-2019	*no events*					
25-09-2019	Ajax - Fortuna Sittard	20:45	Little Mix	20:30		
13-10-2019	-		-		UB 40	20:00
25-10-2019	-		Krezip	20:00	-	
19-11-2019	Netherlands - Estonia	20:45	Volbeat	21:00	Vampire Weekend	20:00
06-12-2019	Ajax - Willem II	20:15	Kensington	21:00	We will rock you	20:00
07-12-2019	-		Kensington	21:00	-	
10-12-2019	Ajax - Valencia	21:00	Viewing party Ajax - Valencia	20:00	Alter Bridge	19:00
27-02-2020	Ajax - Getafe	21:00	-		Bear’s Den	20:00

C.2 Model inputs

In order to have a functioning dynamic model, proper data concerning pedestrians and trains should be put into the model. There are two ”ways” pedestrians can enter the model: as a pedestrian exiting one of the locations on the Boulevard as presented in Figure 5.2 or as a passenger alighting from one of the trains arriving at the Bijlmer ArenA station.

C.2.1 Pedestrian inputs at Boulevard

With respect to the pedestrians coming from the Boulevard, two model inputs are relevant: pedestrian demand coming from the various O/D locations and spread of the generated pedestrians over the various platforms.

Pedestrian demand at Boulevard

In order to estimate the passenger generation at the O/D locations at the Boulevard, the summed inflow counts at the station entrances are used. These counts are analysed per event-type, i.e. per event at a single event venue, in order to make predictions about effects of isolated events at the various. First, has been looked at the flow of passengers during the days visible in Table C.1 where no event is organised. This gives an indication concerning flows at the station during normal operations. This results in a mean, non-event flow as visible in Figure C.1.

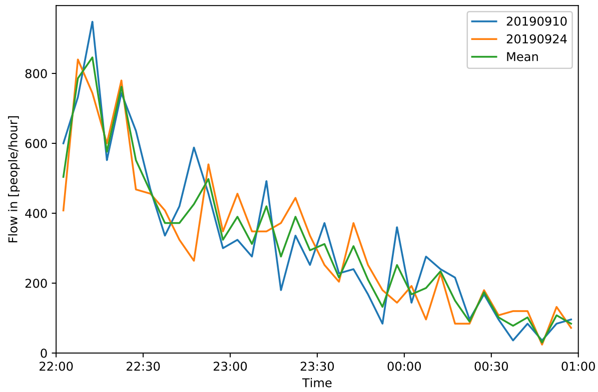
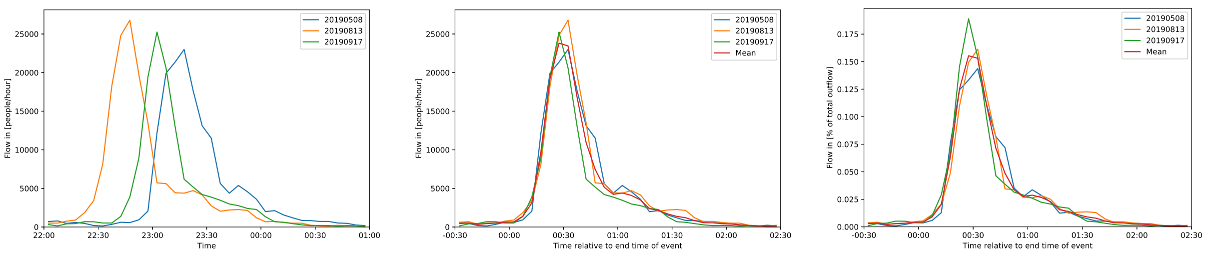


Figure C.1: Historical station inflow profiles and mean for two Tuesdays at the Bijlmer ArenA station.

Subsequently, it is possible to determine the demand that is *added* as a result of an event at a specific venue. The procedure described below is similar for all event situations (including non-event), however only specific details are presented with regards to an Ajax-match in the Johan Cruijff ArenA.
As a first step, the pedestrian flows of an Ajax match are subtracted by the mean regular flow of Figure C.1. In that way, the effect of pedestrian flows of an Ajax-match can be analysed in an isolated way. The resulting profiles are visible in Figure C.2(a).
Secondly, events do not end at the same moment. This can be due to different starting times of the matches, but also to aspects like additional and overtime. Therefore, the flow data is moved such that the end time of the matches is aligned based on the real-time match reporting done by Ajax on Twitter [AFC Ajax, 2021]. For concerts and other events, such detailed timing data is not available, but this is approximated by end times of Facebook events of the concerts [AFAS Live, 2021, Johan Cruijff ArenA, 2021, Ziggo Dome, 2021] and subsequent visual altering to line up the curves. The resulting profiles for the Ajax matches are visible in Figure C.2(b).
Finally, the flow curves are normalised based on the total number of people that are part of the curve. This is done in order to make sure the total number of visitors and the exact modal split of the matches is removed from the analysis. This has the positive effect that, with regards to predicting the flow curve, the normalised curved can be scaled to the expected or measured number of public transport users. The resulting profiles are visible in Figure C.2(c).



(a) Inflow profiles when non-event flows are subtracted.

(b) Inflow profiles when non-event flows are subtracted and event end times are aligned.

(c) Normalised inflow when non-event flows are subtracted and event end times are aligned.

Figure C.2: Inflow profiles of the Bijlmer ArenA station after various Ajax matches.

The normalised curves of the various event-types can be used to recreate the pedestrian flows for a triple. Based on the total number of public transport users, dividing them over the various venues based on the venue capacities and end times of events, it is possible to create the flow curve for regular triple date 06-12-2019 as visible in Figure C.3. Details with regards to the Goodness of Fit (GoF) of this curve are presented in Table C.2. In this table, the following notation is used:

- x_i and y_i are the modelled and observed measurements, respectively;
- N is the number of measurements;
- $\overline{x}$ and $\overline{y}$ are the sample averages of the modelled and observed measurements, respectively, and
- σ_x and σ_y are the sample standard deviation of the modelled and observed measurements, respectively.

Table C.2: Goodness of Fit (GoF) indicators for the fit of Figure C.3 [Antoniou et al., 2014].

GoF indicator	Equation	Outcome
RMSNE	$\sqrt{\frac{1}{N} * \sum_{i=1}^{N} \left(\frac{x_i - y_i}{y_i}\right)^2}$	0.22
GEH	$\sqrt{2 * \frac{(x_i - y_i)^2}{x_i + y_i}}$	14 of 36 are < 5
MNE	$\frac{1}{N} * \sum_{i=1}^{N} \frac{x_i - y_i}{y_i}$	0.01
r-value	$\frac{1}{N-1} * \sum_{i=1}^{N} \frac{(x_i - \overline{x})(y_i - \overline{y})}{\sigma_x * \sigma_y}$	0.98

What can be observed from Table C.2 is that whereas the correlation between modelled and observed flows is high (i.e., r-value ≈ 1) and the total number of people that are part of the flow is almost equal to the observed number of people (i.e., MNE ≈ 0), there are still some deviations as can be deducted from the RMSNE (RMSNE $>> 0$) and GEH-statistic ($< 75\%$ of measurements has a value < 5). Nonetheless, when analysing Figure C.3 visually, it can be seen that the most important aspects with regards to the peak flow, i.e. the modelled peak value and peak duration, seem to be in accordance with the observed values. Moreover, only a limited number of data is available concerning isolated event flows, as for each of the event types (also the no-event type) only a limited number of dates is used for establishing the curves. Therefore, the modelled flow curve is deemed good enough to serve as input for the model.
An important final aspect regarding the pedestrian demand is that the demand should be assigned to the various O/D locations on the Boulevard. The non-event flows will be coming from origins where there either are employment opportunities or where there is housing. Therefore,

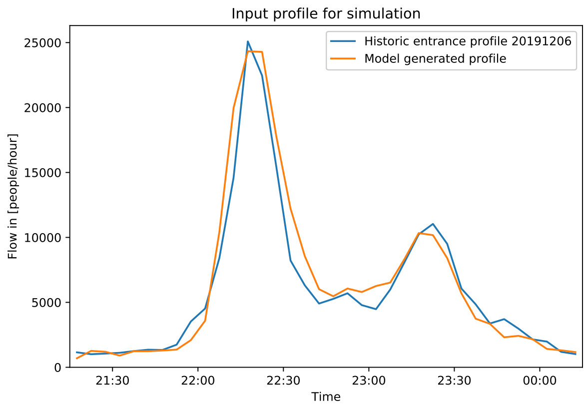


Figure C.3: Comparison of a historic triple station inflow and model generated station inflow based on the events of the same date.

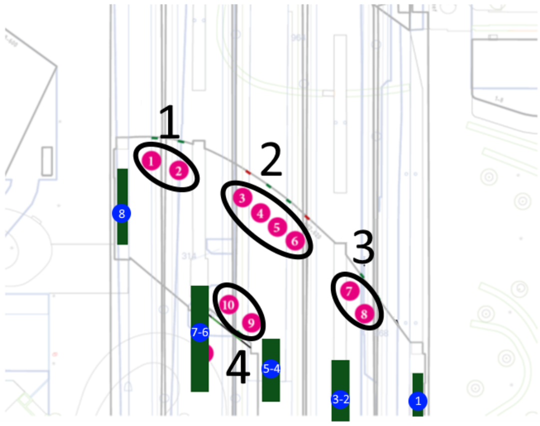
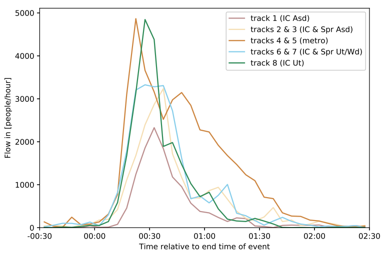


Figure C.4: Overview of the defined entrance sections of the Bijlmer ArenA station.

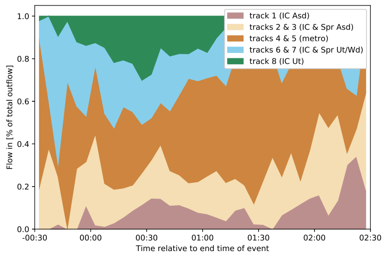
the non-event flows are divided over two O/D locations that visible in Figure 5.2 that encompass such aspects: ”Ziggodome + E,F” and ”Bijlmer”. Moreover, the ”Bus” O/D location is also added as there will be people alighting from the various buses and changing to a train or metro.
The division of what part of the demand originates from which O/D location is based upon the flows per entrance section. Four entrance sections are identified, as visualised in Figure C.4. It is assumed that people entering through entrance section 1 come from the ”Ziggodome + E,F” O/D location, as it is located close to the ArenA Villa mall and in the general direction of various office buildings. Moreover it is assumed that people entering through entrance sections 2 and 3 come from the ”Bijlmer” O/D location as these sections are the most logical entrances to take when approaching the station from the direction of the Bijlmer. Finally, it is assumed that people entering through entrance section 4 come from the bus station as that is the only logical source of pedestrians on that side of the station within the scope of the research.
For the demand generated by the event venues, the isolated extra demand is assigned to the O/D location of the respective venue. Since the ArenA has three O/D locations, the ArenA demand is split up over these locations based on the share of visitor inflows of events as visible in Table B.1. This assumption is made as often people chose the same route out of an (event) venue as the route through which they entered.

Spread of pedestrians over platforms

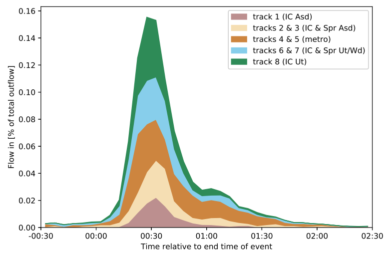
In order to estimate the passenger division over the various platforms, the platform inflow counts are used. Again, for each individual event-type, the division over the various platforms can be determined based on looking at platform entries during various isolated events. Again, the subsequent described procedure is similar for all event situations (including non-event), however only specific details are presented with regards to an Ajax-match in the Johan Cruijff ArenA.
It can be determined how many passengers enter a specific platform during a specific time interval using the counting sensors at the check-in gates of the platform (see Figure 5.4(a)). This inflow per platform is visualised for the averaged Ajax-match data in Figure C.5(a). These flows can in turn be expressed as a share of the total platform inflows during a specific time interval, as is visualised in Figure C.5(b). Finally, these shares can be applied to the total demand to provide insights into the total demand of pedestrians going to a specific platform. This is visualised in Figure C.5(c).
As these division of demand over the various platforms can be made for each event situation separately, the divisions can be specifically targeted towards pedestrian classes that are based on the demand of a specific event.



(a) Mean inflow of the various platforms.



(b) Relative shares of the flows towards various platforms.



(c) Relative shares of the flows towards various platforms applied to the mean demand curve as visible in Figure C.2(c).

Figure C.5: Details with regards to the platform inflows at the Bijlmer ArenA station after Ajax matches.

C.2.2 Pedestrian inputs as alightings from trains

With respect to pedestrians that alight from trains, three model inputs are relevant: the timetable for trains, number of alightings from each train and destinations of alighting passengers.

