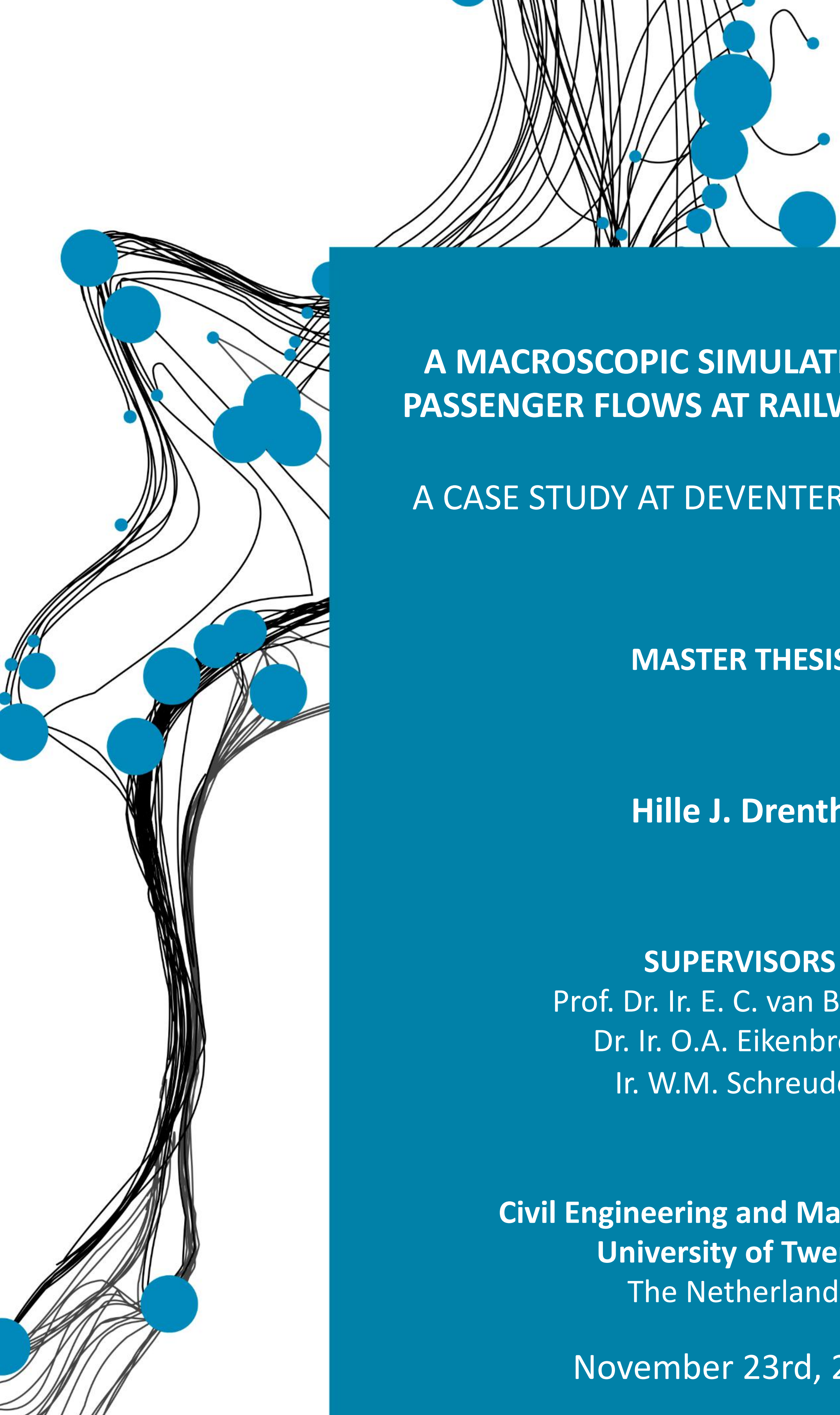

A MACROSCOPIC SIMULATION MODEL OF PASSENGER FLOWS AT RAILWAY PLATFORMS

A CASE STUDY AT DEVENTER TRAIN STATION

MASTER THESIS

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ABSTRACT

This research aims to develop a simulation model that can quickly predict pedestrian flows on a railway platform to analyze instantaneously the effects of platform closures on crowding at a platform. The study is performed to provide a tool that provides a quick evaluation tool for assessing the impact of platform design on passenger crowding. This study utilizes the macroscopic Cell Transmission Model (CTM) to simulate pedestrian densities on railway platforms and the results of this simulation study are validated by comparing the simulation output to data provided by the Dutch national railways operator NS. The model is able to accurately predict outflows at the platform for various scenarios using predefined parameters, providing valuable insights into passenger flow dynamics. It presents an efficient and adaptable simulation model with promising potential for real-world application.

PREFACE

Before you lies the master thesis “A macroscopic model of passenger flows at railway platforms”. It was established in accordance with the criteria for graduating from the University of Twente’s Civil Engineering and Management degree. This thesis was researched and written by myself in collaboration with the consulting company Antea Group. It was a tough journey and wouldn’t be possible without the inspiration and support of others.

I would like to thank my thesis supervisors. Dr. ir. Oskar Eikenbroek, whose guidance and mentorship have been instrumental in shaping the trajectory of my research. His expertise, patience, and belief in my abilities were after each rendezvous a constant source of inspiration. Ir. Wouter Schreuder, your invaluable guidance on navigating professional interactions within the business world and your help with this thesis has been instrumental throughout this journey and will undoubtedly continue to shape my future endeavors. Your expertise and support will someday deliver you your long-wished personal statue, and I am genuinely grateful for your mentorship. Moreover, I express my heartfelt thanks to my professor Prof. Dr. Eric van Berkum for his invaluable contributions to my academic and personal growth last years.

To my fellow graduate students and friends, your companionship and shared intellectual discussions have been a source of motivation and comfort. I would like to specifically mention Karsten and Thom, who have been my confidants and co-conspirators in navigating the challenges and endeavors during the endless study sessions in this master’s trajectory. In addition, I want to express my gratitude to Vanja and Vera for always being a source of inspiration and assistance. Your encouragement and unlimited support have been my pillars of strength.

I must extend my heartfelt gratitude to my family. Heleen and Nanne, your unending love, and belief in my abilities have been my rock. I would not be where I am today without your unwavering support. My brother, Jan, who remained steadfast in offering invaluable motivation and feedback, even during the final weekend before submission.

Finally, to my partner, Muriël, your unwavering patience, boundless love and support have not only been the bedrock of my academic life but also the motivating force behind all challenging moments. Your resolute belief in me has consistently provided the resilience needed to overcome obstacles. I am immensely grateful for your constant presence and the countless times you went above and beyond to help, even during the late hours, which made this academic journey truly possible.

This thesis is a reflection of the collective efforts, sacrifices, and belief of those who have touched my life. While these acknowledgments are but a glimpse of the many who have contributed to my academic growth, they serve as a reminder that knowledge is a collaborative venture, and no achievement is truly individual.

Hille Drenth
Enschede, October 25, 2023

SUMMARY

The efficient movement of passengers on railway platforms is paramount for ensuring safety and comfort during travel. Predicting pedestrian flows in such environments is a complex task due to the intricate interactions between passengers and their surroundings. The creation of a simulation model capable of quickly forecasting passenger flows on railway platforms holds significant promise in offering valuable insights into passenger flow dynamics. This tool can be instrumental for engineers and railway operators, enabling them to optimize platform designs during construction and enhance passenger safety. The following thesis introduces a macroscopic model designed to predict passenger flows at railway platforms, addressing these critical concerns.

Chapter 1: Introduction sets the stage by exploring the motivation behind this research. It also provides essential context regarding the prediction of pedestrian flows, encompassing the various approaches used in the literature and their inherent limitations. The chapter concludes by emphasizing the knowledge gap in understanding pedestrian behavior at platforms and the need for a practical tool to assess the impact of bottlenecks in railway stations.

Chapter 2: Research structure outlines the parameters of this study. It defines the research scope, including geographical and temporal considerations. The chapter establishes the research objective, which centers on the development of a simulation model for predicting pedestrian flows on railway platforms quickly and accurately. It also outlines the key research questions, including different modeling approaches, accurate prediction during peak hours, and factors influencing the model's performance. These questions converge to address the primary research question: "How to determine the level-of-service concerning the predicted pedestrian density on a railway platform with a simulation model that can easily be adapted to evaluate the impact of a cordoned-off construction area?".

Chapter 3: Theoretical Background delves into the fundamental principles, design standards, and regulations guiding railway platform layouts. It also introduces a prevalent method for assessing pedestrian flows and its application in this research. Moreover, the chapter explores various modeling strategies for simulating pedestrian flows and articulates the choice of the Cell Transmission Model (CTM) as the most suitable approach for this study.

Chapter 4: Methodology offers a comprehensive exploration of the model's construction. It delineates the structure of the Cell Transmission Model, rooted in the macroscopic fundamental diagram theory. The chapter shows how the model handles different pedestrian flows, incorporates Dutch rolling stock, and integrates essential input variables, such as pedestrian characteristics. Specific attributes related to the case study are also detailed. The chapter further discusses the model calibration process, which involves adjusting parameters to match real-world pedestrian flows.

Chapter 5: Results provides insights into the study's findings. It starts by establishing the replication number for confidence intervals, followed by the model calibration and validation

methods. The chapter scrutinizes the effects of various model parameters through sensitivity analysis, shedding light on the impact of parameter changes on train outflow. The chapter culminates by examining the implications of closing a railway platform and the ensuing bottlenecks.

Chapter 6: Discussion engages in a critical discussion of the research and its outcomes. It scrutinizes the assumptions underpinning the model and delineates the study's limitations, particularly its reliance on the macroscopic flow theory and data from a limited set of railway platforms. The chapter closes by offering recommendations for future research, including the potential consequences of implementing level boarding.

Chapter 7: Conclusion summarizes the main findings and their significance. It underscores the value of using the Cell Transmission Model to assess platform closures' impact on passenger flows. Despite some simplifications, the model exhibits practical utility and highlights areas for future refinement, such as considering factors related to waiting location attractiveness.

In summary, this thesis endeavors to advance our understanding of pedestrian flows on railway platforms by introducing a valuable predictive tool. By addressing these research objectives, the study seeks to provide a quick evaluation tool for assessing the impact of platform design on passenger crowding. Each chapter contributes a distinct piece to this research, and collectively, they provide a comprehensive exploration of this critical subject matter.

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1 INTRODUCTION

The introductory chapter first motivates this research and the relation to the client for whom the thesis is performed (Section 1.1). It is followed by a literature review on the prediction of pedestrian flows (Section 1.2) to gain initial information and identify knowledge gaps (Section 1.3).

1.1 Motivation

The national railway infrastructure in the Netherlands is managed by ProRail. This management incorporates construction, maintenance, management, renewal, expansion, and security of the Dutch rail network. However, ProRail does not perform infrastructure construction and maintenance by itself; instead, it is sub-contracted to maintenance contractors. One of these contractors is Antea Group, an international engineering and environmental consulting firm. Antea Group's Rail Advisory Division is responsible for the design of the engineering work of ProRail's rail infrastructure.

Railway platform construction and renovation projects are among the rail sector's project categories in which Antea Group is active. When activities such as maintenance or construction work are taking place at a train station, certain parts of the platforms or walkways may be temporarily closed. This may affect the flow of pedestrian traffic, since it can create bottlenecks that potentially cause pedestrian congestion on the platform. It is important to anticipate these effects while determining the plan for construction work to find a balance between loss of function of the platforms and the costs of these temporary closures (ProRail Spoorontwikkeling, 2005).

Currently, the Rail Advisory division uses its expert experience to achieve the right balance in the finding of the described optimum problem. ProRail, however, demands a more detailed examination of the effects of these closures based on the normative numbers of passengers boarding and alighting at a platform. Therefore, Antea Group aims to predict the effects of forthcoming events and conscientiously incorporate them into the design procedure. This suggests a change to a quantitative approach that is predicated on scenario evaluation. The quantitative analysis must provide predictive information about how pedestrians will be affected when platforms or walkways are closed.

In summary, the goal of Antea Group is to build a model that can accurately offer information on pedestrian flows on a railway platform based on given numbers of boarding and aligning passengers in various scenarios to make a comparison between these scenarios possible within a minute. Furthermore, it should be possible to integrate the developed model into an optimization algorithm so that the building site architecture can be automatically optimized in the future.

1.2 Prediction Pedestrian flows

The number of pedestrians throughout the day fluctuates at the train stations. This also applies to the quantity of pedestrians who move over platforms. So, at railway stations, the number of pedestrians changes rapidly and can fluctuate by multiple orders of magnitude every day (Hänseler, Bierlaire, Farooq, & Mühlematter, 2014). These flows can vary from several individuals in off-peak hours to crowds of people during peak hours or events. Analysis of pedestrian flows in real-life is impractical due to the fact that it is costly and causes unnecessary inconvenience for pedestrians (Hänseler, van den Heuvel, Cats, Daamen, & Hoogendoorn, 2020).