Timetable for trains

To construct a timetable of trains and metros that stop at the Bijlmer ArenA station around events, there first has been looked at the regular timetable for the station. The timetable data is accessible via Treinposities.nl [2021].
The regular timetable is however also extended during events by letting trains stop that usually pass through the station without stopping or even with trains that are deployed especially for the events. In order to create a suitable timetable for the model, the extra trains that stop at the Bijlmer ArenA station are analysed for their reoccurring presence during the various triple event dates for the triple dates as visible in Table C.1. The extra trains reoccurring at different event dates are added to the timetable for the model besides the trains that are part of the regular time table.
Finally there are the incidental extra trains. These are often based on the end times of events and are therefore not necessarily reoccurring at other event dates. These trains are added to the timetable of the model based on the end time of a modelled event and the timetable at a historical event date of an event that ended at a similar moment.

Alighting passengers

The number of alighting passengers is determined based on the platform outflow. Since the flows are aggregated over five minutes, an arriving train should also be assigned to a five-minute time slot. Subsequently, it can be assumed that the entire platform outflow from that interval on to the next interval where a train arrives can be seen as passengers alighting the first-mentioned train. Figure C.6 shows the mean outflow of the platform of track 1 during Ajax-matches and a timetable used during an Ajax match.
It is of course possible that multiple trains arrive at a platform during the same five-minute interval. If that is the case, the total flow that would be assigned to the first train arriving during the interval is spread equally over all the trains that arrive during the interval.

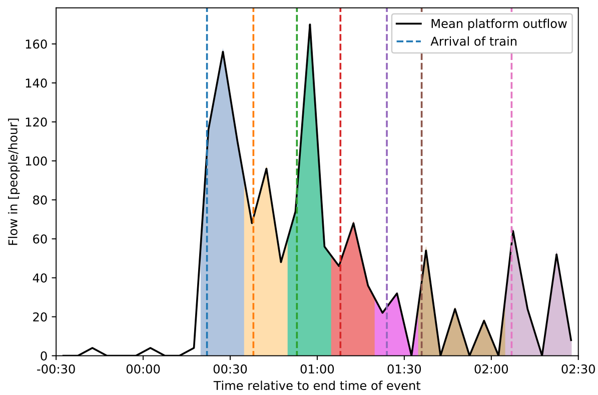
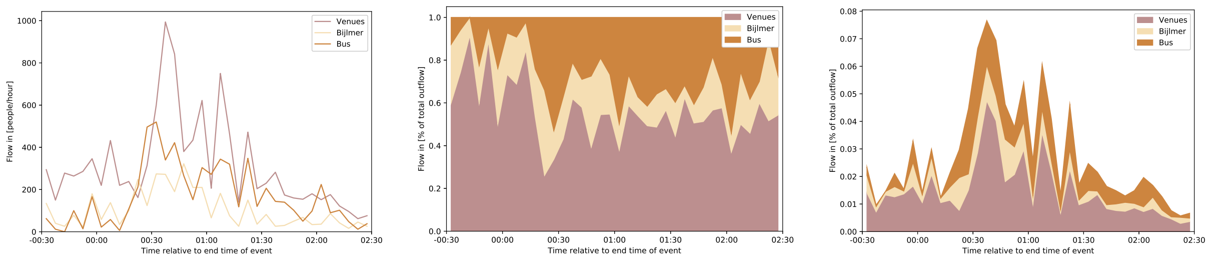


Figure C.6: Average outflow profile of the platform of track 1 after an Ajax match. Coloured areas indicate the catchment of pedestrians alighting the train of the similar colour. Because of assignment of trains to 5-minute intervals, these catchment can start before arrival of a train.

Spread of alighting passengers over Boulevard destinations

While the number of alighting passengers might only be minor, it is nevertheless important to also assign them a logical destination, since their destination choice might influence the flows in the station hall and therefore potential crowding issues. It is assumed that people exiting through entrance sections 1 and 2 (see Figure C.4) have a destination at one of the event venues, people exiting through entrance section 3 have the Bijlmer as their destination and people exiting through entrance section 4 have the bus station as their destination. The people having a destination at one of the event venues are further split up with regards to the different O/D locations of the venues based on the relative share of the people *originating* at the various O/D locations.



(a) Mean outflow towards the various destinations outside the station.

(b) Relative shares of the flows towards destinations outside the station.

(c) Relative shares of the flows towards various destinations outside of the station applied to the outflow profile.

Figure C.7: Details with regards to the station outflow at the Bijlmer ArenA station after Ajax matches.

C.3 Run time, warm-up period and replications

In order to have statistically relevant outcomes from the model, it is important to analyse aspects like model run time, model warm-up and the needed number of replications.

C.3.1 Simulation run time

For the simulation run time it is important to look at the shapes of the flow curves. As a guiding example, the flow curve of Figure C.3 shows that the peak starts to grow at about 21:45. The curve peaks at about 22:15, declines up to about 23:00, grows up to 23:15 and goes back to a relatively steady state after 23:45. Therefore, it would be most interesting to look at the period between 21:45 and 23:45. This means that the model has a simulation run time of 2 hours.

C.3.2 Warm-up period

As the model will describe a peak flow situation rather than a steady state flow situation, a warm-up period is not necessarily needed to create a steady state. Nonetheless, it remains relevant to make sure the model is not entirely empty for when the data collection starts, as flows that are present before the peak starts can possibly influence the peak flows. Moreover, the routing (which will be further elaborated upon with regards to the calibration in Appendix C.4) also needs time to establish its parameters based on travel time of pedestrians that finished their routes, meaning that some initial pedestrians are needed in the model before the data collection starts. Therefore, based on visual analysis of the model, it is selected that a warm-up time of 30 minutes is used, as after 30 minutes the routing is set up and a realistic number of pedestrians is part of the model.

C.3.3 Number of replications

To make sure the outcomes are of statistical relevance, multiple replications with different random seeds are needed for the simulation. This can be based on analysing a maximum allowed relative error of a Key Performance Indicator (KPI) using a confidence interval. First, the method for determining the number of replications is described. Subsequently, the results of when the method is applied to the model that is part of the research are presented. Since for the calibration and the analysis of measures different KPIs are used, a different number of replications is needed for the different situations.

Method

The number of replications can be based on analysing a maximum allowed relative error of a KPI using a confidence interval. The relative error is the relative difference between the true mean value of a KPI and the observed mean value of the KPI, as described by Law [2015]:

$$\gamma = \frac{|\bar{X} - \mu|}{\mu} \tag{C.1}$$

Where:

- γ is the relative error;
- $\bar{X}$ is the observed mean value, and
- μ is the true mean value.

Since the value of μ is unknown, the relative error has to be estimated. The actual relative error is at most [Law, 2015]:

$$\gamma = \frac{\gamma'}{1 - \gamma'} \tag{C.2}$$

Where:

- γ is the maximum relative error, and
- γ' is the corrected target value of the relative error.

Re-writing this equation yields an equation which can be used in the confidence interval to determine the number of replications, since γ' is the corrected target value of the relative error [Mes, 2019]:

$$\gamma' = \frac{\gamma}{1+\gamma} \tag{C.3}$$

Where:

- γ' is the corrected target value of the relative error, and
- γ is the desired maximum relative error.

Using the aforementioned confidence interval method, the following equation is analysed [Mes, 2019]:

$$n^* = \min_n \left(\frac{t_{i-1,1-\frac{\alpha}{2}} * \sqrt{S_i^2/i}}{|\bar{X}_i|} \leq \frac{\gamma}{1+\gamma} \right) \tag{C.4}$$

Where:

- n^* is the determined number of replications;
- t is the t-value based on i replications and confidence level α;
- S_i^2 is the variance at the current analysed number of replications;
- $\bar{X}_i$ is the mean at the current analysed number of replications, and
- γ is the maximum desired relative error.

This procedure can be analysed for each time interval, as each interval has a respective outcome, i.e. $\bar{X}_i$ value.

Results

The method for determining the number of replications is used twice:

- Once for determining the number of replications with regards to the calibration KPI, and
- Once for determining the number of replications with regards to the experiment KPIs.

Replications for calibration

The KPI selected determining the number of replications during the calibration is the normalised share of station inflow per entrance section. In other words, the station inflow for each 5 minute interval per entrance section as indicated in Figure C.4 can be normalised based on the entire station inflow after an event. The model that is used for calibration is initially run with 30 different random seeds. Subsequently, Figure is created based on the method described above.
What becomes visible when analysing Figure C.4 is that for door section 1 a clear majority of the time intervals are able to generate a 95% confidence interval with a maximum error of $\gamma = 5\%$ within 30 replications. For other door sections, however, more than 30 replications are needed to achieve a maximum error of $\gamma = 5\%$. Nonetheless, for door sections 2 and 3, a 95%

Time period	Door section 1			Door section 2			Door section 3			Door section 4		
Gamma value:	20%	10%	5%	20%	10%	5%	20%	10%	5%	20%	10%	5%
22:30-22:35	7	15	nan	nan	nan	nan	3	21	nan	21	nan	nan
22:35-22:40	9	21	nan	21	nan	nan	13	30	nan	25	nan	nan
22:40-22:45	3	10	23	nan	nan	nan	25	nan	nan	23	nan	nan
22:45-22:50	4	5	8	20	nan	nan	10	28	nan	nan	nan	nan
22:50-22:55	3	5	10	11	22	nan	23	nan	nan	26	nan	nan
22:55-23:00	4	4	4	4	13	28	13	nan	nan	23	nan	nan
23:00-23:05	2	3	3	4	9	24	8	nan	nan	23	nan	nan
23:05-23:10	3	3	3	5	9	23	17	nan	nan	10	30	nan
23:10-23:15	4	5	11	4	8	24	12	25	nan	13	nan	nan
23:15-23:20	8	13	27	8	16	nan	8	20	nan	15	nan	nan
23:20-23:25	6	10	28	2	8	20	7	18	nan	15	nan	nan
23:25-23:30	5	9	22	4	12	26	6	15	nan	20	nan	nan
23:30-23:35	3	6	20	4	6	20	8	26	nan	11	nan	nan
23L35-23:40	6	11	28	6	11	30	15	28	nan	20	nan	nan
23:40-23:45	7	12	nan	8	18	nan	7	14	nan	9	nan	nan
23:45-23:50	9	20	nan	10	26	nan	11	23	nan	7	nan	nan
23:50-23:55	10	20	nan	14	nan	nan	13	28	nan	25	nan	nan
23:55-00:00	7	13	27	19	nan	nan	14	nan	nan	13	nan	nan
00:00-00:05	4	6	11	6	10	27	15	nan	nan	14	nan	nan
00:05-00:10	2	6	12	5	9	20	13	28	nan	15	nan	nan
00:10-00:15	3	3	10	5	10	27	8	15	nan	24	nan	nan
00:15-00:20	2	6	15	3	6	16	6	13	nan	20	nan	nan
00:20-00:25	2	6	8	6	10	19	8	23	nan	13	nan	nan
00:25-00:30	3	4	13	6	11	26	8	17	nan	12	nan	nan

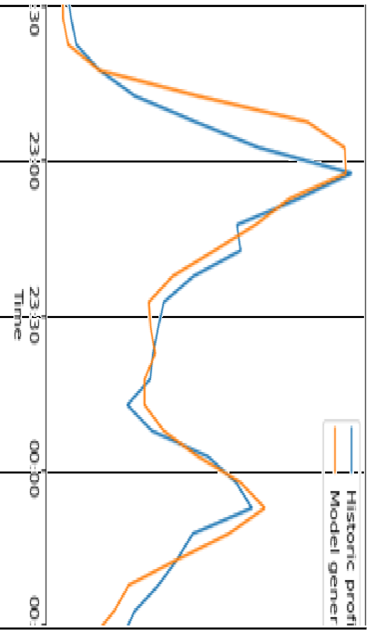


Figure C.8: Needed number of replications to achieve a 95% confidence interval with a size based on various γ values for the different door sections with regards to number of pedestrians entering the station through the respective door sections for the calibration. In case that 'nan' is stated in the table it means that more than 30 replications are needed to achieve the respective 95% confidence interval.

confidence interval with a maximum error of $\gamma = 10\%$ seems achievable within 30 replications for a majority of the time intervals. This means that a larger spread of output data is allowed while keeping the same statistical confidence.
Based on these observations, it is decided to let the model run 30 times. This is acceptable to do, as in order to decrease the size of the confidence interval further, a significant increase in the number of runs is needed in order to reduce the values of $t_{i-1,1-\frac{\alpha}{2}}$ and variance S_i^2. Given the actual run time of the model, it is not deemed desirable to keep increasing the number of replications beyond 30.

Replications for experiments
The KPIs selected for the experiments are elaborated upon in Section 5.2.7. These are:

- Crowd density before check-in gates;
- Crowd density on platforms;
- Station inflow;
- Travel time to the platforms, and
- Crowd density at buffer sections.