However, a computer-based model can provide a picture of future pedestrian flows without disturbing reality. Therefore, it acts as a digital twin (Grieves, 2015). This can be done by using a simulation tool so that a user can gain insight into pedestrian flows by evaluating different scenarios (Davidich & Koster, 2013) without disturbing reality on the forehand. Simulation approaches can be divided into microscopic modeling approaches and high level of detail but are slow to operate, and fast, less detailed, macroscopic modeling approaches (Duives, Daamen, & Hoogendoorn, 2013). In between, a mesoscopic model is more time-efficient compared to the microscopic level. Where microscopic models tend to determine the flow of pedestrians considering pedestrians as individuals (Tordeux, Lämmel, Hänseler, & Steffen, 2018) are pedestrians in, a mesoscopic model considered as a flow or volume.

1.3 Knowledge gap

When it comes to identifying the flow characteristics on railway station platforms, there is a significant information gap in the field of transportation research. Research on the passenger capacity of these platforms has been limited. However, a glimpse of clarity appears in Van Den Heuvel (2022), which makes a persuasive case that the passenger capacity of railway platforms may be limited to three key elements: 1) standards of the width of the buffer zone along the edge of the platform, 2) for the maximum queue at a platform exit and 3) timetabled train dwell times to limit congestion.

However, a crucial element within these promising standards remains obscure. As passengers navigate these platforms, the behaviors, decisions and responses are perplexing difficulties that hold the key to unlocking more accurate forecasts. Pedestrian behavior characteristics at platforms are, for example, walking speed, route choice and waiting position. Its behavior is described at three levels: 1) strategic, 2) tactical, and 3) operational level (Daamen, 2004). At the strategic level, a pedestrian makes choices about the activities they wish to engage in, including the sequence of these activities. While certain activities, such as purchasing a sandwich, are optional, others are obligatory, such as buying a ticket before boarding a train in cases where a passenger does not yet have one. The tactical level of pedestrians has established a list of activities they intend to carry out. The sequence in which these activities are executed is based on the prevailing circumstances. The level of operation of pedestrians makes decisions for the immediate next time period.

The lack of insight into pedestrian behavior introduces a significant layer of complexity to the overall understanding of the problem. As a result, precise predictions become difficult to make and the riddle remains unresolved. In view of this problem, a practical approach takes precedence. Furthermore, the absence of a readily applicable tool for rapidly assessing the impact of platform bottlenecks remains a particularly pertinent concern in the context of this study.

2 RESEARCH STRUCTURE

This chapter defines the scope of the research (Section 2.1), outlining its boundaries and context. It proceeds to establish the research objective 2.2), which serves as the guiding purpose. The research questions 2.3) follow, guiding our quest for answers aligned with the research objective. Additionally, this chapter offers an introductory glimpse into the key characteristics of the case study (Section 2.4), essential for understanding its real-world context. Finally, the research technique (Section 2.5) will enlighten the methodology employed in this research. These elements provide a foundation for subsequent chapters, ensuring a focused and purposeful exploration that contributes to the field of study.

2.1 Scope

Since Antea Group's Rail advisory group designs the engineering works at Dutch train stations, this research focuses on railway platforms of stations in the Netherlands. The research considers a case study of railway platforms at Deventer railway station. This project focuses on developing a specific simulation model tailored for passengers traveling with NS train types. The scope of this project is limited to addressing issues and optimizing performance during peak hours. Modeling for scenarios outside these peak hours, as well as comparing the model's results with non-peak hour data, is beyond the current project's boundaries. While we aim to thoroughly test and validate our model, the scope of this project is limited to a predefined station (Deventer). Expanding the testing to include additional stations is not within the scope of this project. Since Antea Group is interested in the capacity of pedestrian flows on the platform, a macroscopic level of detail will be required. Therefore, individual pedestrian behavior is not of interest in the scope of this thesis.

2.2 Research objectives

The main objective of this research is to develop a model that could quickly predict pedestrian flows on rail platforms to analyze and distinguish the effects of potential closures on crowding at a platform. Therefore, the pedestrian flows on the platform have to be modeled. This model should be able to show the densities (number of passengers per square meter) on the platform during peak hours, should translate this into a crowding assessment, and should be able to generate these results in a few minutes so that consultants can run it while weighing different alternatives for the cordoned-off working areas.

2.3 Research questions

In order to achieve the aforementioned objective, the following main research question is drawn up:

How to determine the level-of-service concerning the predicted pedestrian density on a railway platform with a simulation model that can easily be adapted to evaluate the impact of a *cordoned-off construction area?*

Sub research questions
The main research question is split into three sub-questions:

1. *What are the different modeling approaches that can be used to model pedestrian densities at a railway platform, and how do they compare in terms of their suitability and accuracy in relation to the available data?*
2. *How to accurately predict the pedestrian density on a railway platform based on simulation during peak hours?*
3. *What are the key factors that influence the performance of the model?*

2.4 Case study

This research will be conducted with a case study at the Dutch train station Deventer. This station was chosen because it has both a side and an island platform and only serves one railway operator (NS). Therefore, for data collection, this study is only dependent on data from one operator. Also, since this station is located near the Antea Group's office and is part of the authors' commute trip, site visits are possible to gain knowledge of the station and the pedestrian and train processes.

Deventer station is located in the eastern part of the Netherlands in the province of Overijssel. As a major transport hub, it serves as a gateway to the city of Deventer. Additionally, it facilitates transfers between the north-south Zwolle-Arnhem railway line and the east-west Almelo-Amersfoort railway line, as shown in Figure 2.1. Six series of trains have a stop in Deventer: 1 international intercity (140/240), 4 national intercities (1500, 1600, 1700, and 3600), and finally 1 regional sprinter train (7000). All these train series serve Deventer station in both directions (Nederlandse Spoorwegen, 2023). An overview of these series is shown in Table 2.1. For clarity, these series are explained for one direction, but each series runs in both directions.

Table 2.1: Overview of train series serving Deventer railway station

Series	Train type	Route
140/240	NS International / DB Fernverkehr intercity	Amsterdam Centraal – Deventer – Berlin Hbf
1500	NS intercity	Amsterdam Centraal – Deventer
1600	NS intercity	Schiphol Airport – Deventer – Enschede
1700	NS intercity	Den Haag Centraal – Deventer – Enschede
3600	NS intercity	Roosendaal – Deventer – Zwolle
7000	NS sprinter	Apeldoorn – Deventer – Almelo

In 2019, Deventer station handled a daily average of 25.154 passengers. 21.458 of these passengers have Deventer as their origin or destination, and 3.696 people need to transfer to another train at Deventer (Nederlandse Spoorwegen, n.d.). These figures represent the latest data prior to the significant detrimental impact of the Covid pandemic on passenger numbers in 2020 and 2021 (Nederlandse Spoorwegen, 2022). According to ProRail's categorization (ProRail, 2023), this quantity of passengers places the station in the Mega category, being the second highest category.

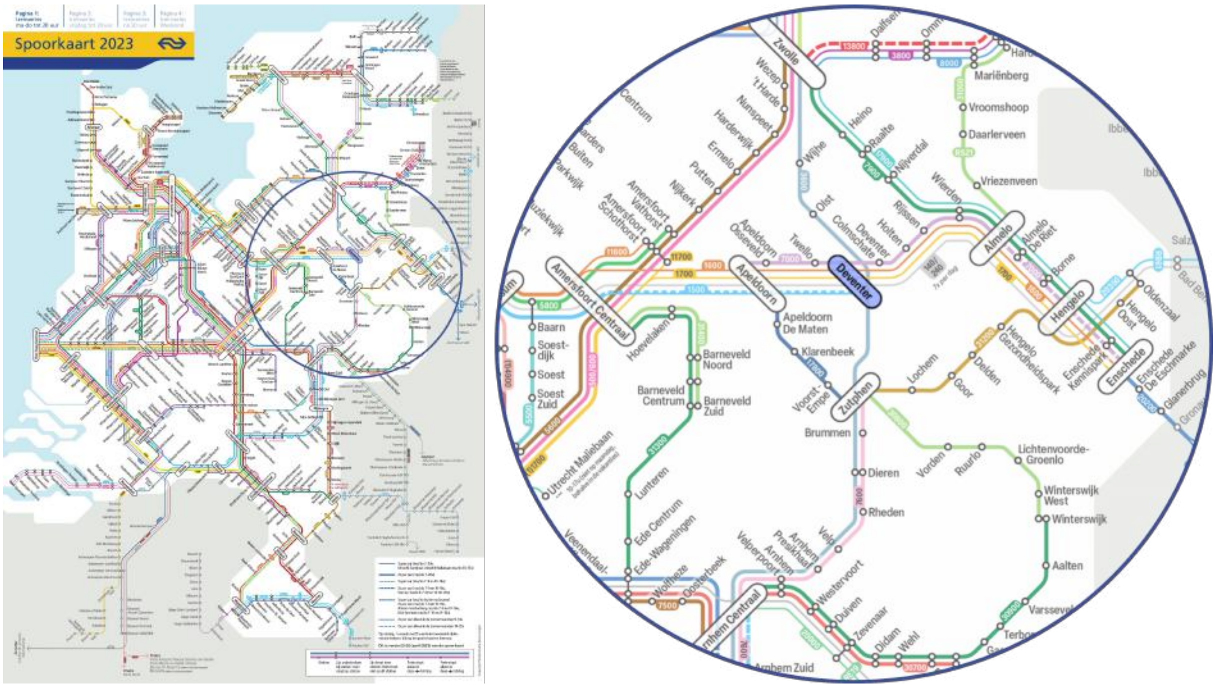


Figure 2.1: Location of Deventer station in the Dutch railway network. [Adapted from (Nederlandse Spoorwegen, 2023)]

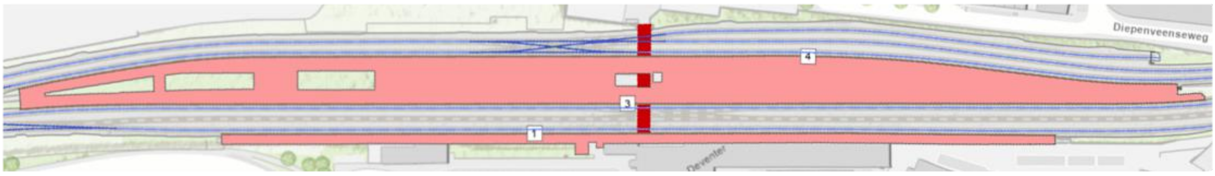


Figure 2.2: Layout of Deventer station (Prorail, 2023)

The layout of Deventer station consists of one side platform and one island platform, as shown in Figure 2.2. The side platform is located next to track 1 and generally serves the terminating intercity trains from and towards Amsterdam Central (1500 series) and the intercity trains to Enschede (1600 and 1700). The island platform is located between tracks 3 and 4. Track 3 serves mostly the intercity trains towards Zutphen (3600), the sprinters towards Almelo (7000), and the international intercity towards Berlin (140/240). Finally, track 4 serves predominantly the intercity trains from Enschede (1600 and 1700) and towards Zwolle (3600), the international intercity towards Amsterdam (140/240), and the sprinter towards Apeldoorn (7000).

The two platforms are connected to each other by a transfer tunnel (shown in red in Figure 2.2). This tunnel also connects the platforms to the two entrances of the station. The main entrance is located on the south side of the station and the secondary entrance is located on the north side. The main entrance facilitates a connection to the city center and connections to other means of transport: buses, taxis, guarded bicycle sheds, shared public transport bikes, and a kiss-and-ride zone). The secondary north entrance facilitates an unguarded bike shed and a connection to an adjacent neighborhood.

2.5 Research technique

To answer each of the aforementioned research questions, various types of techniques are applied. Therefore, some approaches are outlined for responding to the research questions based on the monitoring-measures-modeling structure that is applied to the subquestions. Figure 2.3 presents a condensed summary of the research structure along with brief explanations of how the approach to responding to the many research topics is linked.

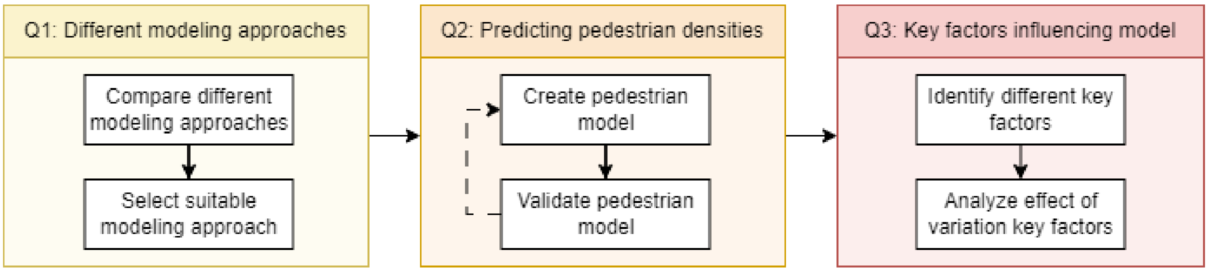


Figure 2.3: Overview of research technique

In an effort to establish a solid foundation for the simulation methodology, the initial step involves an exhaustive explanation of the design standards governing Dutch railway platforms. This should provide deep insight into the spatial arrangement, architectural attributes, and functional characteristics that underscore the railway stations in the Netherlands. In addition, an important emphasis is placed on understanding the dynamics of pedestrian congestion at these stations, which will help clarify the many factors related to pedestrian flow at the stations. The best method to forecast crowding in this study is then chosen after a comparison of several simulation approaches that cater to the prediction of pedestrian flows is conducted.