Each KPI is analysed for the no-measure situation in the regular triple scenario to determine the number of needed replications. Ideally, one would determine a number of replications for each individual experiment as the modelled experiments differ quite substantially. However, given the limited available time of research, it is decided to base the number of replications on the no-measure situation in the regular triple scenario. Similarly to the situation for the calibration,

Time period	Buffer section 1			Buffer section 2			Buffer section 3		
Gamma value:	20%	10%	5%	20%	10%	5%	20%	10%	5%
22:30-22:35	6	16	nan	6	16	nan	23	nan	nan
22:35-22:40	11	21	nan	11	21	nan	nan	nan	nan
22:40-22:45	11	21	nan	2	4	17	8	21	nan
22:45-22:50	2	4	17	2	2	3	8	17	nan
22:50-22:55	2	4	17	2	3	3	5	8	30
22:55-23:00	2	2	3	6	9	16	4	7	18
23:00-23:05	2	2	3	4	7	16	5	9	nan
23:05-23:10	2	3	3	3	7	19	4	18	nan
23:10-23:15	2	3	3	6	11	nan	10	nan	nan
23:15-23:20	6	9	16	10	23	nan	17	nan	nan
23:20-23:25	6	9	16	5	15	nan	15	nan	nan
23:25-23:30	4	7	16	5	8	25	14	30	nan
23:30-23:35	4	7	16	4	6	12	9	15	nan
23L35-23:40	3	7	19	3	4	18	8	17	nan
23:40-23:45	3	7	19	2	2	3	5	11	nan
23:45-23:50	6	11	nan	4	5	10	3	13	30
23:50-23:55	6	11	nan	2	2	2	3	3	nan
23:55-00:00	10	23	nan	2	2	5	5	12	nan
00:00-00:05	10	23	nan	2	2	2	2	2	nan
00:05-00:10	5	15	nan	5	7	19	5	10	nan
00:10-00:15	5	15	nan	6	10	22	3	4	23
00:15-00:20	5	8	25	2	2	2	5	15	nan
00:20-00:25	5	8	25	5	8	25	9	20	nan
00:25-00:30	4	6	12	6	10	19	3	15	nan

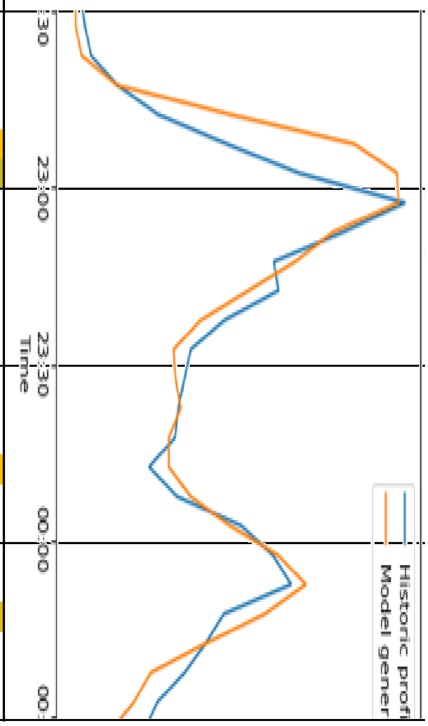


Figure C.9: Needed number of replications to achieve a 95% confidence interval with regards to *the density in the buffer sections*.

Time period	Door section 1			Door section 2			Door section 3		
Gamma value:	20%	10%	5%	20%	10%	5%	20%	10%	5%
22:30-22:35	2	2	2	17	nan	nan	11	22	nan
22:35-22:40	3	3	21	7	nan	nan	4	11	28
22:40-22:45	3	3	21	3	21	nan	2	2	2
22:45-22:50	4	6	9	5	10	25	4	6	nan
22:50-22:55	4	6	9	4	6	13	8	16	nan
22:55-23:00	3	3	4	4	5	12	8	14	nan
23:00-23:05	3	3	4	5	8	24	5	11	23
23:05-23:10	3	3	4	5	11	27	9	16	nan
23:10-23:15	3	3	4	7	19	nan	7	14	nan
23:15-23:20	2	4	5	11	29	nan	4	25	nan
23:20-23:25	2	4	5	13	nan	nan	10	25	nan
23:25-23:30	3	3	4	7	16	nan	4	6	nan
23:30-23:35	3	3	4	7	12	nan	3	4	nan
23L35-23:40	3	3	3	4	5	nan	2	2	2
23:40-23:45	3	3	3	3	3	nan	11	27	nan
23:45-23:50	3	6	10	4	6	30	6	13	nan
23:50-23:55	3	6	10	3	3	3	5	16	nan
23:55-00:00	5	10	26	5	7	22	9	25	nan
00:00-00:05	5	10	26	2	11	22	11	24	nan
00:05-00:10	4	12	22	6	12	nan	5	19	nan
00:10-00:15	4	12	22	2	6	27	7	14	nan
00:15-00:20	4	6	11	5	7	nan	7	16	nan
00:20-00:25	4	6	11	8	16	nan	7	26	nan
00:25-00:30	4	6	9	3	16	nan	10	26	nan

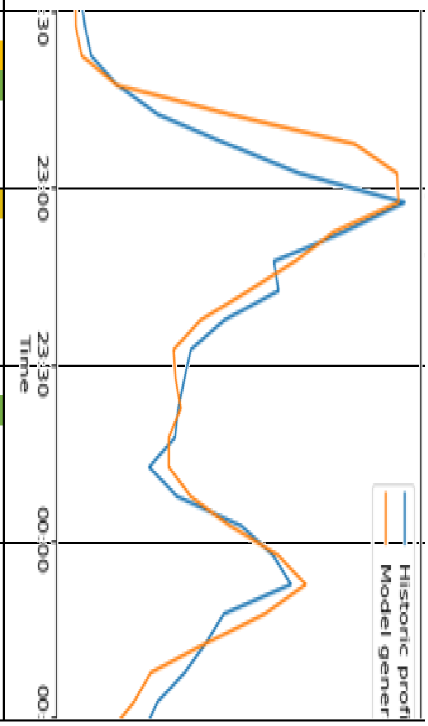


Figure C.10: Needed number of replications to achieve a 95% confidence interval with regards to *the number of pedestrians entering the station through the respective entrance sections when entrance section 4 is excluded*.

Time period	Pre gates section 1			Pre gates section 2			Pre gates section 3			Pre gates section 4			Pre gates section 5		
Gamma value:	20%	10%	5%	20%	10%	5%	20%	10%	5%	20%	10%	5%	20%	10%	5%
22:30-22:35	nan	nan	nan	nan	nan	nan	4	8	28	7	15	nan	26	nan	nan
22:35-22:40	nan	nan	nan	23	nan	nan	11	28	nan	10	nan	nan	7	nan	nan
22:40-22:45	nan	nan	nan	3	5	7	3	3	13	3	7	nan	7	20	nan
22:45-22:50	nan	nan	nan	7	15	nan	3	6	11	5	15	nan	3	5	20
22:50-22:55	nan	nan	nan	10	18	nan	7	14	30	4	8	16	3	3	3
22:55-23:00	nan	nan	nan	5	7	23	5	8	15	3	4	5	3	3	5
23:00-23:05	nan	nan	nan	5	8	28	3	5	14	3	5	11	3	5	10
23:05-23:10	6	nan	nan	4	8	nan	4	5	21	3	5	7	4	9	nan
23:10-23:15	6	nan	nan	5	7	nan	5	6	20	4	7	nan	6	9	nan
23:15-23:20	7	11	nan	2	5	9	7	16	nan	8	17	nan	2	2	nan
23:20-23:25	7	11	nan	10	23	nan	3	17	nan	7	nan	nan	4	6	24
23:25-23:30	9	19	nan	3	12	nan	4	6	24	7	19	nan	5	7	23
23:30-23:35	9	19	nan	6	21	nan	3	7	21	4	8	26	2	2	2
23L35-23:40	6	9	nan	8	20	nan	4	8	19	3	3	4	3	3	5
23:40-23:45	6	9	nan	3	3	18	4	8	15	3	4	19	4	10	29
23:45-23:50	8	18	nan	3	8	18	2	2	19	2	2	2	4	7	23
23:50-23:55	8	18	nan	10	nan	nan	3	4	12	3	3	5	3	3	7
23:55-00:00	6	9	nan	5	8	20	5	7	12	4	7	12	2	2	3
00:00-00:05	6	9	nan	15	nan	nan	4	8	19	4	9	28	2	5	19
00:05-00:10	7	13	nan	3	15	nan	3	3	27	5	15	29	4	6	12
00:10-00:15	7	13	nan	6	9	18	2	3	5	7	11	24	5	8	17
00:15-00:20	14	25	nan	3	9	30	5	8	18	3	4	17	3	4	28
00:20-00:25	14	25	nan	3	8	nan	5	8	27	7	14	nan	8	15	nan
00:25-00:30	13	nan	nan	4	9	nan	3	3	16	2	2	2	8	14	nan

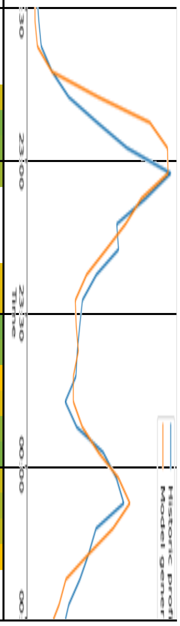


Figure C.11: Needed number of replications to achieve a 95% confidence interval with regards to *the density in front of the various check-in gates sections*.

Time period	Platform 1			Platform 2&3			Platform 4&5			Platform 6&7			Platform 8		
Gamma value:	20%	10%	5%	20%	10%	5%	20%	10%	5%	20%	10%	5%	20%	10%	5%
22:30-22:35	nan	nan	nan	nan	nan	nan	17	nan	nan	nan	nan	nan	nan	nan	nan
22:35-22:40	nan	nan	nan	2	2	2	12	nan	nan	nan	nan	nan	nan	nan	nan
22:40-22:45	nan	nan	nan	12	nan	nan	2	20	nan	20	nan	nan	28	nan	nan
22:45-22:50	nan	nan	nan	23	nan	nan	4	10	30	11	nan	nan	5	25	nan
22:50-22:55	nan	nan	nan	3	5	nan	6	11	24	2	2	nan	2	2	3
22:55-23:00	nan	nan	nan	6	13	29	2	5	14	4	6	18	8	21	nan
23:00-23:05	nan	nan	nan	4	5	10	3	3	4	3	5	8	3	4	6
23:05-23:10	5	26	nan	4	8	17	3	4	7	3	4	7	3	3	4
23:10-23:15	5	26	nan	2	2	3	5	9	23	3	4	5	4	5	7
23:15-23:20	5	10	nan	3	4	18	5	10	19	6	12	26	11	nan	nan
23:20-23:25	5	10	nan	3	4	nan	6	10	20	7	11	23	4	nan	nan
23:25-23:30	7	19	nan	8	16	nan	2	6	16	8	14	nan	7	13	nan
23:30-23:35	7	19	nan	6	19	nan	4	9	18	2	8	nan	6	19	nan
23L35-23:40	10	27	nan	3	23	nan	3	4	10	6	11	nan	11	25	nan
23:40-23:45	10	27	nan	6	11	nan	3	4	10	3	13	nan	19	nan	nan
23:45-23:50	11	nan	nan	3	14	nan	5	8	17	3	12	nan	nan	nan	nan
23:50-23:55	11	nan	nan	17	nan	nan	4	5	9	3	20	nan	nan	nan	nan
23:55-00:00	30	nan	nan	8	22	nan	5	7	13	2	22	nan	29	nan	nan
00:00-00:05	30	nan	nan	6	21	nan	3	4	10	6	13	nan	27	nan	nan
00:05-00:10	3	7	nan	3	4	5	4	5	21	5	13	nan	nan	nan	nan
00:10-00:15	3	7	nan	3	6	10	4	5	9	3	4	26	nan	nan	nan
00:15-00:20	8	20	nan	7	13	nan	5	8	17	4	10	20	nan	nan	nan
00:20-00:25	8	20	nan	4	22	nan	2	3	17	3	6	24	nan	nan	nan
00:25-00:30	2	2	2	8	21	nan	3	3	16	5	7	22	nan	nan	nan

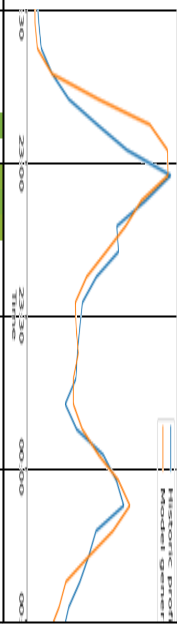


Figure C.12: Needed number of replications to achieve a 95% confidence interval with regards to *the density on the platforms*.