The selected technique is then used to develop a simulation model that predicts pedestrian flows on the Deventer station railway platforms. The simulation model is part of a tool that these pedestrian flows could predict with only a few input parameters. Afterward, the results of this simulation research are validated by evaluating the model's performance using data provided by the Dutch national railways operator NS. These data consist of a cumulative travel time distribution of passengers leaving specific trains and these distributions are compared to the distributions generated by the model developed in this study.

In pursuit of comprehensive accuracy and reliability, a sensitivity analysis is performed as the final step. This analysis aims to unveil the underlying intricacies of the simulation by systematically varying key factors and observing their impact on the simulation's outcomes. By discerning these influential factors, a deeper understanding of the model's behavior is gained, and critical elements that significantly affect the simulated pedestrian flows are identified.

3 THEORETICAL BACKGROUND

This chapter serves as a theoretical foundation that underpins the research. It begins by examining the principles, design standards and regulations for the layout of railway platforms, as defined by the Dutch government, ProRail and NS (Section 3.1). Subsequently, it delves into the methodology for assessing pedestrian flows (Section 3.2). Finally, the most suitable method for the simulation of pedestrian flows on rail platforms is designated, based on the different available methods presented in earlier research (Section 3.3).

3.1 Layout of the platform

According to the design regulations for passenger platforms, a platform is divided into three zones: the primary, secondary and tertiary zone (ProRail, 2020). Figure 3.1 shows an indicative overview of these zones. The primary zone is the area that connects the main entrances to the platform and where the majority of passengers wait. Along the secondary zone of the platform, longer trains can stop, especially during peak hours (6:30-9:00 and 16:00-18:30). The tertiary zone is located at the platform's end(s), where the width of the platform is particularly limited due to the track layout. This zone is utilized only in special cases where more platform length is required outside the secondary zone. There is no safe space for people waiting in this narrow zone.

Figure 3.1: Indicative length distribution of primary, secondary and tertiary zones of two platform types [Adapted from (ProRail, 2020)]

Across the width, the platform is divided into four zones. This division is shown in Figure 3.2. Seen from the side of the track, these sections are the danger zone, the walking zone, the waiting area, and the object zone. In the danger zone, passengers may be exposed to dangerous forces caused by air turbulence from passing trains. The walking zone is the area on the platform where travelers can move to spread out along the length of the platform, which runs parallel to the track. The waiting zone is part of the platform where, theoretically, travelers wait for the arrival of their train. Despite the fact that some passengers wait outside this zone, all waiting passengers are arithmetically allocated to this part of the platform. Finally, the part of

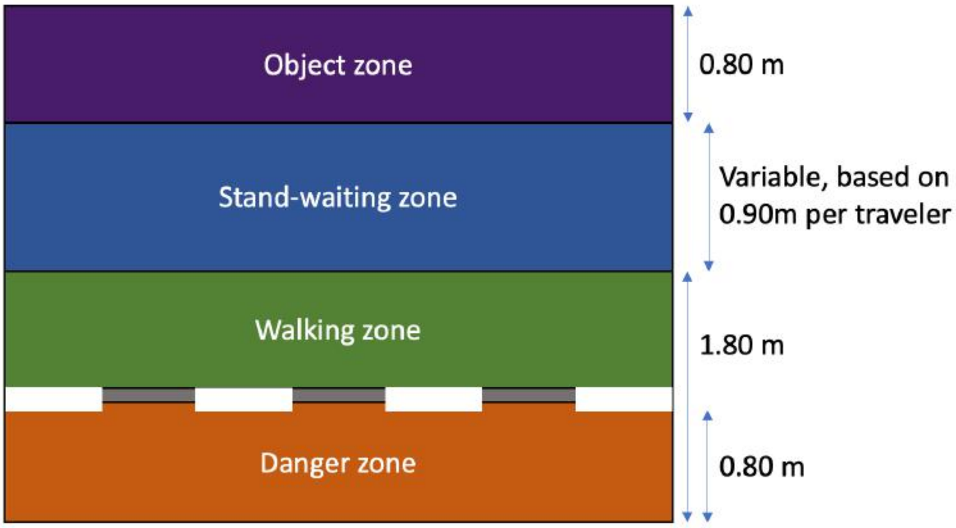


Figure 3.2: Width distribution of the four zones on a platform[Adapted from (ProRail, 2020)]. Only the stand-waiting zone and walking zone are included in the simulation model.

the non-rail side of the platform reserved for platform furniture is the object zone. During the design of a new/renovated platform, it is arithmetically assumed that waiting passengers will not use this area.

The requirements for the minimum width of the platform depend on the maximum of the following three situations (ProRail, 2020):

- **Minimal platform width** -The minimum width of the primary and secondary zones of the platform must be 2.40 meters, excluding objects. When a tertiary zone is allowed to be used, it must be at least 1.80 meters wide.
- **Number of waiting passengers** - The area of the waiting zone shall be at least equal to 0.90 m² times the number of departing passengers in the zone in question (primary/secondary) of the normative train: the busiest train expected during regular operation (ProRail, 2020)
- **Number of boarding and alighting passengers** - The net platform area excluding the functional footprint of the objects shall be sufficient for all departing travelers on the basis of 0.90 m² per traveler and for all arriving travelers on the basis of 1.50 m² per traveler. Furthermore, the net width, excluding the functional footprint of objects and a 0.90-meter strip along the platform's edge, should be wide enough to accommodate 42 arriving passengers per meter per minute.

3.2 Assessing the pedestrian flows

The flows and densities of pedestrians can be categorized using different methods. To standardize the assessment of pedestrian densities, the concept of Level-of-service (LOS) was introduced by Fruin in 1971. The LOS concept categorizes the level of service into different levels, ranging from A (free circulation) to F (complete breakdown) as shown in Figure 3.3. The concept of levels is based on the evaluation of several parameters such as pedestrian speed, crowding, comfort, and safety (Fruin, 1971).

This LOS concept is commonly used in pedestrian flow studies nowadays, as it provides a standardized way of assessing pedestrian densities and flows (Hänseler, Bierlaire, & Scarinci, 2016).

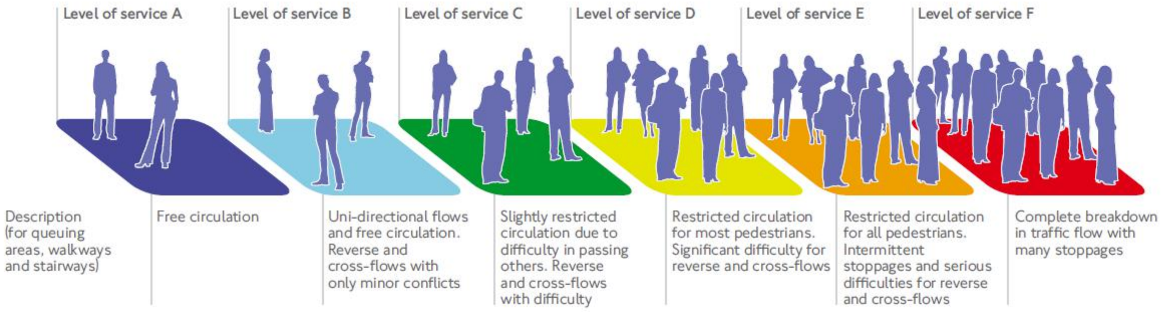


Figure 3.3: Explanation of the concept of level-of-service (Tranport for London, 2012)

Table 3.1: Level-of-Service intensities of platform sections (ProRail Spoorontwikkeling, 2005).

Level of Service	**Intensity** (pedestrians per meter width per minute)	**Average (test) value** (pedestrians per meter width per minute)
A	22-23	22
B	23-33	28
C	33-49	41
D	49-66	57
E	66-82	74
F	82 or more	

It helps to compare different scenarios and identify areas where improvements are needed. For this reason, ProRail has adopted the concept of LOS to assess pedestrian flow in train stations in the Netherlands. By adopting this LOS concept, ProRail can assess the performance of flows trough train stations and identify areas for improvement. This approach allows for a systematic and objective assessment of pedestrian flows. The intensities used by ProRail are presented in Table 3.1 and represent the number of people per meter width, passing a cross section.

To provide a comfortable and safe space for all travelers, ProRail has adapted the guidelines from Fruin to set standards to ensure a specific level of quality based on intensities, as shown in Figure 3.4 (Prorail, 2021). These design guidelines provide guidance on how to design train stations in the Netherlands to improve transfer functionality and meet the necessary standards. The Operating Standard outlines how to manage and maintain these stations to ensure that they continue to meet the standards. The Minimal Standard sets the criteria for when a station is deemed unacceptable and requires corrective action. The Operating Space refers to the space within which a decreasing quality (e.g. transfer pressure or degeneration) can be kept above the minimum desired level with timely preventive measures. Finally, the tolerated space refers to the space where the station does not meet the standards but is allowed to continue operating under certain conditions.

The guidelines are defined with pedestrian intensities. Based on the relationship measured between flow and density by Fruin (1971) as shown in Figure 3.5, these pedestrian intensities (persons per minute per meter width) can be transformed using the ProRail guidelines in Figure 3.6 into critical average densities (persons per m^2) as shown in Figure 3.7. The corresponding values are shown in Table 3.2. It should be noted that the practical capacity that ProRail wields is lower than the theoretical absolute maximum capacity (also known as the system capacity) according to Fruin (1971), which is also endorsed by Van Den Heuvel (2022).

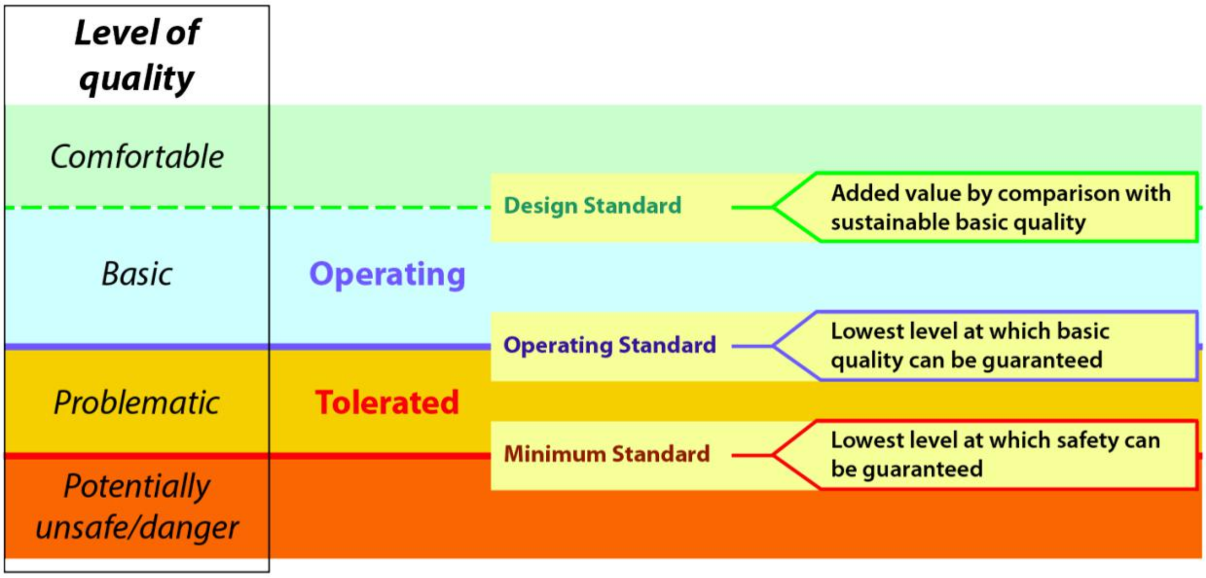


Figure 3.4: Definitions of Minimum Standard, Operating Standard and Design Standard with respect to the specific level of quality (Van Den Heuvel, 2022)

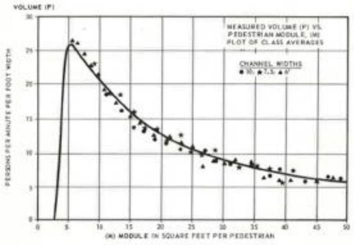


Figure 3.5: Pedestrian volume versus space for unidirectional traffic flows (Fruin, 1971)

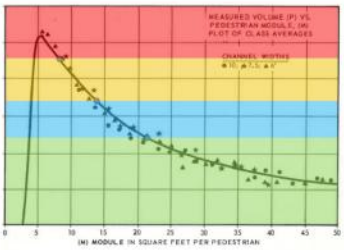


Figure 3.6: Flow guidelines according to ProRail

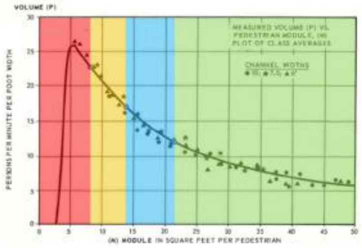


Figure 3.7: Determined density guidelines

Table 3.2: Density assessing criteria for Dutch railway platforms

Critical standard	**Maximal intensity (Pedestrian per meter width)**	**Maximal density (pedestrian/m^2)**
Design Standard	42	0.50
Operating Standard	56	0.77
Minimum standard	74	1.31

3.3 Pedestrian simulation at railway platforms

Prediction of pedestrian flows is usually done using a model. These models are distinguished based on their detail level: microscopic, mesoscopic and macroscopic.