Time period	Platform 1			Platform 2&3			Platform 4&5			Platform 6&7			Platform 8		
Gamma value:	20%	10%	5%	20%	10%	5%	20%	10%	5%	20%	10%	5%	20%	10%	5%
22:30-22:35	2	2	17	5	7	15	2	2	6	3	3	4	6	10	19
22:35-22:40	7	13	nan	4	11	24	3	3	4	3	5	7	2	6	10
22:40-22:45	7	13	nan	4	5	11	2	2	3	3	4	5	3	4	7
22:45-22:50	3	4	nan	3	4	6	3	3	3	3	4	5	2	3	4
22:50-22:55	3	4	nan	2	3	3	2	3	3	3	3	4	3	3	4
22:55-23:00	5	7	15	2	2	3	2	3	3	2	3	3	3	3	4
23:00-23:05	5	7	15	3	3	4	2	2	3	2	2	3	2	2	2
23:05-23:10	3	3	4	2	2	3	3	3	3	2	3	3	3	3	4
23:10-23:15	3	3	4	2	3	3	2	3	4	2	3	3	3	4	6
23:15-23:20	2	2	2	3	3	4	2	2	2	2	2	7	5	7	28
23:20-23:25	2	2	2	2	2	3	3	3	4	2	2	2	3	3	4
23:25-23:30	3	3	4	2	2	2	2	2	3	2	3	4	2	3	4
23:30-23:35	3	3	4	3	4	5	2	2	3	3	5	7	2	2	3
23L35-23:40	3	3	5	2	2	3	2	3	3	3	3	4	2	4	5
23:40-23:45	3	3	5	3	4	5	3	3	3	3	3	4	2	3	3
23:45-23:50	2	2	2	3	3	3	3	3	3	3	4	6	2	2	3
23:50-23:55	2	2	2	3	4	5	3	3	4	2	3	4	3	4	6
23:55-00:00	3	6	10	3	4	6	2	2	2	2	2	3	2	2	2
00:00-00:05	3	6	10	3	4	5	2	3	3	2	3	5	3	3	4
00:05-00:10	2	2	2	2	3	3	2	3	3	3	3	4	2	2	2
00:10-00:15	2	2	2	2	2	3	3	3	3	3	3	4	3	3	4
00:15-00:20	2	3	3	3	3	5	3	3	4	3	3	4	9	13	nan
00:20-00:25	2	3	3	3	3	5	2	2	2	3	4	6	9	17	nan
00:25-00:30	2	2	7	2	2	3	2	2	2	2	2	2	4	7	15

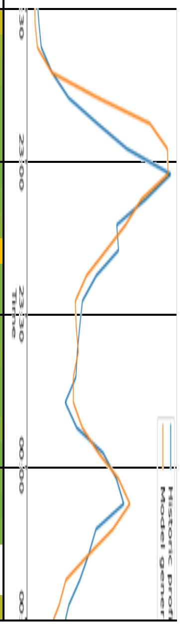


Figure C.13: Needed number of replications to achieve a 95% confidence interval with regards to *the travel time to the various platforms*.

the model is initially run with 30 different random seeds as this is deemed to be the maximum number of runs given the run time of the model and the available time for the research.

Looking at Figure C.9 it becomes clear that the model cannot generate a 95% confidence interval with a maximum error of $\gamma = 5\%$ within 30 replications for all intervals concerning all entrance sections. Nonetheless, for main first peak, it is able to obtain such an interval for all the entrances. Since entrance section 3 is not the most used entrance section, it might also be possible to use at least 18 replications, as it still leads to a 95% confidence interval with a maximum error of $\gamma = 5\%$ on the busiest moment, while still covering a substantial number of intervals for the other buffer sections. This cuts a substantial number of replications which can save simulation time.

Looking at Figure C.10 a relatively similar pattern is visible as in Figure C.9. This is explainable since while the analysed variable is different, the density in the buffer section before an entrance should have a correlation with the number of people passing through an entrance section. Based on the same argumentation as used for the buffer sections, it is possible to say that it would be a good trade off between model quality and simulation time to use at least 23 replications, in order to have a 95% confidence interval with a maximum error of $\gamma = 5\%$ on the busiest moment at the main peak for all entrance sections.

Looking at Figure C.11 it is striking that for the earlier intervals for gates section 1 many replications are needed. This is explainable due to the fact that early in the simulation relatively few trains stop at the platform serving track 1, meaning that a slight change in number of people going to that platform leads to a large confidence interval. Following the argumentation used at the buffer and entrance sections, it is possible to say that it would be a good trade off between model quality and simulation time to use at least 23 replications, in order to have a 95% confidence interval with a maximum error of $\gamma = 5\%$ on the busiest moment at the main peak for all check-in gates sections except for platform 1. However, in order to have a bit more reliability, it would also be relevant to choose at least 28 replications.

Figure C.12 shows similarities with Figure C.11, which is explainable due to the fact that the crowd waiting at the check-in gates will subsequently wait at the platforms. Following the argumentation used at the other KPIs, it is possible to say that it would be a good trade off between

model quality and simulation time to use at least 18 replications, in order to have a 95% confidence interval with a maximum error of $\gamma = 5\%$ around the busiest moment at the main peak for all platforms, except for platform 1. Nonetheless, in order to have a 95% confidence interval with a maximum error of $\gamma = 10\%$ for platform 1 for a substantial number of intervals, it would be beneficial to use at least 27 replications.
Figure C.13 interestingly shows a relatively low number of replications in order to achieve a 95% confidence interval with a maximum error of $\gamma = 5\%$ for almost all intervals. Following the argumentation used at the other KPIs, it is possible to say that it would be a good trade off between model quality and simulation time to use at least 15 replications, as this will lead to a 95% confidence interval with a maximum error of $\gamma = 5\%$ for most of the intervals, also around the main peak.
All in all, when looking at the various augmentations given above, it would be best to use at least 28 replications in order to get statistically confident results from the model for the analysed KPIs. However, it should also be noted that even this number of replications does not lead to a 95% confidence interval with a maximum error of $\gamma = 5\%$ for all KPIs for all intervals. As also stated above, 30 replications is deemed to be the maximum number of replications given the simulation time of the model and the available. time. Combining these two last-mentioned aspects, and the fact that 30 replications is only 2 more than the minimum needed replications for some degree of confidence for all KPIs, it is decided to use 30 replications for the experiments.

C.4 Calibration

Besides statistically relevant outcomes, it is also important that the model mirrors reality as good as possible. To do this, the model is calibrated for the routes taken by pedestrians which they use to enter the station. The choice set for the routes consists of routes through either one of the four entrance sections as presented in Figure C.4.

C.4.1 Routing criterion

In order to let pedestrians choose between the routes, there are three potential criteria to base route choice on: travel time, density and count of other pedestrians. Travel time is a relevant criterion as people often try to optimise their travel time. Density can also be relevant, as specifically pedestrians also might be looking at non-congested routes, but this counteracts the ‘follow the masses’ principle that is often applicable to dense crowd flows. Counts of pedestrians are very similar to density, but disregard the space that the pedestrians occupy. Ideally, a combination of the travel time and density criteria is used to incorporate both behavioural aspects. Unfortunately, the Vissim/Viswalk software does not allow to combine routing criteria. Therefore, it has been decided to use the travel time criterion.

C.4.2 Routing method

Besides the criteria, four different methods are possible to implement in the used modelling software Vissim/Viswalk, that are presented in Table C.3.
The best route method is not incorporated in the calibration, as while it might be possible to give good results, its explanatory power with regards to equally dividing the remainder of the flow over the other options than the best option is not necessarily realistic for the case study.
The parameters can be different for each routing set. A different routing set is available for each destination platform, resulting in 5 potential parameters to alter. It is however chosen to alter these parameters simultaneously, as the destinations (the platforms) are located very close to one another and the calibrated values will therefore likely be very minimal. Besides the respective parameters of the various methods, an additional parameter is relevant for all

Table C.3: Different pedestrian routing methods with regards to travel time tt_i for route i as defined by PTV [2021].

Method	(Mathematical) explanation
Best route	A fixed percentage of pedestrians choose the best route, the remaining percentage is divided equally over the other options.
Kirchhoff	Probability of route choice is calculated using Kirchhoff parameter E: $p_i = \frac{\left(\frac{1}{tt_i}\right)^E}{\sum_{j=1}^{N}\left(\frac{1}{tt_j}\right)^E}$
Logit	Probability of route choice is calculated using logit parameter c: $p_i = \frac{e^{\frac{-tt_i}{c}}}{\sum_{j=1}^{N} e^{\frac{-tt_j}{c}}}$
Logit of reciprocal	Probability of route choice is calculated using logit reciprocal parameter z: $p_i = \frac{e^{\frac{z}{tt_i}}}{\sum_{j=1}^{N} e^{\frac{z}{tt_j}}}$

methods, which is the number of pedestrians incorporated in determining the average travel time for each route.

To see what method suits the routing best, the three methods that remain after discarding the ‘best route’ method have been tried using the default parameter values. There has been looked at the Root Mean Squared Normalised Error (RMSNE), for which the equation has been presented in Table C.2. The use of the RMSNE means that there will be one value for each individual entrance section. In order to have a single value that describes the quality of the model, the individual RMSNE value per entrances section is weighted by the total share that is entering through the respective door section.

As the shares of people entering through entrance sections 3 and 4 are significantly lower than for entrance sections 1 and 2 (as visible in Figure C.14), it has also been decided to analyse the model quality using the Root Mean Squared Error (RMSE) indicator:

$$\text{RMSE} = \sqrt{\frac{1}{N} * \sum_{i=1}^{N} (x_i - y_i)^2} \tag{C.5}$$

This indicator does not normalise the errors, giving a better absolute insight into the model quality. Similar to the RMSNE, the individual RMSE value per entrances section is weighted by the total share that is entering through the respective door section to get a single RMSE value for the entire model.

For the calibration, the same input data set is used as for the determining of the number of replication. I.e., the input flows as visible in Figure C.3 are used. The resulting outcomes with regards to the various methods are presented in Figure C.14. The respective outcomes of the RMSNE values are presented in Table C.4.

What can be concluded from Figure C.14 and Table C.4 is that at a first glance, the fits are not necessarily good, but the Kirchhoff routing method has the best fit. However, since parameter values might play a large role in the fit, there has also been looked at two of the methods for further analysis. Since the Kirchhoff and ‘regular’ logit method have the best values for both the RMSNE and RMSE indicators, these are analysed for further enhancement.

As is visible in Table C.3, the Kirchhoff routing method has a parameter E and the logit routing method has a parameter c. These can be altered to create a better quality model.

C.4.3 Calibration of Kirchhoff parameter E

Initially, a wide range of values has been tried for E to identify where local minima are located with regards to RMSNE and RMSE values. The outcomes of this analysis are presented in Figure C.15 and Table C.5.
It can be seen in Table C.5 that the best situation with regards to both RMSNE and RMSE value can be achieved with $E = 7.0$. Therefore, a more detailed analysis around this value is analysed in C.16 and Table C.6.
All in all, the best situation is achieved when $E = 6.0$ or 7.0. Therefore, the outcomes of these values are compared to the analysis using the logit routing method.

C.4.4 Calibration of logit parameter c

Similarly to the Kirchhoff method, a wide range of values has been tried for c to identify where local minima are located with regards to RMSNE and RMSE values. The outcomes of this analysis are presented in Figure C.17 and Table C.7.
It can be seen in Table C.7 that the best situation with regards to both RMSNE and RMSE value can be achieved with $c = 17$. Therefore, a more detailed analysis around this value is analysed in C.18 and Table C.8.
All in all, the best situation is achieved when $c = 17$. Therefore, the outcomes of this value are compared to the analysis using the Kirchhoff routing method.

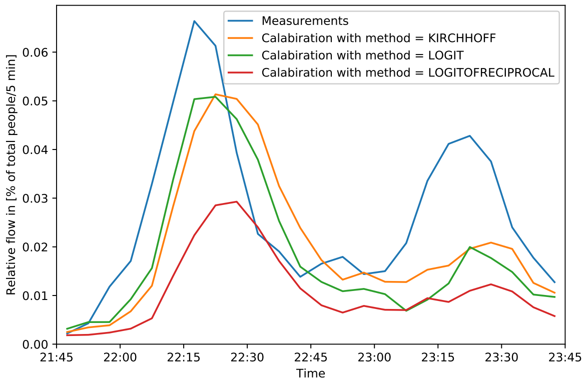
C.4.5 Analysis of calibration of routing methods

What becomes clear when comparing both the Kirchhoff method with its parameter E and the logit method with its parameter c is that both methods do not seem to capture routing behaviour that is present in the case study area very good. Both have an RMSNE value of larger than 0.7, indicating that the quality of reproducing reality is not very good. Nonetheless, when analysing Figures C.16 and C.18, the overall trends of two peaks in inflow, specifically for entrance section 1, seem to be present, though not as persisting as in the real-life situation.
It is expected that this has to do with the facts that 1) only travel time serves as routing criterion for the route choice and that 2) there are two peaks in the pedestrian input. Take a hypothetical situation with two possible routes and a flow profile similar to the one used for calibration. Over time, the number of people taking the fastest route grows as it initially is the most attractive route. Because of the crowding as a result of the first peak in flow, the travel time on this route becomes longer and the other route becomes more attractive, spreading the crowds over the two routes. Once the first peak decreases and a little later the second peak begins, the two routing option are, say, equally attractive based on the historical travel times. However, in real life, the initially fastest route is likely to become the main route of choice again since the crowding (and therefore delay in travel time) has decreased significantly so that the initially fastest route will be significantly faster again. Nonetheless, this is not incorporated in the model for some time as potentially not as many pedestrians have taken the fastest route since it has become faster again. Therefore, as the travel time is based on a fixed number of past pedestrians that completed the route, the software does at first not know this route is significantly faster again. It might be possible to circumvent this aspect when density is taken into account together with travel time, but, as mentioned before, the software does not allow for this. Also, the number of pedestrians incorporated in determining the average travel time on a route is relevant for further analysis
Nonetheless, while the model quality with regards to reproducing a real-life situation for the case study is not deemed very high, it is deemed good enough to analyse the effects of potential measures on a crowd. Therefore, it has been chosen to implement the logit routing method. A

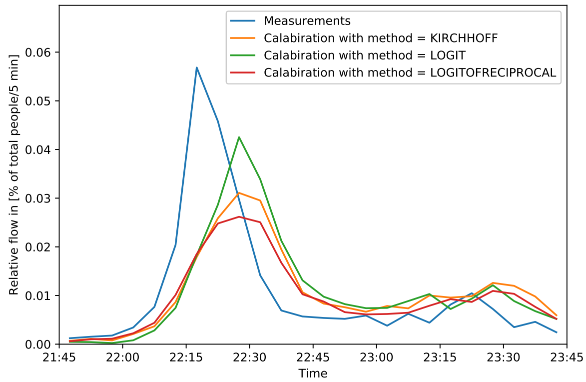
final, even more detailed calibration step with regards to the value of parameter c is carried out. The results of this analysis are presented in C.19 and Table C.9.
All in all, the best situation is achieved when $c = 17.5$. Therefore, the logit routing method with parameter value $c = 17.5$ is selected for the routing method in the model.