Microscopic models aim to offer the most realistic and visually appealing representation of pedestrian movements, considering the various forces that influence an individual's behavior. The social force model (Helbing & Molnar, 1995) is a highly regarded example of this type of model and is widely used in the field (Tordeux et al., 2018). This model uses the forces individuals encounter to each other and the surroundings to determine the next step of each individual. However, the computational expense and complex algorithms associated with microscopic models make them challenging to implement and calibrate, often requiring specialized software. This makes it difficult to obtain real data-based results from these models, as highlighted by Hoogendoorn2009AModels Hoogendoorn2009AModels. Moreover, these complex algorithms result in long simulation durations for these algorithms, and although the visual representation seems credible, a lot of deviation from reality is observed. (Van Den Heuvel, 2022). Despite these limitations, the increased realism and visual appeal offered by microscopic models make them often a preferable tool in the study of pedestrian movements.

Macroscopic models simulate the flow of pedestrians based on the concept of treating pedestrians as a ”thinking fluid” (Tordeux et al., 2018). These models utilize fundamental diagrams to predict the flow of pedestrian traffic by depicting the relationship between the flow rate (expressed as pedestrians per hour) and the traffic density (pedestrians per km). Using this information, macroscopic models can predict the propagation of traffic flows. These macroscopic models are computationally cheap (Hänseler et al., 2014) and therefore have a quick calculation time. This makes it possible to run multiple stochastic models in a short time span. Based on this fast run time and the limited input parameters, the calibration of these models is relatively easy, compared to microscopic models (Hoogendoorn & Bovy, 2001). Despite their quick calculation time, these models have some potential drawbacks. The models do not consider individual interactions between pedestrians and solely rely on the relationship between flow and density. However, these interactions are generally incorporated within the flow-density relationship.

Mesoscopic models provide a middle ground between microscopic and macroscopic approaches in pedestrian simulation. By taking a hybrid approach, these models consider the flow of pedestrians at both an aggregate and individual level. Unlike macroscopic models, mesoscopic models account for individual behavior in their simulations, resulting in more realistic predictions (Hänseler et al., 2020). However, these models do not provide the same level of detail as microscopic models, as they do not consider individual interactions between pedestrians and their environment (Tordeux et al., 2018). Since mesoscopic models are less sophisticated than microscopic models, they are less computationally expensive than microscopic models. However, compared to macroscopic models, the higher level of detail of mesoscopic models makes it a more sophisticated algorithm with higher computation times.

Since the model should be able to provide a fast analysis of the effect of different sizes of bottlenecks at railway platforms, the objective of the model is to operate fast. Therefore, a macroscopic model appears to be the most suitable. Hänseler et al. has performed a study (Hänseler et al., 2014) with the well-established Cell Transmission Model of Daganzo (Daganzo, 1994). This model is often applied in pedestrian studies (Hänseler et al., 2014), requires limited input parameters, and is computationally cheap. Therefore, this modeling approach meets several criteria of the objective: namely, to be able to show the densities of pedestrians on the platform during peak hours and generate these results in a few minutes.

4 METHODOLOGY

This chapter outlines the research methodology of the study. Starting by explaining the Cell Transmission Model's operation and implementation for pedestrian flows (Section 4.1), the core of our analysis. Subsequently, it presents an interpretation of various platform pedestrian flows (Section 4.2), followed by an explanation of the simplification of the platform layout (Section 4.3). Furthermore, it delves into the incorporation of pedestrian characteristics (Section 4.4). The chapter also clarifies case-specific attributes (Section 4.5) and outlines the stochastic simulation approach (Section 4.6). Finally, it encompasses the crucial aspects of model calibration and validation (Section 4.7), ensuring the reliability and accuracy of our research findings.

4.1 The Cell Transmission model

The pedestrian densities at the railway platform are forecasted with the Cell Transmission Model (CTM) introduced by Daganzo in (1995). CTM is a macroscopic traffic flow model that has been widely used in transportation engineering and traffic management for simulation of vehicle flows. The CTM is based on the kinematic wave theory, which assumes that traffic flow behaves like a wave that propagates through the roadway network. The CTM divides the roadway network into cells, each of which represents a segment of the roadway with a fixed length. The CTM assumes that the traffic flow within each cell is homogeneous and that the flow rate is a function of the density of vehicles within the cell.

The CTM is a discrete-time model, which updates the traffic flow at discrete time intervals. The model assumes that the traffic flow within each cell is constant during each time interval. The maximum occupancy and the maximum throughput are the two parameters that the CTM defines for each cell. The maximum throughput is the highest possible flow rate that can be attained within the cell, whereas the maximum occupancy refers to the maximum number of vehicles that can be accommodated within the cell. The CTM also defines two parameters for each link between cells: the free flow speed and the jam density. The free flow speed is the speed at which traffic flows when the density of vehicles is low, while the jam density is the density of vehicles at which traffic flow breaks down and the speed drops to zero. The CTM assumes that the free flow speed and the jam density are constant over time (Daganzo, 1995).

To update the traffic flow at each time period, the CTM employs the following algorithmic procedure. The procedure involves calculating the flow rate between consecutive cells based on the density of vehicles within the cell and the maximum throughput of the cell. According to Daganzo the general procedure for updating the network each clock tick involves two steps:

1. Determine the flow on each link.
2. Transferring the flows from step 1 from each link's starting cell to its finishing cell to update the cell occupancies.

Within this model, a distinction is made between ordinary and merge links. The ordinary link has one incoming cell and one outgoing cell, while the merge link has two incoming cells and

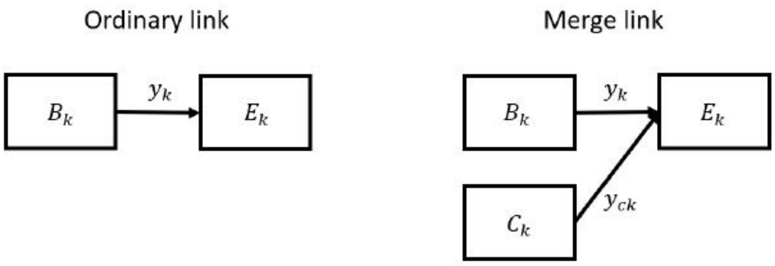


Figure 4.1: Visual representation of ordinary and merge links in CTM

one outgoing cell. Figure: 4.1 shows a visual representation of the used CTM network links. The ordinary link represents one link between two cells such that the traffic flow can only pass to the next cell. Each link k has a corresponding flow (y_k) based on the upstream cell (B_k) and the downstream cell (E_k). The merge link represents the merge of two flows in the forward direction. It consists of two links: one from the primary upstream stream cell (B_k) and one from the complementary upstream cell (C_k).

For the ordinary links, we define the maximum flow that can be sent (S_i) and received (R_I) by cell I in the interval between t and $t+1$ as:

$$S_i(t) = \min\{Q_i(t), n_i(t)\} \tag{4.1}$$

$$R_i(t) = \min\{Q_i(t), N_i(t) - n_i(t)\} \tag{4.2}$$

where, $Q_i(t)$ is the maximum number of vehicles that can flow into cell i when the clock advances from t to $t+1$, $N_i(t)$ is the maximum number of vehicles that can be present in cell i at time t, $n_i(t)$ is the number of vehicles (in this case pedestrians) that can be present in cell i at time t.

With the above definitions of (S_i) and (R_i) the flow on link k from clock tick t to clock tick $t+1$ for an ordinary link can be described as follows:

$$y_k(t) = \min\{S_{Bk}, R_{Ek}\} \tag{4.3}$$

To update the cell occupancies for each cell i the occupancy at the next clock tick ($n_i(t+1)$) is determined by:

$$n_i(t+1) = n_i(t) + y_i(t) - y_{t+1}(t) \tag{4.4}$$

For the merge links, two flows (y_k and y_{ck}) are present. Given the maximum flow that can be emitted by the two sending cells (S_{Bk} and S_{Ck}), the boundary equations for the merging connections should define the advancing flows,y_k and y_{ck}, as a function of the maximum flow that can be received just downstream:R_{Ek}. Here, the primary flow y_k has absolute priority over the merging flow y_ck.

$$y_k(t) = S_{Bk} \text{ and } y_{ck}(t) = S_{Ck}, \quad \text{if} R_{Ek} \geq S_{Bk} + S_{Ck} \tag{4.5}$$

$$y_k(t) = \max\{S_{Bk}, 0\} \text{ and } y_{ck}(t) = R_{Ek} - \max\{S_{Bk}, 0\}, \quad \text{if} R_{Ek} < S_{Bk} + S_{Ck} \tag{4.6}$$

4.2 Pedestrian flows at the platform

The Cell Transmission Model was originally designed for modeling a road network with cars (Daganzo, 1994) and is only able to simulate the traffic flow in the upstream direction. However, at a railway platform, flows in different directions are present:

- **Arriving passengers -** Passengers arriving at the station by train. After the train stops, they disembark the train and travel towards the exit of the station.
- **Departing passengers -** Passengers arriving at the station before the departure of the train and the travel towards the train platform. There, these passengers will wait until the train arrives and after arrival, these passengers will board the train subsequently when the the alighting passengers have disembarked the train.
- **Transferring passengers -** These passengers arrive at the station by train and leave the station by another train. They can change trains at the same platform or travel at the station towards another platform.

The starting point for this model is that all arriving and transferring passengers leave the platform at the same location: the primary exit of the platform. Besides, all departing passengers are already at the platform present when the train stops and disembarking of the train begins. These present waiting passengers limit the maximum available number of passengers N_i, since they already occupy a space for a pedestrian. Since there only remains a flow at the platform in the direction of the exit, a unidirectional flow is present, which is necessary for the Cell Transmission model to operate correctly.

The spatial arrangement of passengers awaiting trains on the platform is notably influenced by their walking time from the entrance, a phenomenon extensively studied by Liu (Liu, Li, Wang, Yuan Cun, & Dian District, 2016). As individuals move farther from the entrance, the concentration of waiting passengers diminishes. In our model, we capture this dependency by employing a triangular distribution along the platform's length. The apex of the triangle represents the platform entrance, with passenger numbers linearly decreasing to zero at both ends of the platform. An illustrative example of this distribution is depicted in Figure 4.2.

It's essential to note that our model simplifies the passenger waiting distribution, focusing solely on walking distance dynamics without incorporating other factors influencing the attractiveness of waiting positions, as explored by Liu (Liu et al., 2016). Consequently, the simulation model operates without necessitating additional specific platform data, streamlining input requirements. However, this streamlined approach hinges on a significant assumption—the exclusion of factors detailed by Liu that could impact waiting preferences. While this simplification reduces the complexity of input data, it represents a trade-off in terms of fully capturing the nuanced determinants of passenger behavior at the platform.

4.3 Modeled layout of platform

The platform is longitudinally divided into a number of cells. The length of the cells is chosen in a way that four cells together form the length of one train carriage. In this way both the Dutch intercity and sprinter material can be modeled. For the current operational intercity stock in the Netherlands, the doors are located at both ends of each carriage. This yields that the distribution of doors for a 3-carriage intercity train is configured in a 1-2-2-1 combination (shown in Figure 4.3): at both ends of the train single sets of doors and in between double sets. For the sprinter type of stock, the doors are homogeneously distributed along the train as shown in Figure 4.4.

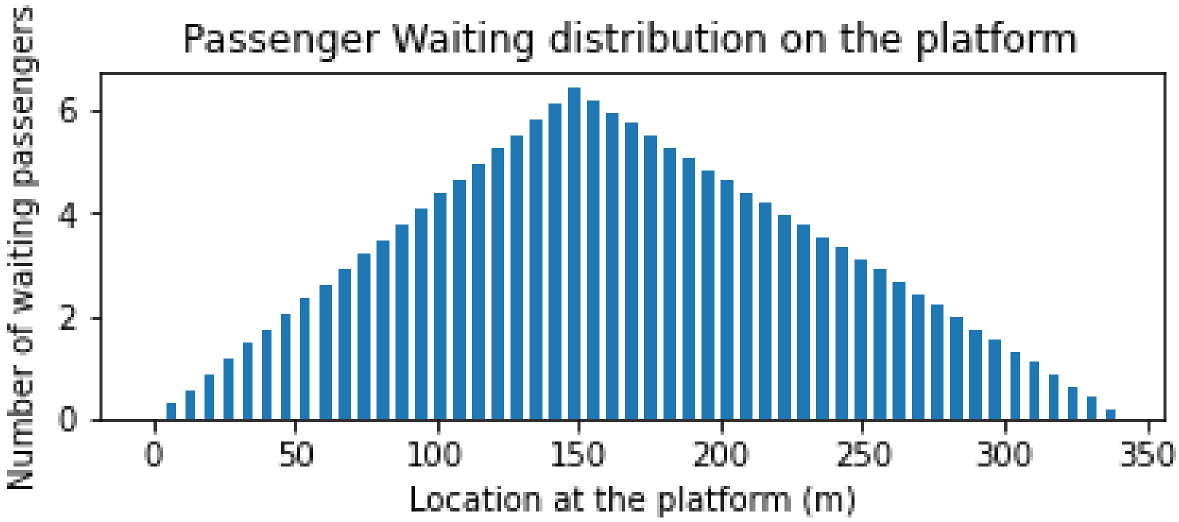


Figure 4.2: Example of Passenger waiting distribution on a platform, with an entrance at 140m

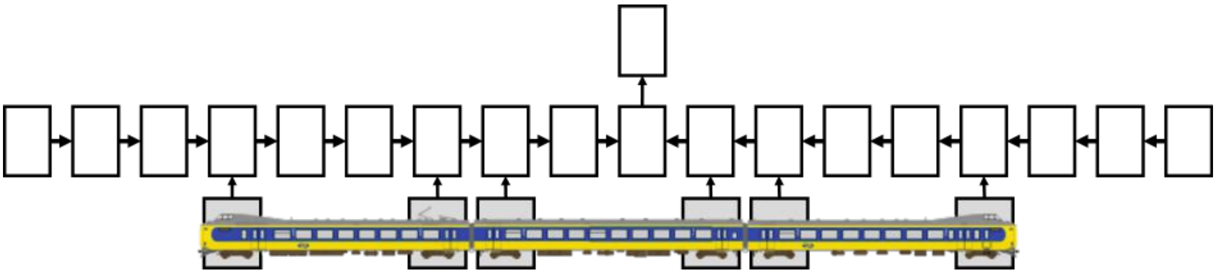


Figure 4.3: Example of CTM at railway platform for NS intercity type

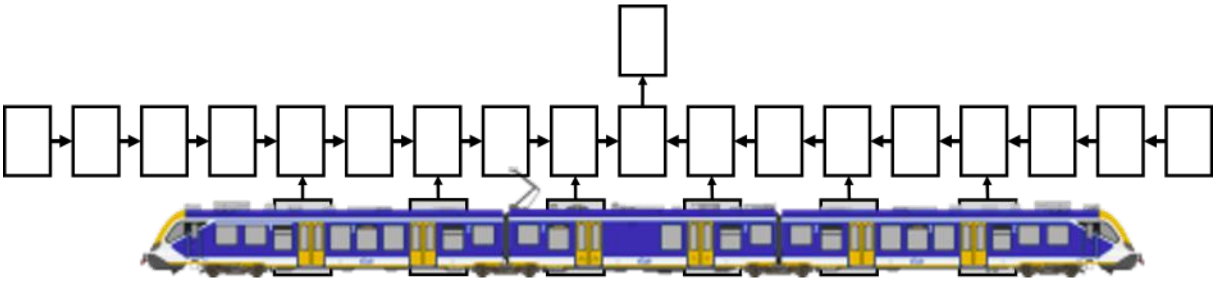


Figure 4.4: Example of CTM at railway platform for NS sprinter type

The length of the carriages differs between the intercity and sprinter types of stock. Therefore the cell length in the developed model depends on the type of stock modelled. Table 4.1 provides an overview of the typical carriage length and corresponding cell length for the rolling stock.

Table 4.1: Typical length of Dutch rolling stock

Type of rolling stock	**Average carriage length (m)**	**Corresponding cell length (m)**
Intercity (ICMm, VIRM, DDZ)	27	6.75
Sprinter (FLIRT, SNG)	20	5

The model is designed such that at the door locations, where passengers disembark the train and enter the platform, merging cells are present to simulate alighting passengers from a train. Between these merge cells, ordinary cells are present which represent the straight movement of passengers along the platform. These flows move in the direction of the primary exit, where passengers enter and leave the platform. Therefore, at the location of the rising point, the two flows merge into one flow towards the drain location at the rising platform. Simplified representations of the platforms are shown in Figures 4.3 and 4.4.

According to the functional design guidelines of ProRail the halting location of a train is coordinated to the exit location and the length of the platform so that passenger walking times are minimized and passengers can distribute themselves evenly across the train (ProRail, 2016). Besides, due to the nature of the model that a cell can consist of only one link (ordinary) or two links (merge) a door location cannot be placed in the same cell where the exit is located. These rules are implemented in the model by locating the center of the train as closest to the exit, taking into account that the train cannot exceed the end of the platform and the doors cannot overlap with the platform exit.

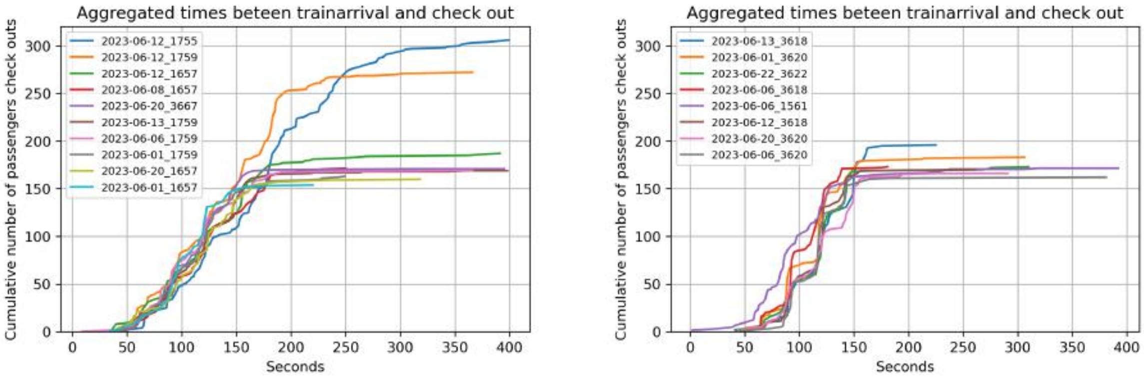
The dimensions of the cells within the CTM are determined by the width of the platform. Nevertheless, as outlined in paragraph 3.1, the danger zone may be susceptible to hazardous forces stemming from air turbulence generated by passing trains. Consequently, this zone has been designated as unsuitable for waiting or as a walkable space on the platform. Thus, individuals are restricted to occupying only the designated walking zone, stand-waiting zone, and object zone in this model.

4.4 Pedestrian characteristics

Numerous researchers have studied the length of time of the boarding and alighting process. The impacts of direction (boarding vs. alighting), step height (level vs. one or more steps), and door width have been studied. In his dissertation, Van Den Heuvel collected previously conducted studies on boarding and alighting rates of trains. He concluded that these boarding and alighting speeds would be expected to be between 0.7 and 1.25 seconds per passenger for typical Dutch rolling stock (Van Den Heuvel, 2022) and these results match the results that Wiggenraad obtained from measurements on typical Dutch rolling stock (ICMm, VIRMm and DDZ) that still operate today (Wiggenraad, 2001). The boarding/alighting speeds relate to boarding/alighting rates of 0.8-1.43 passengers per second. This rate is modeled as a stochastic property of the simulation model which is implemented as a uniform distribution of 0.8-1.43 passengers per second.

Besides, the characteristics of the macroscopic flows at the platform are input parameters for the model. These include the maximal density, maximal trough put flow and free flow speed of the pedestrians. In his PhD thesis, Van Den Heuvel shows that the maximal measured density for pedestrians is around 4 pedestrians per square meter, the maximal flow is circa 1.25 pedestrians per meter per second and the free flow speed is circa 1.25 meter per second (Van Den Heuvel, 2022). These values were chosen as initial values for these parameters in the model. However, since these values show some deviation, these are calibrated based on the results section.

Noteworthy, that the cell length is based on free-flow speed and the clock-tick length: during one simulation tick all pedestrians should be able to advance to the next cell when enough space is available. Since the cell length is already based on the length of the train carriages, the time of the clock tick is will be determined based on the cell length and the free flow speed of the passengers.



(a) Check-out times track 1

(b) Check-out times track 3-4

Figure 4.5: Cumulative check-outs after train arrivals

4.5 Case study characteristics

As noted in section 2.4, in this study the calibration and validation are performed with a case study at Deventer railway station. The station consists of two platforms as shown in Figure 2.2. The first platform (along track 1) is a side platform, which is 340m long, 3.6 meters wide (including the danger zone), and has an exit located at 140m and a width of 5.2 meters. The second platform is an island platform (along tracks 3-4). This platform also has a length of 570m, a primary width at both sides of at least 6.00m, and the exit is located at 250m. The station has two exits, where check-in and check-out gates are placed.

Obtained pedestrian numbers at Deventer station are used for calibration and validation of this study's model. For this case study the outflow curves of the 10 busiest trains (based on the number of alighters) during the month of June 2023 for both the side platform 1 and island platform 3-4 are provided by NS. These curves are presented in Figure 4.5 and show the cumulative number of passengers passing the check-out gates at the station's exit at the time after the train arrived at the platform. Two curves at tracks 3-4 were excluded since those showed corrupt data.

The outflow is aggregated data based on OV-chipkaart scans obtained data, which was used to calibrate and validate the model outputs of times leaving the platform. These pedestrian flow data are based on the check-in and check-out scans performed at the depart and arrival stations. The number of boarders and alighters for each train that NS operates is determined by NS with the ROCKT2 algorithm (Van Den Heuvel & Hoogenraad, 2014). ROCKT2 is an algorithm that assigns travelers to trains based on check-ins/outs and the realized timetable and in this way accurately determines the number of in/out/transfers per train number per station (Schakenbos, Bevort, & Hogenraad, 2022).

Some of these trains ended their journey perforce in Deventer due to disruptions. Since the platforms were potentially crowded, but no data on the present waiting passengers at the platform is available, these trips are excluded from the study. Therefore, 7 trains arriving at platform 1 and 9 trains arriving at platform 3/4 are considered in this study.

The number of boarders and alighters is known and based on the check-in-check-out (CiCo) data: these people enter or leave the station through one of the gates, so from them is known they were present at the station. However, passengers transferring at the station are present at the station and are part of the passenger flows at the platforms. Since these people do not use the CiCo gates, no exact data is known. Based on the ROCKT2 algorithm, the trajectories of passengers are estimated and average factors of transferring passengers based on boarding/alighting passengers are provided by NS for this study. These transferring factors are presented in Table 4.2.

Table 4.2: Multiplication factors for transferring passengers

Track	Peak period	Multiplication factor transferring boarding passengers	Multiplication factor transferring alighting passengers
1	Morning	1.35	1.19
1	Evening	1.33	1.27
3-4	Morning	1.31	1.37
3-4	Evening	1.26	1.41

In addition to the missing transferring passengers, the CiCo data excludes travelers who pay at the gate using their bank card or a QR code they obtained through the NS app or an overseas ticket. An email confirms that, on average, 15% of travellers use their bank card and QR code (J.H. van den Heuvel 2023, personal communication, September 7). Since the majority of these individuals travel outside of peak hours, an additional 10% of the sample was assumed in this study for peak hours. Tables 4.3 and 4.4 provide overviews of the overall number of passengers after aggregating with the previously indicated multiplication factors for both transferring passengers and passengers utilizing bank cards and QR-codes.

Table 4.3: Overview of the aggregated number of boarding and alighting passengers per train at track 1

Date	Train number	Total alighting passengers	Total boarding passengers	Number of carriages	Remark
2023-06-01	1657	204	122	6	
2023-06-01	1759	213	104	10	3 Carriages ended at Deventer
2023-06-06	1759	222	113	11	
2023-06-08	1657	225	169	7	
2023-06-12	1657	249	0	7	Train ended at Deventer
2023-06-12	1755	416	0	6	Train ended at Deventer
2023-06-12	1759	363	0	7	Train ended at Deventer
2023-06-13	1759	223	80	6	
2023-06-20	1657	212	122	6	Train ended at Almelo
2023-06-20	3667	224	244	6	

4.6 Stochastic simulation approach

The observed and simulated travel time distributions are compared for the purpose of comparing the Cell Transmission model's outcomes. On the other hand, the boarding/alighting rate and the passenger distribution along the train are the two stochastic parameters of the CTM in this study. Multiple replications of the model should be carried out in order to get a reliable assessment of its mean performance. The targeted confidence interval, or the anticipated range within which the real mean average is expected to reside, determines how many replications are needed (Robinson, 2014). A significance threshold of 5% and a confidence interval of 95% were used

Table 4.4: Overview of the aggregated number of boarding and alighting passengers per train at track 3-4

Date	Train number	Total alighting passengers	Total boarding passengers	Number of carriages	Remark
2023-06-01	3620	241	121	6	
2023-06-05	3620	214	99	4	Corrupt outflow data
2023-06-06	1561	225	0	6	
2023-06-06	3618	227	23	6	
2023-06-06	3620	213	23	7	
2023-06-12	3618	223	163	6	
2023-06-13	3618	257	160	6	
2023-06-20	3618	262	209	6	Corrupt outflow data
2023-06-20	3620	219	95	4	
2023-06-22	3622	228	168	7	

for this investigation. The Confidence Interval Method (Robinson, 2014) was used to calculate the number of replications for a 95% confidence interval at a 5% significance level.