C.4.6 Calibration of number of pedestrians for average travel time

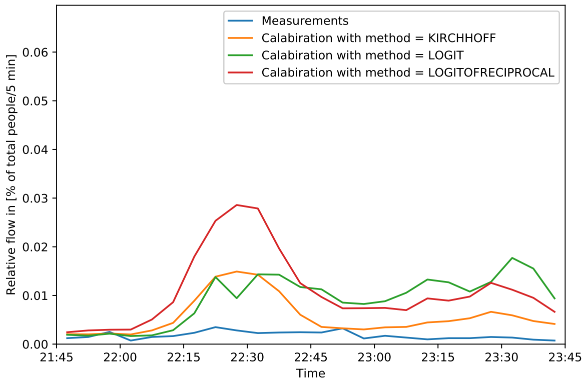
As mentioned above, it is possible that the number of pedestrians incorporated in determining the average travel time for each route can be relevant for how good the model functions. Therefore, a brief analysis has been done for this parameter. This has been carried out using the aforementioned selected logit method with $c = 17.5$. Similarly to the Kirchhoff and logit calibration, a wide range of values has been tried for the number of pedestrians to identify where local minima are located with regards to RMSNE and RMSE values. The outcomes of this analysis are presented in Figure C.20 and Table C.10.
As can be seen in Figure C.20 and Table C.10, there is no extreme deviation with regards to the number of pedestrians. When reflecting to the aforementioned routing aspects, it is possible that either the number of pedestrians is not as influential as potentially expected, or its influence is also dependent on the value of c. Since it is only analysed with one value of c, it remains unclear if this is the case.
In any case, a more specific analysis has been carried out to create the best possible quality of the model. The results are visible in Figure C.21 and Table C.11.
Since a situation where 40 pedestrians are incorporated to determine the average travel time lead to the best situation, this is set as input for the model. However, it should be noted that there are only very small deviations with the other configurations.
Based on the final calibration aspect, it can be concluded that the calibration process led to a RMSNE value of 0.69. This is not necessarily a good result of the calibration process, as in the most ideal situation this value would be 0. Nonetheless, when looking at Figure C.21, the general trend is captured. E.g., entrance section 1 in Figure C.21(a) shows two peaks with a trough in between. Therefore, while the exact share-values are not achieved, it will give relevant insights into the effect of measures on the pedestrian flows around the Bijlmer ArenA station.



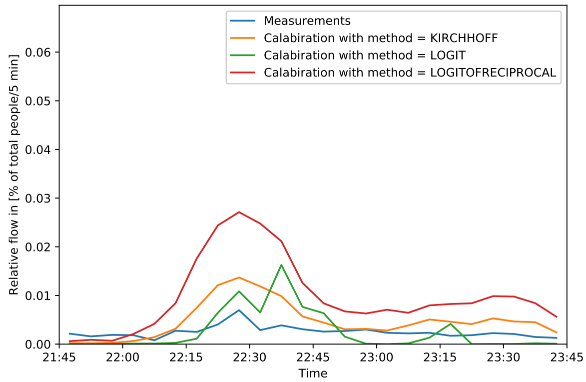
(a) Entrance section 1.



(b) Entrance section 2.



(c) Entrance section 3.

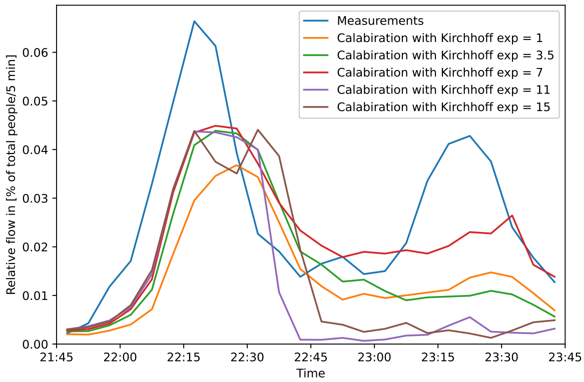


(d) Entrance section 4.

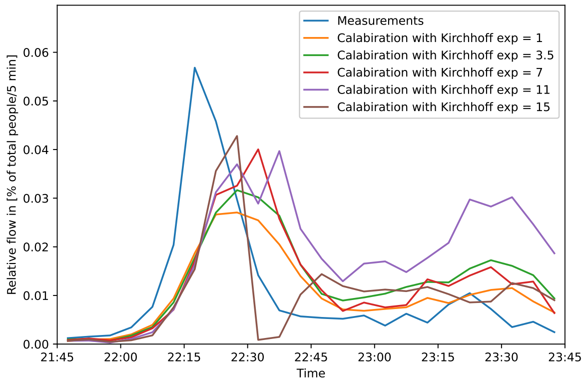
Figure C.14: Normalised inflow profiles for different entrance sections with regards to different routing methods using their default values.

Table C.4: RMSNE and RMSE values for various routing methods using default routing settings.

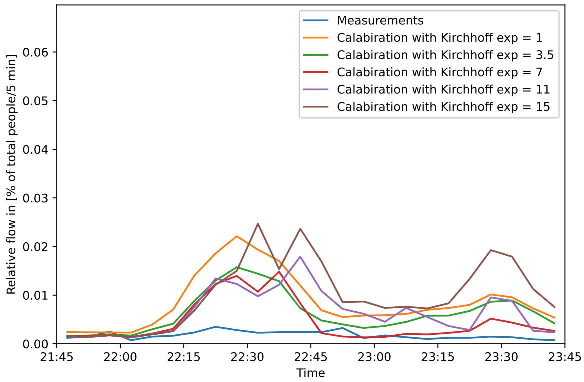
Routing method	**RMSNE value**	**RMSE value**
Kirchhoff	0.73	0.012
Logit	0.88	0.012
Logit of reciprocal	1.03	0.016



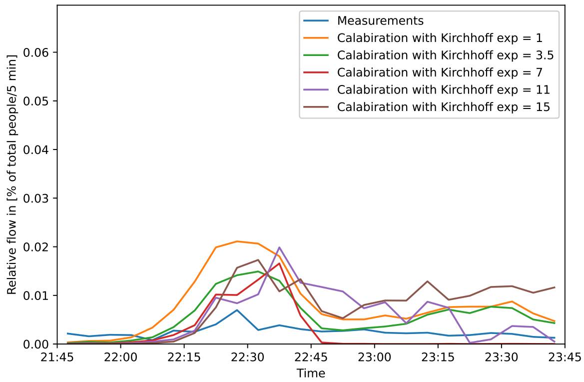
(a) Entrance section 1.



(b) Entrance section 2.



(c) Entrance section 3.

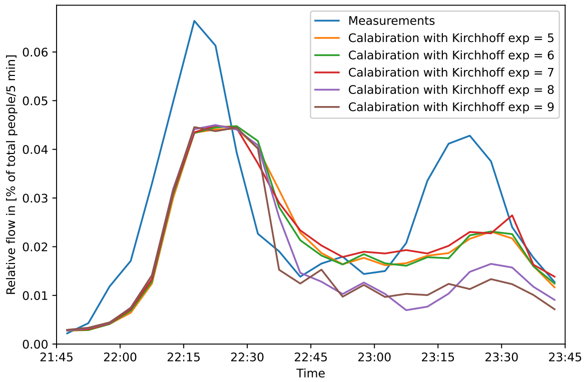


(d) Entrance section 4.

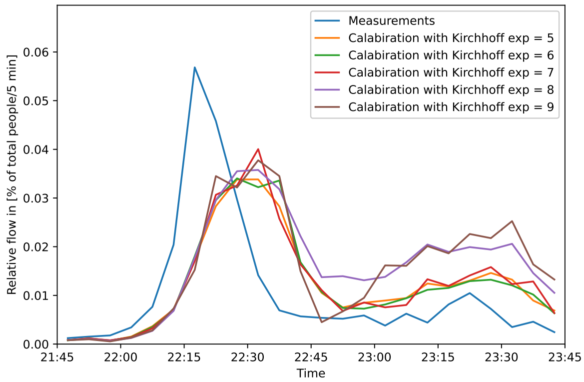
Figure C.15: Normalised inflow profiles for different entrance sections with regards to a broad range of E values using the Kirchhoff routing method to identify local minima.

Table C.5: RMSNE and RMSE values for a broad range of E values using the Kirchhoff routing method to identify local minima.

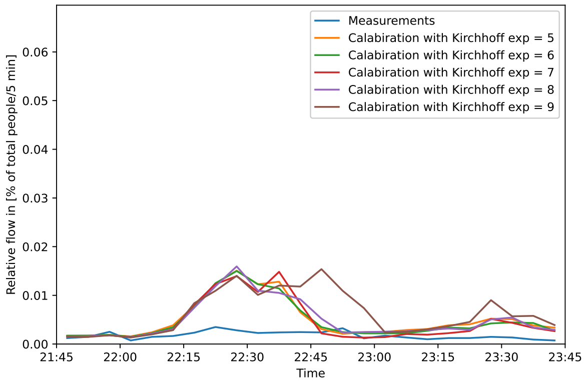
E **value**	**RMSNE value**	**RMSE value**
1.0	0.93	0.015
3.5	0.97	0.014
7.0	0.75	0.011
11	1.5	0.018
15	1.2	0.017



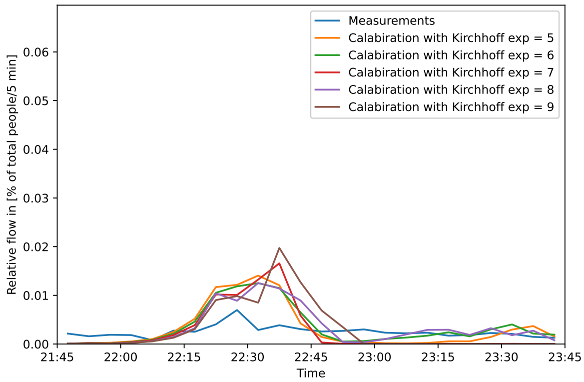
(a) Entrance section 1.



(b) Entrance section 2.



(c) Entrance section 3.

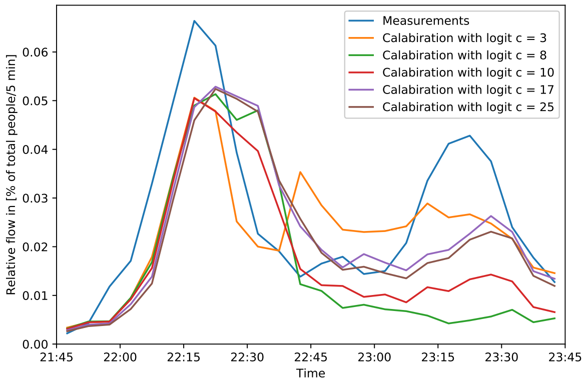


(d) Entrance section 4.

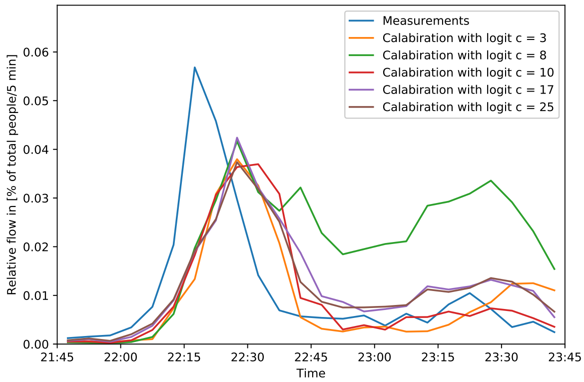
Figure C.16: Normalised inflow profiles for different entrance sections with regards to detailed E values around $E = 7.0$ using the Kirchhoff routing method.

Table C.6: RMSNE and RMSE values for detailed E values around $E = 7.0$ using the Kirchhoff routing method.