4.7 Calibration and validation technique

The flows on the two platforms of Deventer Station are calculated and modeled. Figure 4.5 illustrates that the overall number of train check-outs for both platforms is almost equal. Due to a disturbance that resulted in the trains ending at Deventer rather than continuing on to Almelo, only two trains were able to arrive on track 1, which has many more checkouts. The passenger outflow at both platforms is nearly the same, although the proportions are different. Platforms 1 and 3–4 have 3.6 and 6.0 meters of width, respectively, for both tracks. Thus, it was anticipated that there would be some congestion at platform 1 and none at platforms 3–4. Because of this, platform 3–4 is appropriate for calibrating the maximum density parameter at platform 1 and the free-flow speed parameter for passengers at platform 3–4. In order to calibrate the system, the simulated and empirical outflow curves were compared. The parameter value that produced the best match for all curves at the platform was then chosen.

These curves are transformed to relative outflow curves so that the simulation findings and the outflow curves may be compared. The percentage of passengers who departed the platform relative to the total number of passengers that did so is displayed by the relative outflow curves. Calibration of the maximum density parameters and free-flow speed was done visually comparing the measured and predicted outflow. Validation of the data was carried out visually by examining the outflow curves in relation to the observed outflow and the densities over time at the platform following this calibration.

Following calibration, the Eyeball method (visually comparing the outflow findings to the empirical data and combining this with the author’s expert opinion) was used to confirm the acquired outflow results and visualized platform density. A sensitivity analysis also examines the effect of changing the input parameters on the model’s output.

5 RESULTS

In this chapter, we present the outcomes of our study. Firstly, we delve into the results obtained through model calibration and validation (Section 5.1). We then conduct a sensitivity analysis to assess the impact of parameter variations (Section 5.2). Finally, the chapter includes the practical application of the model with a brief analysis of a hypothetical platform closure's effects (Section 5.3).

5.1 Model calibration and validation

First, the number of replications required to meet the criteria of getting results with a 5% significance level and a 95% confidence interval is ascertained. The Confidence Interval Method (Robinson, 2014) is used to determine the number of replications in order to obtain average journey times with a 95% confidence level at a 5% significance level. According to these findings, a minimum of 35 replications must be carried out in order to produce consistent findings for all scenarios that can be compared to the empirical data.

A visual comparison of the outflow curves at platforms 1 and 3–4 was used to calibrate the free flow speed and maximum density parameters. The free flow speed and maximum density characteristics obtained from this calibration are displayed in Table 5.1:

Table 5.1: Calibrated model parameter values

Parameter	**Value**	**Unit**
Free flow speed	1.2	m/s
Maximum density	1.5	ped/m^2

Two cumulative outflow curves are presented below. The arrival of train 1657 at platform 1 on June 1st, 2023 is depicted in Figure 5.1, whereas the arrival of train 3622 at platform 3–4 on June 22nd, 2023 is shown in Figure 5.2. There is a noticeable overlap between the observed empirical outflow and the predicted cumulative outflow. Other trains' outflows have similar outcomes, albeit some have a few more variations. Appendix A contains all of the outflow comparisons for the flows at platform 1, and Appendix B contains all of the comparisons for the flows at platform 2. These figures depict how passengers should behave at the platform: they should all go in the direction of the exit, and a platooning effect should be observed due to the restricted intake at various door positions.

The CTM model operates by computing the density within each platform cell at every time step. In Figures 5.3 and 5.4, we present the average density at the platform across all simulated runs for the specified trains. The horizontal axis represents time, while the vertical axis corresponds to the platform's distance. Distinct color coding is employed to represent densities: red cells denote high density, whereas green cells signify lower density. Notably, the average density of green cells consistently appears lower than that of red cells.

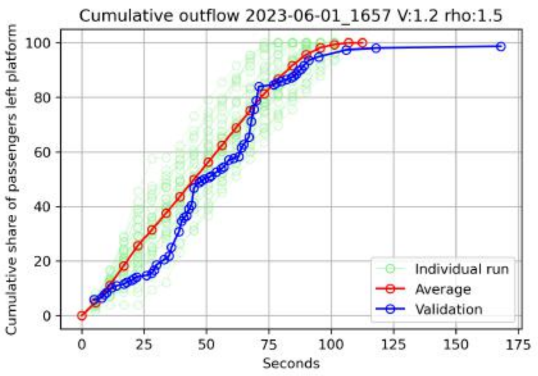


Figure 5.1: Travel times at platform 1 train 1657 June 1st

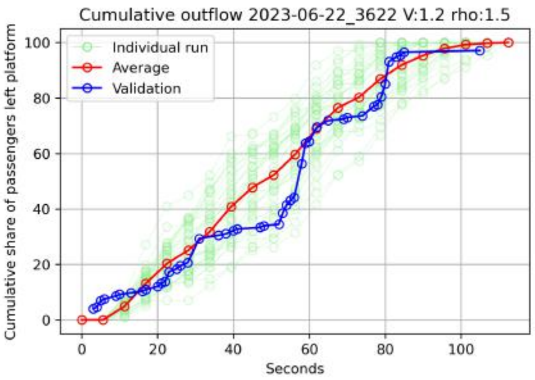


Figure 5.2: Travel times at platform 4 train 3667 June 20th

The observed variations between the validation outflow and the simulation outflow may find an explanation in the unknown distribution of passengers within the train. Our model, grounded in the assumption of an even distribution of passengers along the train carriages, operates under the practical constraint of limited insight into the specific arrangement of passengers within the train. Real-world scenarios often involve a heterogeneous distribution of passengers, influenced by factors such as door locations, seat availability, and passenger preferences. The lack of precise information regarding the spatial distribution of passengers within the train introduces a degree of uncertainty in the simulation outcomes. Variations in passenger outflow along, as evidenced in the outflow curves, may be attributed, at least in part, to the inherent unpredictability of passenger distribution within the train.

A notable pattern is observable in both Figures 5.3 and 5.4, shedding light on passenger behavior during the alighting process. The depicted densities showcase passengers disembarking from the train at the doors and subsequently traversing along the platform towards the exit point located at 140 meters. This dynamic migration of densities, perceptible as a flow towards the exit, underscores the directional movement of passengers post-alighting. The spatial distribution of densities over time effectively captures the sequential nature of passenger actions, providing valuable insights into the temporal and spatial dynamics of platform activity. This observed trend further contributes to our understanding of how passengers navigate and spread within the platform environment during their journey, thereby enhancing the interpretability of the space-time diagram.

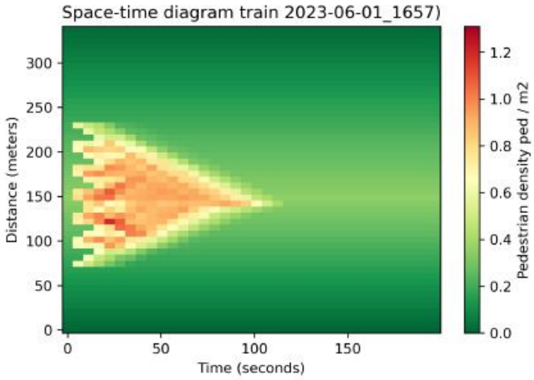


Figure 5.3: Space-time diagram platform 1 train 1657 June 1st

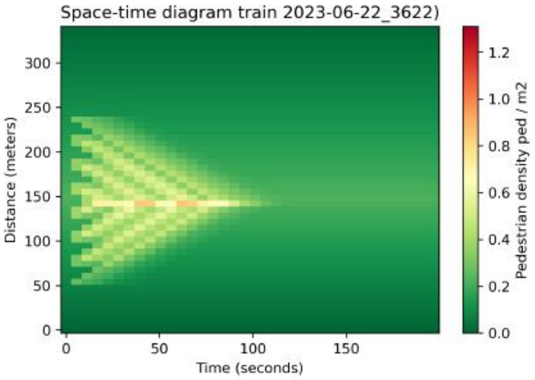


Figure 5.4: Space-time diagram platform 3-4 train 3667 June 20th

Examining Figure 5.3, a noteworthy observation emerges. Despite comparable factors such as the number of passengers boarding and alighting and the train length for both train 1657 on June 1st and train 3622 on June 22nd, there exists a notable disparity in the average density at platform 1. Surprisingly, train 1657 on June 1st induces a higher average density at platform 1 in contrast to the impact of train 3622 on June 22nd on platform 3-4, as depicted in Figure 5.4.

A key factor contributing to this discrepancy lies in the variation of platform widths. Specifically, platform 1 boasts a width of just 3.6 meters, whereas platforms 3–4 exhibit a wider dimension of 5.2 meters on all sides. This dissimilarity in widths becomes a crucial explanatory factor. Despite having an equivalent number of passengers in each cell, platform 3–4 achieves a lower density of passengers per cell compared to platform 1. This intriguing outcome emphasizes the impact of platform dimensions on passenger density, even when other variables remain constant across different trains and platforms.

Disruptions caused three trains at platform 1 (1657, 1755, and 1759, all on June 12th) to terminate their voyage in Deventer. The observed outflow for each of the three trains is slower than the model projection, indicating a notable departure from the outflow patterns predicted by the model. The effect of the interruption, which prevented any trains from departing Deventer railway station in the direction of Almelo, may account for these variations. As a result, those who intended to continue eastward were forced to choose between waiting for a train to advance to Almelo at Deventer station or using alternate routes or forms of transportation. This disruption may result in a far greater number of passengers having to wait at the station, which will undoubtedly affect the density of pedestrians and cause passenger flows to be lower than anticipated. Additionally, because these trains did not depart, there were no passengers on board for these three trains, mimicking an outflow at the station with no people waiting at all.

5.2 Sensitivity analysis

A sensitivity analysis is carried out to get further understanding of the effects of the model's various parameters. The impact of changing a parameter value on the outflow of a specific train (1657 on June 1, 2023) is demonstrated in this research. Variations in the number of passengers boarding and alighting, maximal density, free flow speed, and number of people alighting are all evaluated.

In Figure 5.5, the impact of alterations in free-flow speed on outflow becomes evident. As depicted, a decrease in free-flow speed correlates with an extended outflow time for all passengers, attributable to a reduction in their outflow rate. This aligns seamlessly with expectations, as pedestrians covering the same distance at a slower pace naturally require more time to complete their journey.

Moving on to Figure 5.6, the influence of variations in the highest achievable density at the platform on results is highlighted. Notably, passenger outflow times exhibit an extension when peak densities decrease. An interesting observation is the onset of variations in outflow timings after the initial 30 seconds, suggesting that average densities exceeding 1.3 ped/m^2 are not observed in the early stages of the alighting process. This nuanced understanding underscores the critical role of peak densities in shaping passenger outflow dynamics, particularly during the initial moments of platform activity.

The impact of the quantity of passengers boarding and disembarking is also examined, in addition to the two previously examined characteristics. The impact on outflow curves depending on the amount of persons alighting is seen in Figure 5.7. The low total number of alightings in

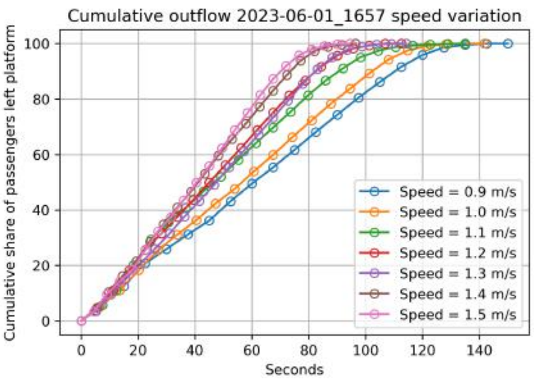


Figure 5.5: Sensitivity analysis free flow speed

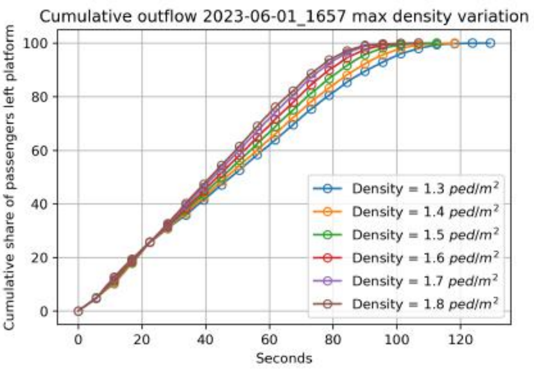


Figure 5.6: Sensitivity analysis maximal density

this instance indicates the platooning effect. Another example of this platooning effect may be seen in Figure 5.2, where people have already fled the train when they approach another door. Thus, tiny platoons of individuals go over the platform rather than combining flows appearing at the entrances. The similar idea is illustrated by the low alighting rates in Figure 5.7.

In conclusion, Figure 5.8 illustrates how the influence affects the quantity of individuals waiting on the platform. The platform density is impacted by these individuals waiting to board the train and taking up space on the platform. As a result, there is less room for passengers to disembark, and decreased outflow rates at the platform are evident when there are more people waiting.