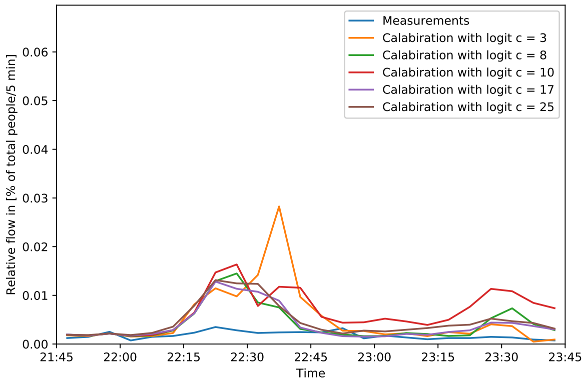
E value	RMSNE value	RMSE value
5.0	0.77	0.012
6.0	0.75	0.011
7.0	0.75	0.011
8.0	0.99	0.014
9.0	1.1	0.014



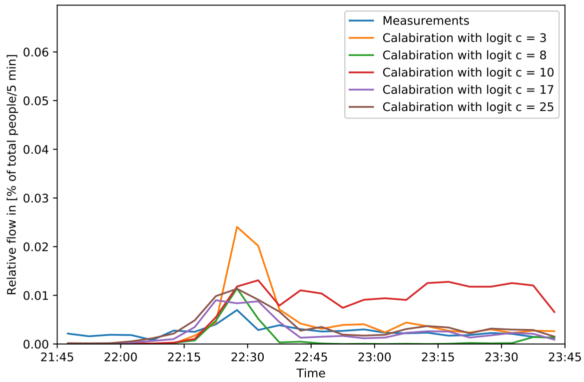
(a) Entrance section 1.



(b) Entrance section 2.



(c) Entrance section 3.

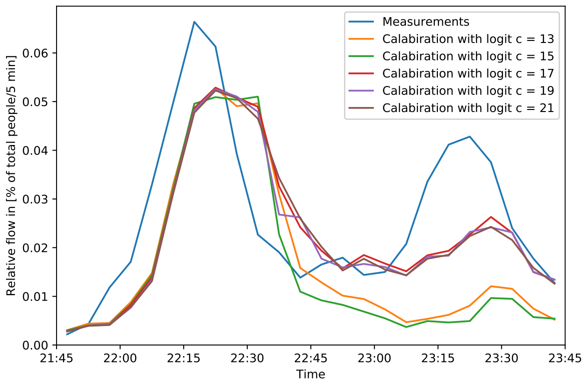


(d) Entrance section 4.

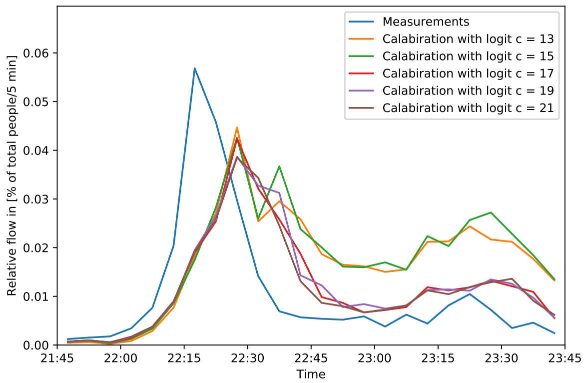
Figure C.17: Normalised inflow profiles for different entrance sections with regards to a broad range of c values using the logit routing method to identify local minima.

Table C.7: RMSNE and RMSE values for a broad range of c values using the logit routing method to identify local minima.

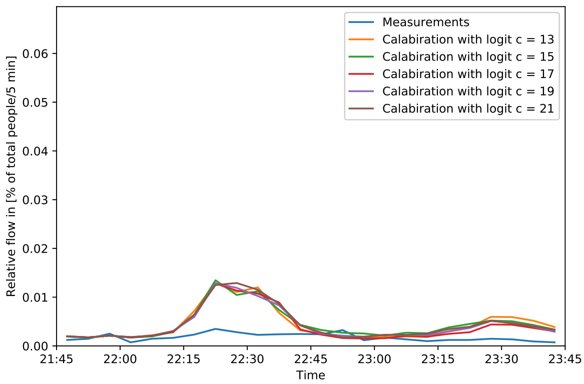
c **value**	**RMSNE value**	**RMSE value**
3.0	0.82	0.010
8.0	1.3	0.018
10	0.91	0.013
17	0.71	0.011
25	0.72	0.012



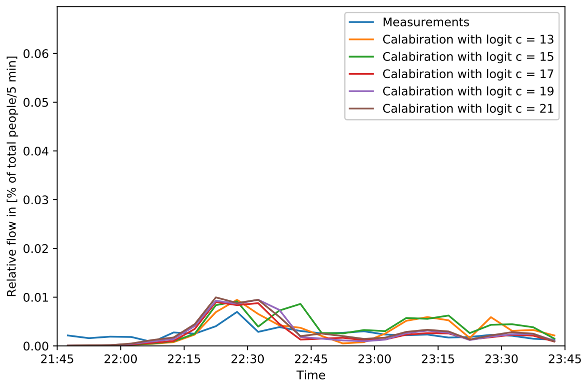
(a) Entrance section 1.



(b) Entrance section 2.



(c) Entrance section 3.

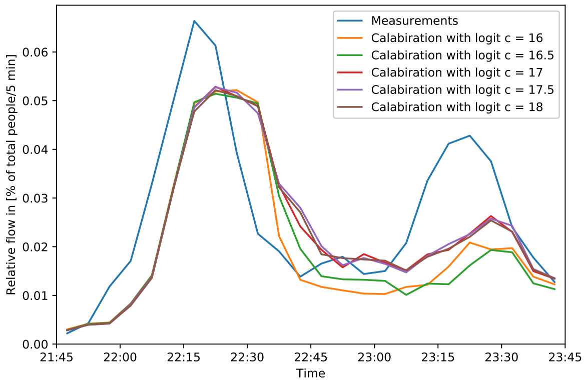


(d) Entrance section 4.

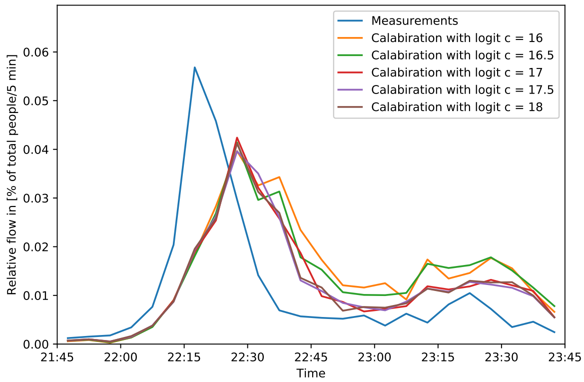
Figure C.18: Normalised inflow profiles for different entrance sections with regards to detailed c values around $c = 17$ using the logit routing method.

Table C.8: RMSNE and RMSE values for detailed c values around $c = 17$ using the logit routing method.

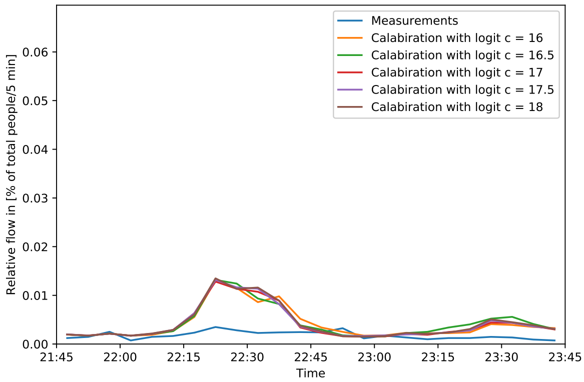
c value	RMSNE value	RMSE value
13	1.1	0.015
15	1.2	0.016
17	0.71	0.011
19	0.72	0.011
21	0.71	0.012



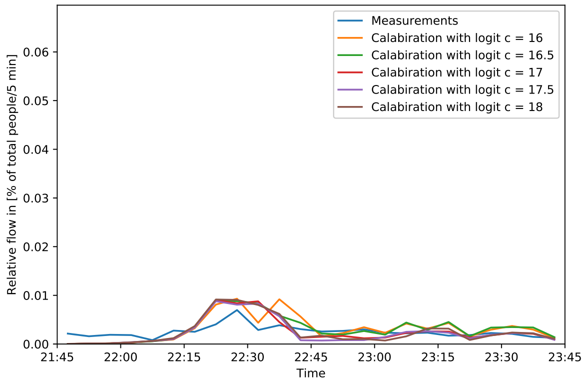
(a) Entrance section 1.



(b) Entrance section 2.



(c) Entrance section 3.

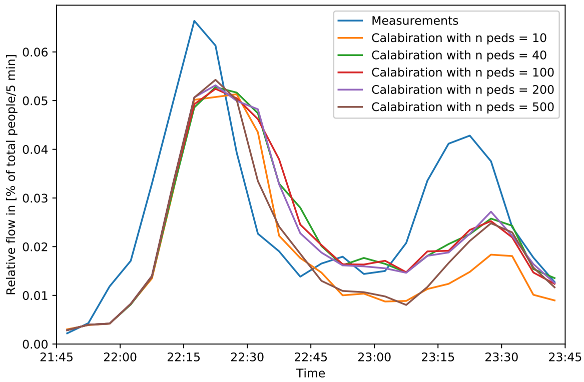


(d) Entrance section 4.

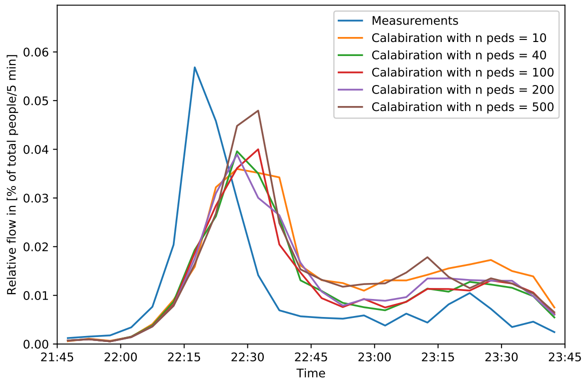
Figure C.19: Normalised inflow profiles for different entrance sections with regards to more detailed c values around $c = 17$ using the logit routing method.

Table C.9: RMSNE and RMSE values for more detailed c values around $c = 17$ using the logit routing method.

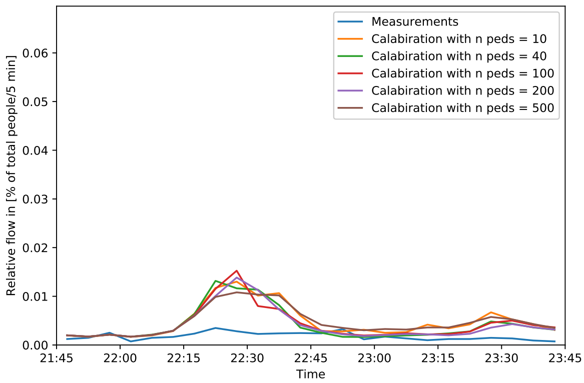
c value	RMSNE value	RMSE value
16.0	0.85	0.012
16.5	0.84	0.013
17.0	0.71	0.011
17.5	0.70	0.011
18.0	0.71	0.011



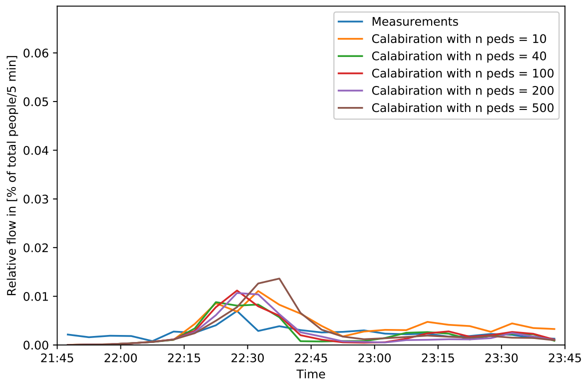
(a) Entrance section 1.



(b) Entrance section 2.



(c) Entrance section 3.

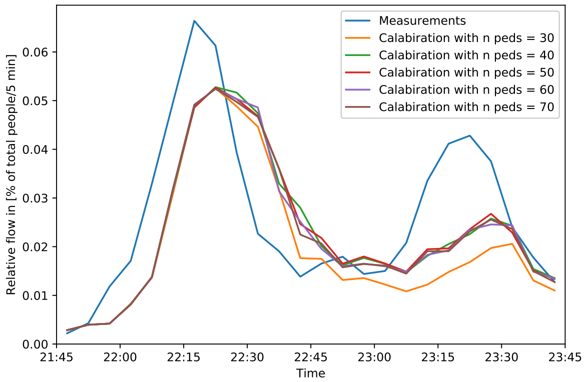


(d) Entrance section 4.

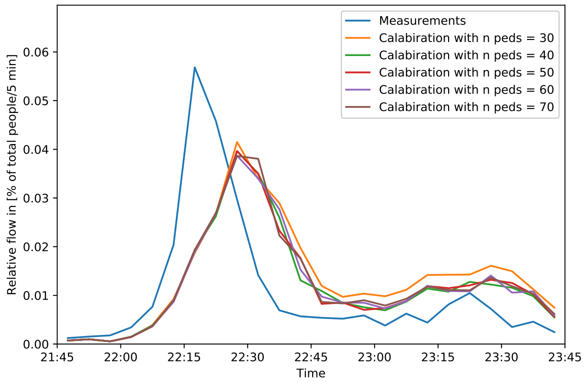
Figure C.20: Broad analysis of normalised inflow profiles for different entrance sections with regards to various numbers of pedestrians incorporated in the determination of average travel time. Routing method is logit with $c = 17.5$.

Table C.10: RMSNE and RMSE values for a large range of numbers of pedestrians incorporated in the determination of average travel time when using the Kirchhoff routing method with $c = 17.5$.

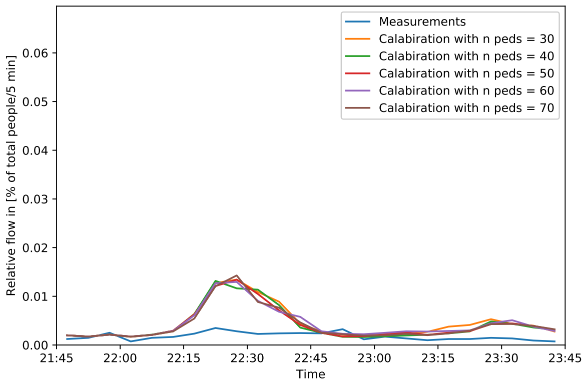
E value	RMSNE value	RMSE value
10	0.87	0.014
40	0.69	0.011
100	0.69	0.011
200	0.71	0.011
500	0.19	0.011



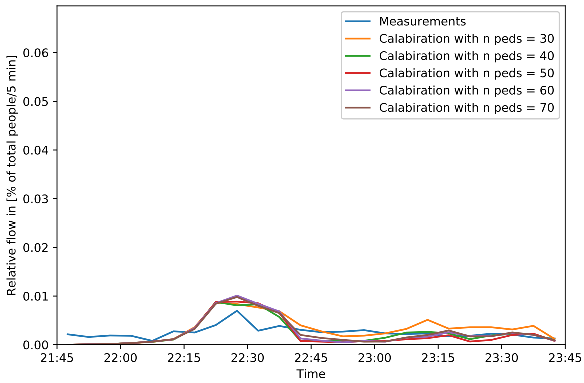
(a) Entrance section 1.



(b) Entrance section 2.



(c) Entrance section 3.



(d) Entrance section 4.

Figure C.21: Detailed analysis of normalised inflow profiles for different entrance sections with regards to various numbers of pedestrians incorporated in the determination of average travel time. Routing method is logit with $c = 17.5$.

Table C.11: RMSNE and RMSE values for various numbers of pedestrians incorporated in the determination of average travel time when using the logit routing method with $c = 17.5$.

E value	RMSNE value	RMSE value
30	0.80	0.012
40	0.69	0.011
50	0.71	0.011
60	0.70	0.011
70	0.70	0.011

C.5 Measure set-up

Four measures are investigated in the research, which each require a set-up within the model. These set-ups are presented in this appendix.

C.5.1 Spreading of peak flow

For the spreading of the peak flow, there has been looked at the effect of strategies that tried to convince people to change the departure time for their trip. The researches found mainly concerned commuting and investigated changes in charging schemes [Huan et al., 2021] or financial rewards [Ben-Elia and Ettema, 2011, Arian et al., 2018] to convince people to change departure time. Also, the effect of provision of travel time information is analysed [Tang and Hu, 2019, Le et al., 2020].
Unfortunately, no study has been found that analyses the influencing of event outflow, meaning that the effects should be based on the commuting data. Therefore, there has been looked at a more general approach to see the effects of 'delaying' a certain portion of the entire crowd for a certain time, incorporating effects of influencing commuters.
Huan et al. [2021] found that it is possible to influence public transport users in such a way that the peak flow decreases up to about 15% by using a changed pricing scheme. Therefore, it is assumed that 15% of the crowd can be influenced with a peak spreading measure. Arian et al. [2018] supply commuters with alternatives that each differ 15 [minutes] in departure time. This is deemed to be a logical potential waiting period, as the timetable of trains departing from the Bijlmer-ArenA station after events seems to on average have roughly 15 [minute] intervals for trains travelling in the same direction. Therefore it is assumed that the 15% of the crowd departs the event venues 15 [minutes] later. This eventually leads to a departure profile for a regular triple as visible in Figure C.22. The altered profile has a peak value which is 9% lower than the regular triple peak.
Important to note is that this measure simply analyses what the effects would be when such a delay in departure time of a portion of the crowd is incorporated. As no data is found concerning the delaying of departure with respect to a specific side-event or anything else that could cause a delay in departure time, an exact measure that should result in such a delay is still something that should be researched.

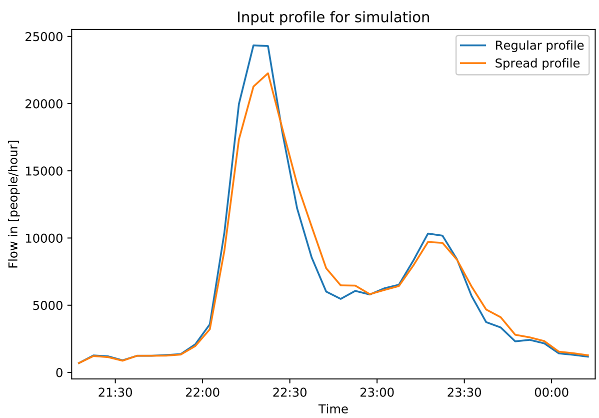


Figure C.22: Comparison of the station inflow profile as based on the historic flow of 06-12-2019 that is also visible in Figure C.3 and a situation where 15% departs the events 15 [minutes] later.

C.5.2 Barriers

The barrier measure stems from the placement of Mojo barriers at the Bijlmer-ArenA station that is already implemented during triple events. Therefore, there are already plans available regarding the exact placement of barriers, as visualised in Figure C.23 that was provided by the Dutch Railways. Moreover, the placements of the barriers and the number of gates has been checked and verified during a visitation of the Bijlmer-ArenA station during an Ajax match on 19-10-2021, as can be seen in Figure C.24.

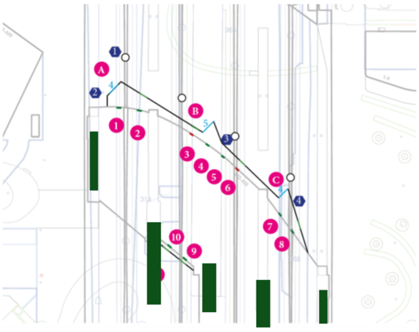


Figure C.23: Visualisation of the placement of the Mojo barriers as provided by the Dutch Railways

Figure C.24: Photo taken during visitation of the Bijlmer-ArenA station on 19-10-2021 showing one of the gates sections in the barrier.

Eventually, these data lead to the implementation of the barriers into the model as visible in Figure C.25. Important to note is that there are also barriers placed between the various entrance sections to make sure that pedestrians in the model will enter the station through the entrance section dedicated to the gates of the entrance section. Moreover, for each entrance section, there is one stand-alone 'gate'. These gates will be used by the alighting pedestrians that leave the station. Through routing methods, it is made sure that pedestrians entering the station will only enter the station through the multi-gate section and the pedestrians leaving the station will only leave the station through the stand-alone gate.

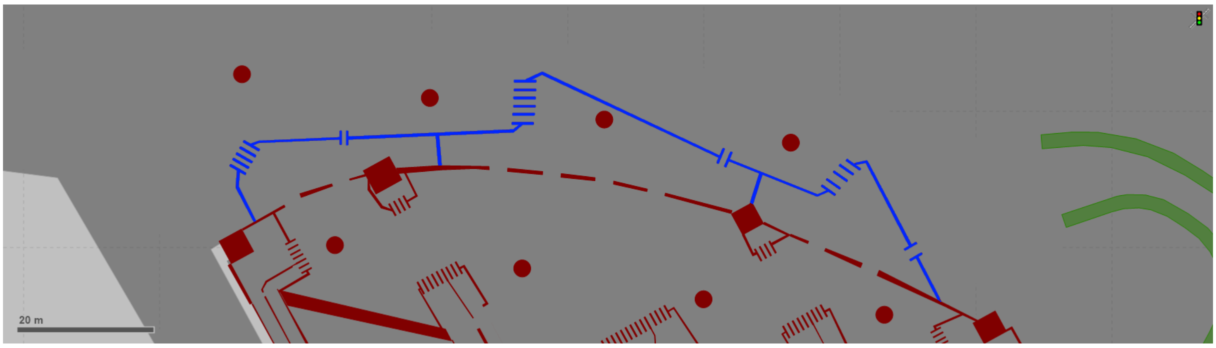


Figure C.25: Implementation of the barriers, as indicated in blue, into the model.

C.5.3 Stream separation

The separation of streams are expected to be achievable by placement of barriers in the station. It is most logical to separate streams based on entrance sections, as that would be a rather intuitive way for division of streams over the various platforms. Therefore, two outermost platforms on each side are assigned to an entrance section, as is the central platform leading to tracks 4 & 5.

This situation is visualised in Figure C.26. Relevant to note is that there is a small passageway between the escalators leading to the platform of tracks 6 & 7. This passageway is implemented to make sure that alighting pedestrians coming from tracks 6, 7 and 8 with a destination at the bus station can exit the station through entrance section 4. At first, this passageway was not implemented, but this lead to progressive deadlocks at entrance section 1 in almost all runs. Therefore, to combat these deadlocks, it is allowed that alighters can pass through the passageway. Through routing it is made sure that people with a destination on the platform of tracks 4 & 5 will not use this passageway, as is the same for alighters of tracks 4 & 5 with a destination at one of the venues.

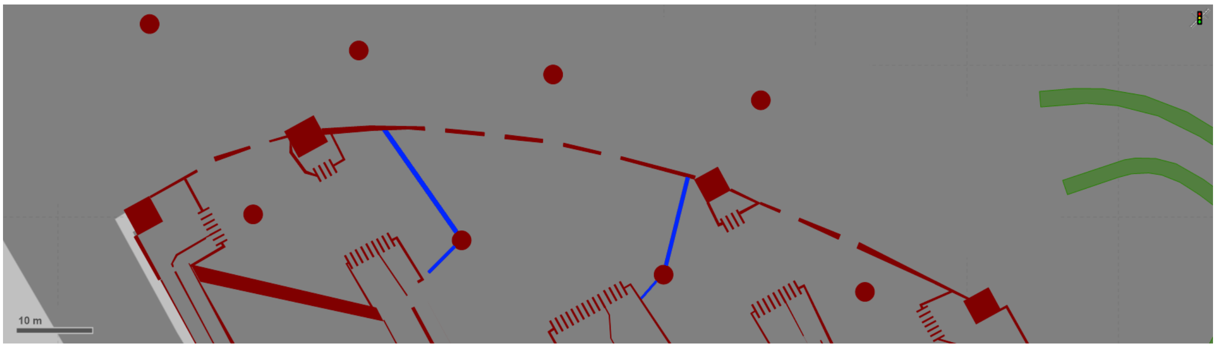


Figure C.26: Implementation of the separation barriers, as indicated in blue, into the model.

C.5.4 Behavioural influencing

A behavioural influencing aspect that has been found in literature concerns the effect of background music as investigated by Zeng et al. [2019]. While their research is very experimental and only concerns one-dimensional pedestrian behaviour, it has been tried to apply the relative effects in free flow speed, capacity flow and crowd density that background music has using the fundamental diagrams as mentioned in the research. An overview of these aspects both with and without application of background music as found by Zeng et al. [2019] is presented in Table C.12.

Table C.12: Flow characteristics as identified by Zeng et al. [2019] for a situation without and with background music.

Characteristic	**Regular situation**	**Background music situation**	**Relative change**
Free flow speed [m/s]	1.4	1.2	-15%
Capacity flow [ped/s]	1.0	0.9	-10%
Standstill density [ped/m^2]	2.5	2.0	-20%

In order to see whether the pedestrian behaviour in Vissim/Viswalk is in line with the ‘regular situation’ of Zeng et al. [2019], a small modelling experiment has been carried out using a bottleneck situation, as visible in Figure C.27. In front of the bottleneck, the density of the crowd is measured. After the bottleneck, the flow and speed of the pedestrians is measured. The free flow speed is incorporated in Vissim/Viswalk by a distribution for desired free flow speeds. Flow characteristics like capacity flow and standstill density are steered in Vissim/Viswalk through the social forces model. Using the standard Vissim/Viswalk values for these aspects, it was found that the free flow speed in Vissim/Viswalk is about 1.05 [m/s], the capacity flow is about 1.10 [ped/s] and the standstill density is about 2.16 [ped/m^2]. It has been tried to mirror the relative effects that background music has on the flow by altering the desired speed distribution and values of parameters in the social forces model.

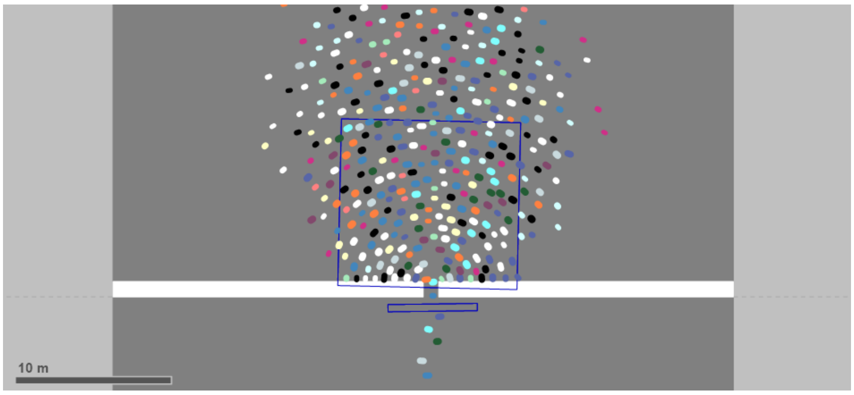


Figure C.27: Visualisation of the bottleneck model used to determine free flow speed, capacity flow and standstill density.