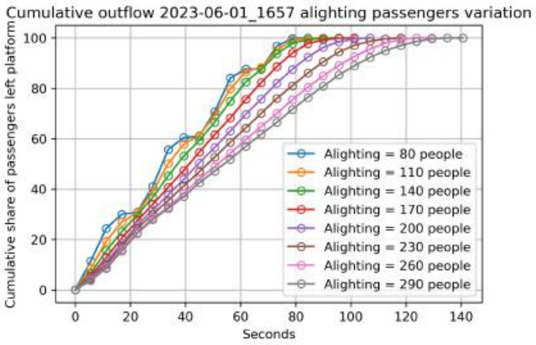


Figure 5.7: Sensitivity analysis alighting passengers

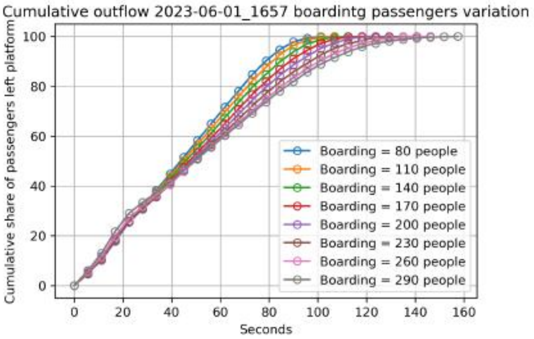


Figure 5.8: Sensitivity analysis boarding passengers

5.3 Effect of closure at platform

This study aimed to investigate the repercussions of closures at a railway platform, specifically focusing on the emergence of bottlenecks. The analysis concentrated on assessing the potential effects of bottlenecks at Deventer train station platform 1. Two hypothetical bottlenecks were simulated for this study, each with residual bottleneck widths of 1.5 and 1.3 meters, to replicate real-world scenarios resulting from closures. These bottlenecks were positioned 170 meters from the beginning of the platform.

Figures 5.9 and 5.10 offer a detailed portrayal of average platform density in simulations with 1.5-meter and 1-meter bottleneck widths, respectively. It is noteworthy that both illustrations underscore a discernible rise in average density compared to the scenario without bottlenecks, as elucidated in Figure 5.3. The intriguing aspect lies in the observation that, despite the initial

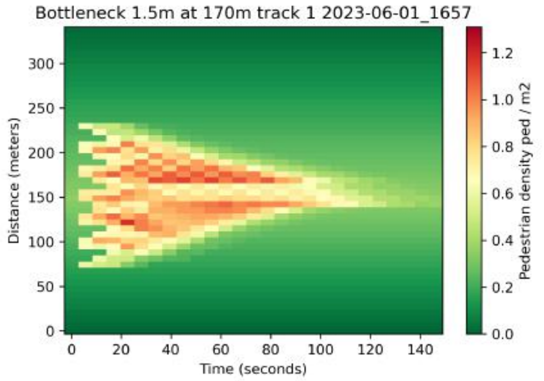


Figure 5.9: Platform density with bottleneck of 1.5m width at 170m

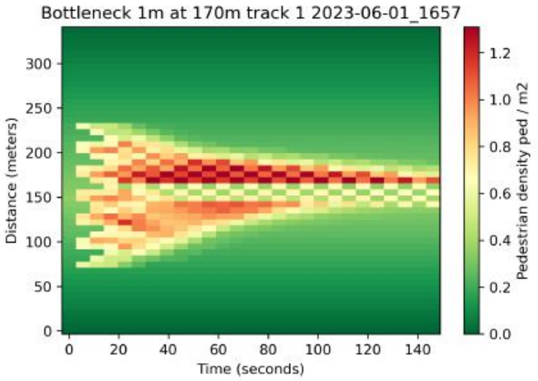


Figure 5.10: Platform density with bottleneck of 1m width at 170m

increase in average densities depicted in Figure 5.3 with a 1.5-meter bottleneck width, a further reduction to 1 meter results in even higher densities.

To delve deeper into the density variations at the platform, a comprehensive analysis involves categorizing densities using the Level-of-Service (LOS) concept. Figures 5.11 and 5.12 present the temporal distribution across different LOS categories during the simulation. Examining Figure 5.11, it becomes apparent that a bottleneck width of 1.5m does not introduce additional *potentially unsafe or dangerous* LOS values. In stark contrast, a narrower bottleneck width of 1m does lead to elevated densities in *potentially unsafe* ranges and even a rise in the number of *busy* and *problematic* categories.

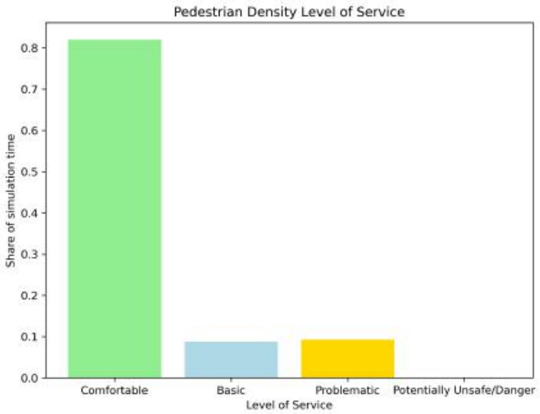


Figure 5.11: LOS with bottleneck of 1.5m width at 170m

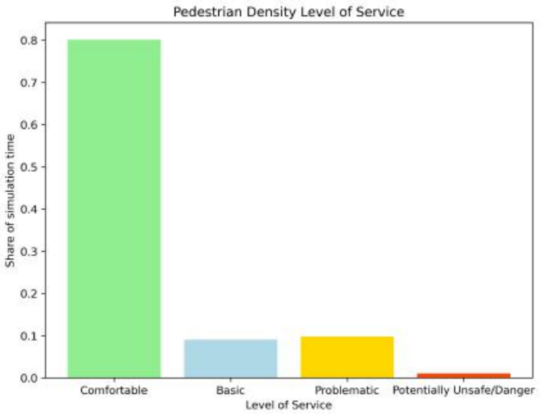


Figure 5.12: LOS with bottleneck of 1m width at 170m

This nuanced insight suggests that, from a safety perspective, implementing a bottleneck width reduction to 1 meter during construction works could result in undesirable density levels at the platform. Therefore, careful consideration and reconsideration of construction strategies and bottleneck dimensions are imperative to ensure both operational efficiency and passenger safety.The intensified congestion near the bottleneck can be attributed to reduced passenger throughput, elucidating the greater impact observed with the 1.3-meter bottleneck. This congestion manifests as a jam upstream of the pedestrian flow, as evident in Figures 5.9 and 5.10, contrasting with the reference scenario shown in Figure 5.3. The findings underscore the critical importance of considering bottleneck width in railway platform closures, emphasizing that even relatively small reductions in available space can significantly impact passenger flow and overall congestion levels.

In order to analyze these bottlenecks, 35 separate runs of simulation and aggregation took 1.09 seconds on a laptop running Windows 10 Enterprise with an Intel(R) Core(TM) i5-10310U CPU operating at 1.70GHz and 2.21GHz and with 16.0GB of RAM. This demonstrates the ability to quickly analyze many scenarios.

6 DISCUSSION

In this chapter, we delve into a comprehensive discussion of the key facets and discoveries of our simulation model, shedding light on its limitations, the contextual relevance of previous research, and the potential impact for future studies and railway operations. It is crucial to recognize the foundational assumptions that underpin our simulation.

Setting the stage for the simulation involved making several key assumptions. Primarily, we limited the simulation to uni-directional passenger flow, excluding considerations of cross flows or other complex movements. This focus solely on simulating passenger flows at the railway platform, with an exclusion of flow characteristics at the stairs, may explain deviations between the model output and validation data, given that the validation data from NS includes the stairs in the pedestrian trajectory. Additionally, assumptions were made about waiting passengers remaining stationary, contrasting with the reality where waiting passengers sometimes move along the platform.

Another notable limitation revolves around the one-dimensional nature of our model, which exclusively accounts for flows in a singular direction along the horizontal plane. The adoption of a 1D model was a deliberate choice aimed at streamlining efficiency and simplicity in our simulation methodology. While this decision facilitated rapid and dependable results, it inherently constrains the model's ability to fully depict the intricacies of passenger dynamics, especially in scenarios involving varied horizontal movements. Consequently, the model may have limitations in its applicability to situations where bidirectional flows or diverse horizontal pedestrian movements are pivotal. Future refinements to the model could explore avenues for incorporating a more nuanced representation of platform dynamics, thereby broadening its scope to encompass the complexity of passenger behaviors in diverse scenarios.

To simplify the merging flows at the platform, absolute priority was assigned to passengers alighting the train over those already on the platform. While preventing queues inside the train, this simplification may not represent the most realistic scenario at railway platforms. Moreover, the simulation did not integrate insights from Liu's research, which emphasized the influence of the attractiveness of (seating) locations on passenger choices, due to the unknown nature of attractiveness variables at the railway platforms.

Another limitation pertains to the assumption regarding the uniform distribution of passengers along the train carriages. The research operated under the premise that passengers are evenly dispersed throughout the train. However, it is reasonable to anticipate that the distribution of passengers along the train is influenced by the attractiveness of waiting locations at the platforms of preceding stations. Regrettably, this crucial factor was not integrated into our current study, marking an avenue for valuable exploration in future research. Investigating the correlation between passenger distribution along train carriages and the appeal of waiting areas at previous stations holds the potential to enhance the accuracy and realism of our simulation model.

Moreover, a cross-station analysis can shed light on the potential ripple effects of system-wide changes or infrastructure improvements, providing a strategic foundation for decision-making in the realm of railway planning and management. As passenger preferences and behaviors may vary across different locations, a network-wide investigation offers the opportunity to tailor interventions and optimize services based on the unique characteristics of each station, fostering a more responsive and passenger-centric railway system. This acknowledgment underscores the importance of considering additional variables in future investigations to provide a more nuanced and comprehensive understanding of passenger behavior and its impact on railway operations.

The introduction of a system facilitating level boarding raises intriguing questions regarding its potential implications for boarding and alighting speeds. Analyzing these consequences is vital for future planning, and it's worth noting that this approach leans towards a forward-looking perspective, as it is not overly conservative in its outlook.

In conclusion, while our simulation model has provided valuable insights, these limitations underscore the need for a cautious interpretation of its findings. Future iterations of the model should aim to address these limitations, potentially incorporating additional dimensions and complexities to enhance its representational accuracy and broaden its applicability to a wider array of scenarios.

7 CONCLUSION

In conclusion, this research represents a noteworthy advancement in comprehending passenger flow dynamics, particularly concerning the comparison to the level-of-service concept at railway platforms. The incorporation of the macroscopic Cell Transmission Model (CTM) emerges as a valuable method, poised to make a substantial contribution to evaluating the repercussions of platform closures on passenger densities. The CTM's efficient and reliable simulation capabilities, highlighted by its ability to predict outflows that align closely with OV-Chipkaart data, provide a promising foundation for its potential practical application in real-world corporate scenarios.

While the primary focus was on developing a simulation model rather than an optimization algorithm, the efficiency demonstrated by our model, executing 35 individual runs and aggregating results within a mere 1.09 seconds, hints at its potential for broader applications. This efficiency encourages further exploration and hints at the feasibility of incorporating this model into an optimization algorithm to determine optimal layouts for construction activities at railway platforms.

Nevertheless, this model relies upon several substantial simplifications, encompassing the restriction of flows to uni-directional outflow, the exclusion of cross flows, the simplification of the waiting distribution to be solely dependent on the distance to the entrance, and the assumption of a uniform distribution of passengers along the train. While these simplifications were imperative for the current study, they inherently unveil avenues for potential refinement and future exploration. Recognizing these limitations acts as a catalyst, stimulating future research endeavors aimed at enhancing and fine-tuning our approach. Addressing these simplifications paves the way for the evolution of the simulation model, rendering it more adept at capturing the intricacies of real-world scenarios and broadening its practical applications.

Additionally, as the railway industry evolves with innovations like level boarding systems, our research lays the groundwork for addressing crucial questions about their potential implications on boarding and alighting speeds. This aspect of the study offers an exciting opportunity for further exploration and potential contributions to the advancement of the field.

In summary, this research not only offers valuable insights into passenger flow dynamics, particularly in comparison to the level-of-service concept at railway platforms but also introduces an efficient and adaptable simulation model with promising potential for real-world applications. The encouraging results from the application of the macroscopic Cell Transmission Model underscore its reliability and efficacy in predicting passenger outflows. This encouragement serves as a guiding beacon for future research endeavors, steering the focus towards optimizing railway operations and enhancing the overall passenger experience.

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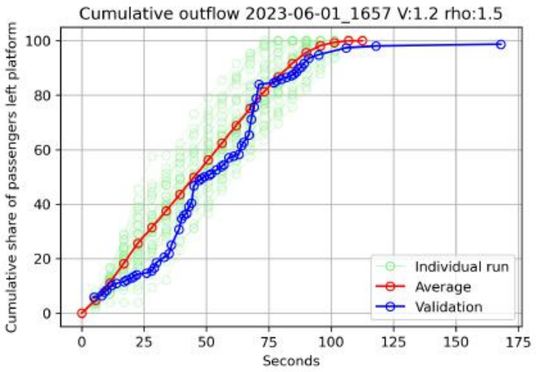
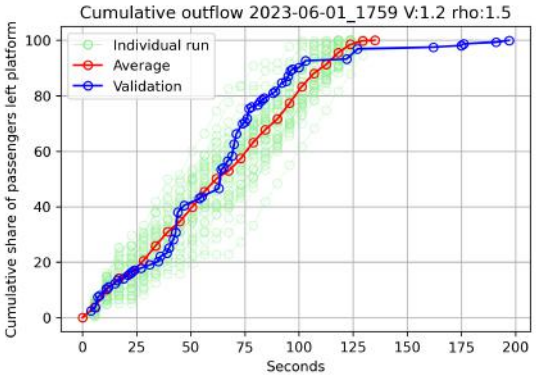
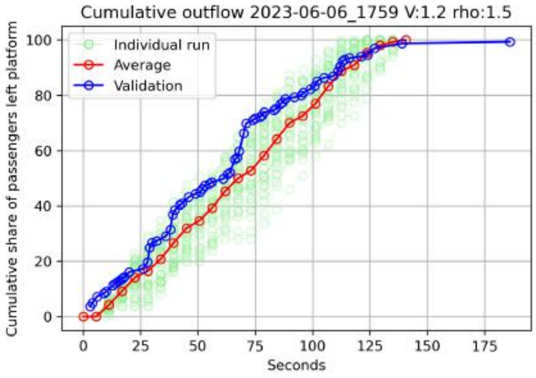
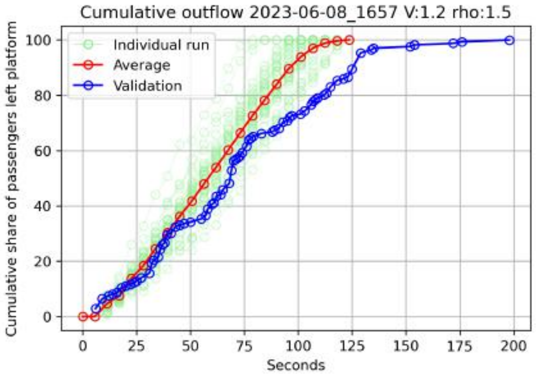
A APPENDIX A - OUTFLOW CURVES PLATFORM 1

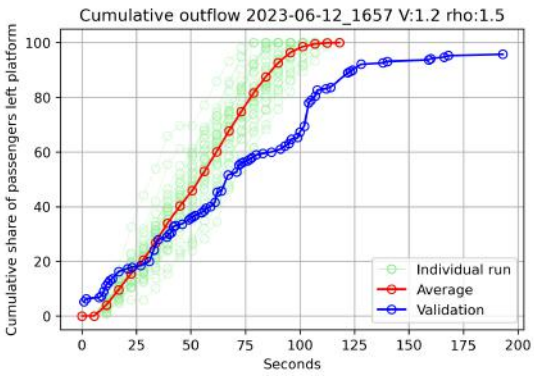
In this appendix the outflow curves of platform 1 are presented







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Cumulative share of passengers left platform
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60
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Seconds
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Average
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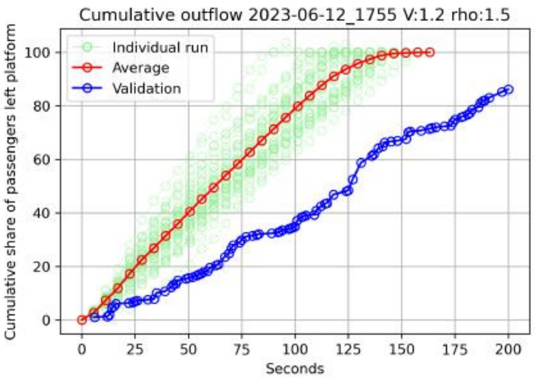
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Seconds
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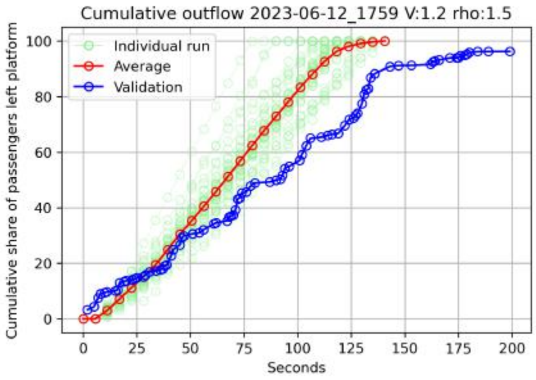
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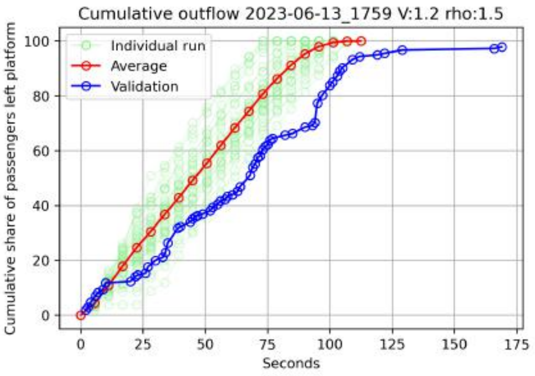
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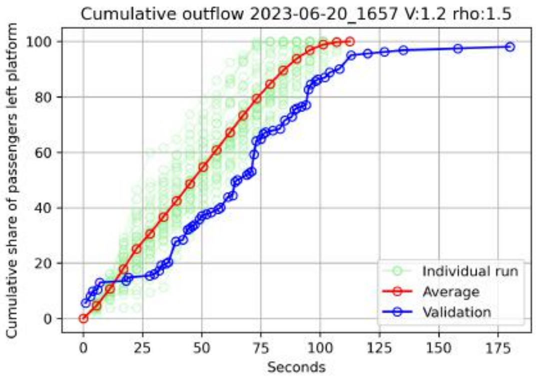
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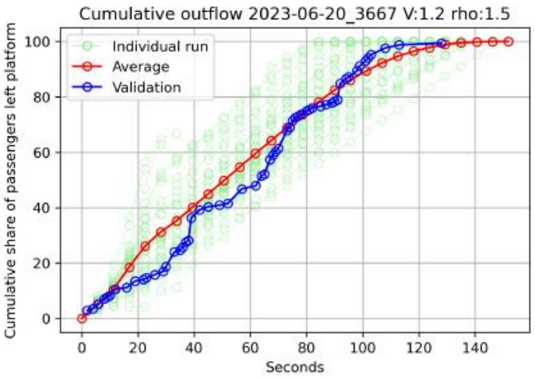
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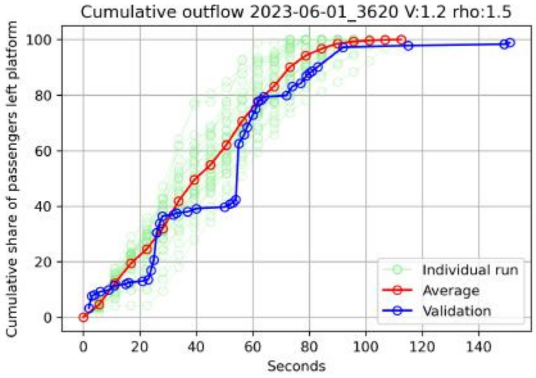
140
Seconds
Individual run
Average
Validation

B APPENDIX B - OUTFLOW CURVES PLATFORM 3-4

In this appendix, the outflow curves of platform 1 are presented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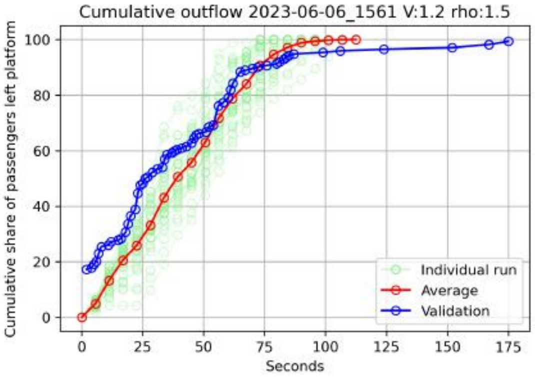
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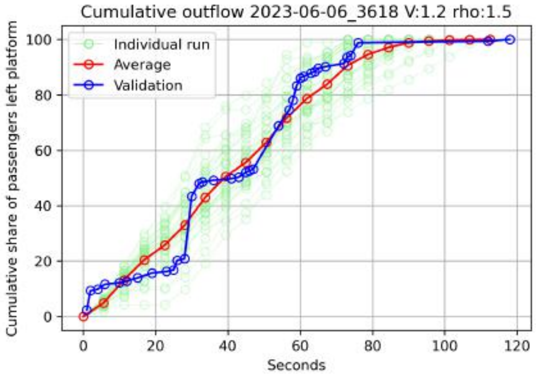
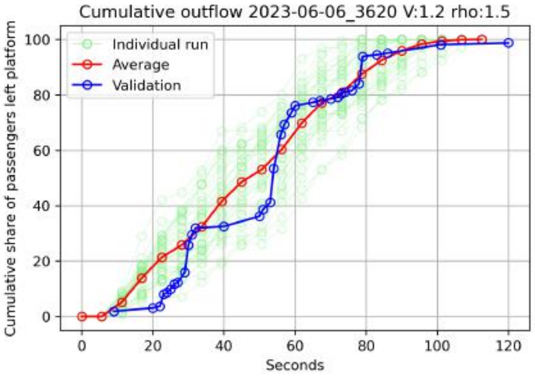
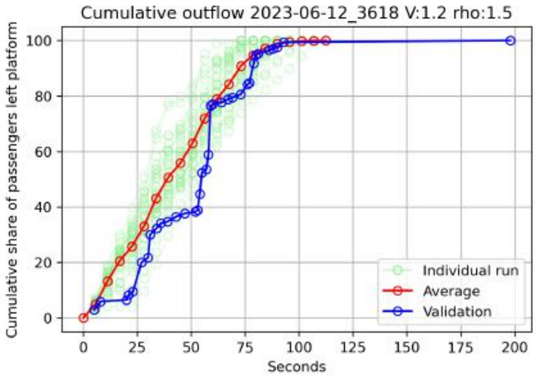
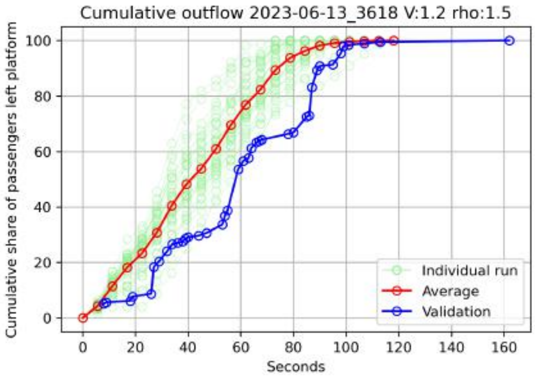
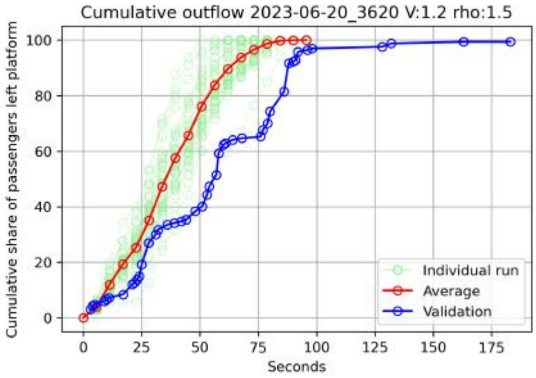
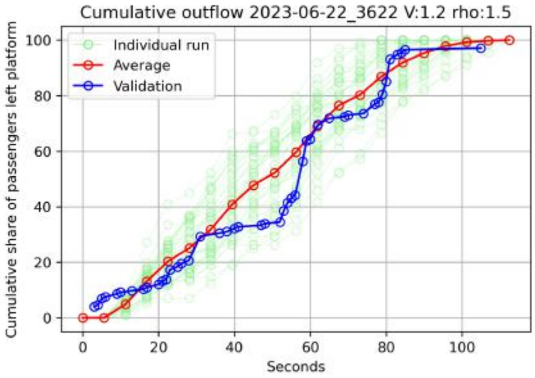

Cumulative outflow 2023-06-06_3618 V:1.2 rho:1.5


Cumulative outflow 2023-06-06_3620 V:1.2 rho:1.5


Cumulative outflow 2023-06-12_3618 V:1.2 rho:1.5
Cumulative share of passengers left platform
Seconds
0
25
50
75
100
125
150
175
200
0
20
40
60
80
100
Individual run
Average
Validation


Cumulative outflow 2023-06-13_3618 V:1.2 rho:1.5
Cumulative share of passengers left platform
Seconds
0
20
40
60
80
100
120
140
160
0
20
40
60
80
100
Individual run
Average
Validation


Cumulative outflow 2023-06-20_3620 V:1.2 rho:1.5
Cumulative share of passengers left platform
Seconds
0
25
50
75
100
125
150
175
0
20
40
60
80
100
Individual run
Average
Validation


Cumulative outflow 2023-06-22_3622 V:1.2 rho:1.5
Cumulative share of passengers left platform
Seconds
0
20
40
60
80
100
0
20
40
60
80
100
Individual run
Average
Validation