The social forces model has a range of parameters, that are not necessarily easy and intuitive to interpret [Kretz et al., 2018]. Table C.13 gives an overview of the parameters that are part of the social forces model in Vissim/Viswalk.

Table C.13: Overview of the parameters of the social forces model, its function in the model, its effects on pedestrians part of the modelling software and behavioural aspects related with the effects. Description of function and effect are largely based on description of the social forces model in the Vissim manual and Viswalk examples [PTV, 2021].

Parameter	**Function**	**Effect**	**Behavioural aspect(s)**
τ	Element of driving force without which a pedestrian never would reach a destination.	Increasing value decreases acceleration and density and increases corner radius.	Sort-of reaction time.
ReactToN	Number of pedestrians that are considered in the social forces of a single pedestrian.	Increasing value decreases density and makes a crowd less jittery.	Awareness of surrounding crowd members.
A Social (isotropic)	Determines the base strength of the repulsing force between two pedestrians.	Increasing value leads to more likeliness of deadlock, larger headways and smaller flow.	Accepted distance towards another pedestrian.
B Social (isotropic)	Influences the strength of the repulsing force between two pedestrians.	Increasing value leads to larger headways and a clearer acceleration wave.	'Politeness' towards other crowd members with regards to giving way.
λ	Take account for the fact that people and events behind a person do not influence the movement as much as events in front.	Increasing value leads to more efficient counter flow and bottleneck flow.	Feeling of pressure of the person behind.

Table C.13 continues on the next page.

Continuation of Table C.13.			
Parameter	**Function**	**Effect**	**Behavioural aspect(s)**
A Social (mean)	Influences the strength of the social force between two pedestrians similar to 'A Social (isotropic)', but incorporates the relative speed between two pedestrians	Similar to 'A Social (isotropic)'	Similar to 'A Social (isotropic)', incorporating potential moment of interaction.
B Social (mean)	Influences the strength of the social force between two pedestrians similar to 'B Social (isotropic)', but incorporates the relative speed between two pedestrians	Similar to 'B Social (isotropic)'	Similar to 'B Social (isotropic)', incorporating potential moment of interaction.
VD	Accompanies 'A social (mean)' and 'B social (mean)' as prediction time horizon for potential conflicts.	Increasing value leads to larger degree of evading opposing pedestrian	Accepted distance toward another pedestrian.
Noise	Random force that is added to the systematically calculated forces if a pedestrian remains below his desired speed for a certain time.	Increasing value leads to better prevention of deadlocks	'Politeness' in very busy environments.

Based on this overview, the three parameters are identified to be most relevant to altering the capacity flow and standstill density: τ, A Social (isotropic) and B Social (isotropic). Their relevance for alteration is described in Table C.14.
Using the calibration method described by Kretz et al. [2018] for the desired speed distribution and the social forces parameters mentioned above, it has been tried to re-create similar effects as the relative effects of the background music in the case of Zeng et al. [2019]. Eventually, using the parameter values as stated in Table C.15, the effects of Table C.16 are achieved. While not perfect, they are deemed close enough to mirror the relative effects. Therefore, the altered values for the desired speed distribution and the social forces parameters as presented in Table C.15 are implemented into Vissim/Viswalk for the behavioural influence measure.
As might become clear when comparing the parameter values in Table C.15 to the descriptions of the effects of parameter changes in Table C.13, the implemented parameter changes are not necessarily in line with the expected effects. This demonstrates the complexity and non-intuitive functioning of the social forces model [Kretz et al., 2018]: by *increasing* a single parameter of the model, a similar effect might emerge compared to when multiple parameters (including the single parameter) are *decreased*.

[1] Desired speed distribution.

Table C.14: Relevance for alteration of parameters values regarding .

Parameter	Relevance for calibration
τ	Is a key parameter with regards to acceleration and density.
A social (isotropic)	Accepted distance towards other pedestrians is key in the standstill density.
B social (isotropic)	Accompanying parameter of A social (isotropic) and influences headways and acceleration.

Table C.15: Overview of the changed parameter values to the desired speed distributions and social forces model to mirror the relative effects of background music.

Parameter		Regular value	Altered value
Des. sp. dist.[1] in [km/h]	Male	[3.49 - 5.83]	[2.97 - 4.96]
	Female	[2.56 - 4.28]	[2.18 - 3.35]
τ in [s]		0.45	0.40
A Social (isotropic)		2.72	2.55
B Social (isotropic)		0.250	0.195

Table C.16: Flow characteristics as based on the regular parameter settings in Vissim, as should theoretically follow based on the relative changes found by Zeng et al. [2019] and as follows from the parameter settings in Table C.15.

Characteristic	Regular value	Theoretically altered value	Situation using altered values in Table C.15
Free flow speed [m/s]	1.05	0.9	0.9
Capacity flow [ped/s]	1.10	1.0	0.9
Standstill density [ped/m^2]	2.16	1.7	2.0

D MODEL OUTPUT DETAILS

This appendix presents the details regarding the model output. It is described how the statistical significance is determined and how the output results are filtered to not incorporate runs where non-solving deadlocks occur.

D.1 Determination of statistical significance

In order to determine whether the effects of measures lead to a statistically significant different result than the no measure situation, a paired-t test will be executed. This test bases the rejection of the statistical null hypothesis on the mean and standard deviation of the differences between two configurations. In the case of this research, there will specifically be looked at the peak values of the various KPIs to see whether these peaks are significantly different from one another.
Relevant to note with respect to the paired-t test, is that the use of common random numbers for the randomness in the model can be applied to have a better insight into statistical significance. Using common random numbers “induces positive correlation between the observations on the different [configurations]” [Law, 2015], which is beneficial when analysing statistical significance as positive correlation means that similar results will be present when the measure does not have any effect. The other way around, when the measure does have important effects, its statistical significance will be highlighter sooner.
The first step of the paired-t test is to determine the mean difference between two KPIs, which is done through [Law, 2015]:

$$\overline{Z}(n) = \frac{\sum_{j=1}^{n} X_{measure,j} - X_{none,j}}{n} \tag{D.1}$$

Where:

- $\overline{Z}(n)$ is the mean difference of the peak values of the KPI;
- $X_{measure,j}$ is the peak value of the KPI in the analysed measure in replication j;
- $X_{none,j}$ is the peak value of the KPI the no measure situation in replication j, and
- n is the number of replications incorporated in the analysis.

Subsequently, the variance of the mean difference is determined through [Law, 2015]:

$$\widehat{\text{Var}}\left[\overline{Z}(n)\right] = \frac{\sum_{j=1}^{n} \left[X_{measure,j} - X_{none,j} - \overline{Z}(n)\right]^2}{n * (n-1)} \tag{D.2}$$

Where $\widehat{\text{Var}}\left[\overline{Z}(n)\right]$ is the variance of the mean difference.
With the mean and variance known, it is possible to establish the paired-t confidence interval using [Law, 2015]:

$$\overline{Z}(n) \pm t_{n-1,1-\alpha/2} * \sqrt{\widehat{\text{Var}}\left[\overline{Z}(n)\right]} \tag{D.3}$$

Where:$t_{n-1,1-\alpha/2}$ is the t-statistic based on $n-1$ degrees of freedom with confidence level $1-\alpha/2$ where α is the degree of significance.
When 0 does not fall within the paired-t confidence interval, the null hypothesis is rejected, indicating that a measure leads to statistically significant results. Within this research, $\alpha = 0.05$ is selected in order to analyse significance.

D.2 Deadlocks during simulation

During visual inspections of individual simulation runs, it became clear that during some runs non-solving deadlocks occurred. An example of a deadlock is visible in Figure D.1. While it has been tried to solve deadlocks as good as possible using specific routing paths and small barriers in order to separate conflicting flows in the most natural ways possible, still deadlocks occurred. It has been decided to remove runs that encounter deadlock from the result analysis, as non solving deadlocks give unrealistic insights into the crowd situation.

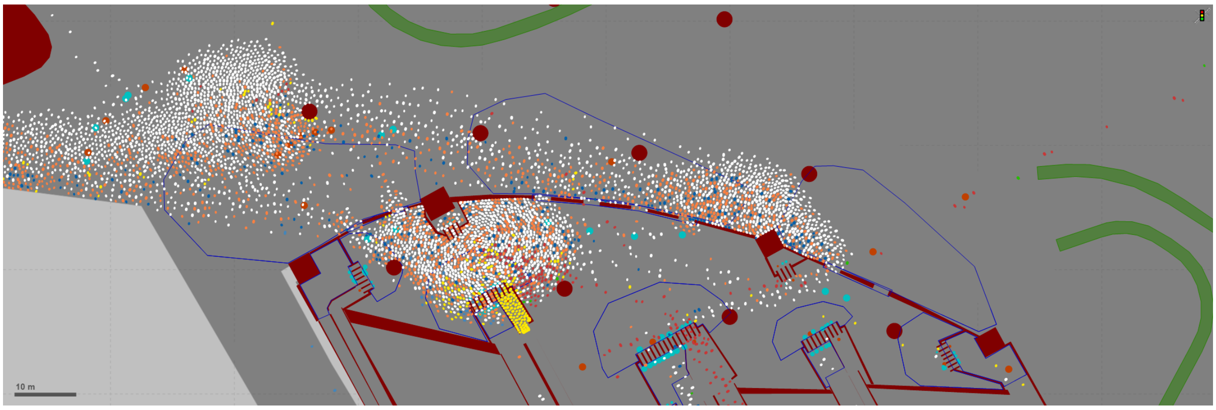
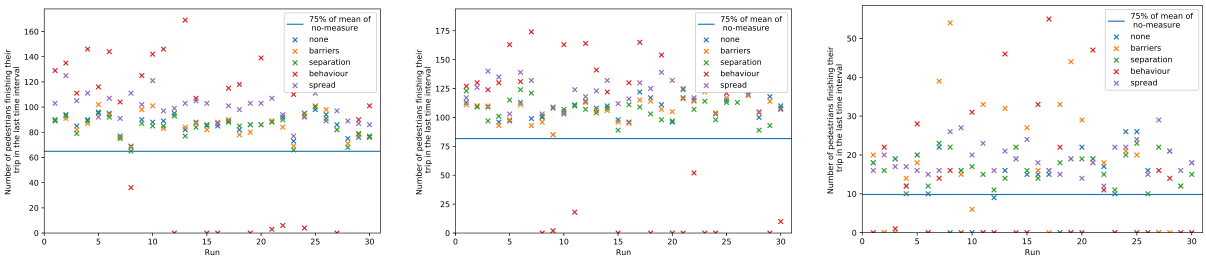


Figure D.1: Visualisation of deadlock occurring within the station in front of the check-in gates leading to track 6 & 7.

The procedure used to identify which runs encounter deadlock is based on the number of people completing their trip to the platforms, since in case of a deadlock few to no pedestrians will reach the platforms. Specific attention is paid to the platform of tracks 6 & 7 since the area before the check-in gates is specifically sensitive for deadlocks occurring as a result of a substantial number of both boarding and alighting passengers passing through this area.
First of all, it is important to note that each scenario is analysed individually, since as a result of the various scenarios the number of people reaching the platforms differs substantially.
Secondly, a threshold value needs to be defined under which runs are discarded as they are likely to have a non-solving deadlock. The initial starting point for this is to only look at the situation where there is no measure in place. Of this situation, the mean number of people reaching the platform of tracks 6 & 7 in the last data-collection interval is calculated. Only the last data-collection interval is analysed since in situations where a non-solving deadlock occurs, the deadlock will be present during the last data-collection interval. These deadlocks will drastically reduce the value of the mean number of people reaching the platform, making it possible to identify deadlock runs if the mean is higher than the value of an individual run. However, it might be that there is no deadlock occurring, leading to the discarding of non-deadlock runs simply because their number of people reaching the platform during the last data-collection interval is lower than the mean. Therefore, the threshold value with regards to discarding a run

is set at 75% of the mean. Figure D.2 shows that this threshold value is able to distinct between runs that lead to a deadlock and those that do not.



(a) Regular triple. (b) 20% increase. (c) Extreme triple.

Figure D.2: Number of pedestrians reaching the platform of tracks 6 & 7 during all runs in the various scenarios. The blue line indicates the 75% value of the mean number of pedestrians reaching that platform that serves as threshold to indicate deadlocks.

Thirdly, this threshold value is applied to all measures, as it is assumed that all measures will still have a relatively similar platform inflow as a result of the scenario. Of course a measure will influence the exact platform inflow, though it is still expected that because of taking the 75% of the mean number of people reaching the platform in the no-measure situation, the runs that will be discarded are runs with non-solving deadlock occurring.
In the end it is possible to determine for each measure and each scenario how many runs do not encounter a non-solving deadlock. An overview of this is presented in Table D.1.

Table D.1: Number of simulation runs per measure and scenario where no deadlock as visible in Figure 5.16 occurs.

Measure	**Nr. of runs without deadlock**		
	Regular triple	20% increase	Extreme triple
None	30	30	22
Barriers	30	30	20
Separation	30	30	30
Behaviour	21	18	15
Spread	30	30	30