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Analysis of the operational efficiency and capacity of Mölndals Bro bus terminal

Integrating dynamic queue modeling and PTV Vissim simulation for performance evaluation and capacity assessment

Master's thesis in Infrastructure and Environmental Engineering

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Cover: Animated picture showing people boarding a bus at one of the berths at Mölndals bro

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Abstract

Urbanization, climate goals, and the need for efficient transportation have highlighted the importance of an attractive and effective public transport system. Buses play a crucial role in urban mobility due to their flexibility and cost-effectiveness. This study focuses on Mölndals bro, one of Gothenburg's major bus terminals, aiming to evaluate its future capacity using queue theory and microsimulation. The objectives include: (1) conducting a comprehensive data analysis to understand bus arrival patterns and dwell times, (2) developing a dynamic queue model based on queue theory to assess the station's capacity and probability of queue formation, and (3) performing microsimulations using PTV Vissim to explore different scenarios and evaluate system performance. The scenarios included, the station as it is operating today, the addition of another bus line, the addition of a new bus line plus two added berths. The findings indicate that none of the tested scenarios would experience significant congestion or queues, with the probability of a full station below 5% in each direction. The addition of two extra berths would further enhance capacity and proved to be the best solution to increasing capacity. The study underscores the significant impact of dwell time and scheduling on the operational capacity of Mölndals bro. This research provides valuable insights for decision-makers, as the method could be used as a tool, although it should not be the sole basis for major decisions, but rather a guidance tool for evaluating bus station capacity.

Keywords: Queue theory, microsimulation, PTV Vissim, dwell time, capacity, bus terminal

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Johan & Georgia, Gothenburg, June 2023

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1
Introduction

Population growth, increased traffic congestion, and environmental concerns are all factors that contribute to people seeking alternatives to car travel. Because of this, municipalities and governments aim to encourage individuals to utilize public transport or explore alternative modes to the car such as walking and cycling. As a result, there is a growing demand for adequate public transportation, and this trend is expected to persist in the future. To cope with the large demands of public transport cities worldwide need to make large investments in both rail and road public transport to increase the capacity and effectiveness. Sweden has set forth ambitious environmental and climate objectives, and the Region of Västra Götaland shares a similar commitment. By 2030, Västra Götaland aims to reduce climate emissions by 85% (Region Västra Götaland, 2023). Achieving these ambitious climate targets poses a significant challenge, however, through collaborative efforts among Region Västra Götaland, municipalities, the Swedish Transport Administration, and other stakeholders, it is possible to establish favorable conditions for more sustainable travel practices. In some instances, it involves utilizing existing alternative options, while in others, national or municipal policy instruments are necessary to facilitate the transition toward a more transportation-efficient society. Encouraging greater usage of public transport, cycling, and walking instead of individual car travel not only reduces the environmental and climate impact of transportation but also liberates street space (Region Västra Götaland, 2021).

Gothenburg, like other bigger cities around the world, is not immune to the global trend of increasing urbanization, and it is projected that its population will grow by 150,000 residents by 2035 (Region Västra Götaland, 2021). This growth will place additional strain on the transportation infrastructure, reducing mobility and transport efficiency. To address this challenge, the cities of Gothenburg, Mölndal and Partille have set a goal to increase the number of passengers using public transportation by 40% by the same year (Koll2035, 2018). As part of the bigger traffic supply programme, Målbild Koll2035 aims to focus on the public transport goals of the region that are set to be achieved by 2035. The objectives are mainly to achieve a 20-25 percent reduction in travel times and a 70 percent increase in capacity for public transport. To accomplish this, the transportation system relies on the implementation of various traffic concepts, namely Metrobus, City Line, Tram, and Citybus, but also through streamlining their current concepts (Region Västra Götaland, 2021).

Despite Mölndal being an independent municipality, its association with Gothenburg City results in a strong connection between the public transportation systems of both cities, with a travel distance of approximately 10 minutes. As the combined population of Gothenburg, Mölndal, and Partille is estimated to reach 800,000 individuals, the region has put forth the early mentioned comprehensive traffic supply action plan Målbild Koll2035 in order to achieve specific goals by the year 2035. The main three objectives are to support sustainable urban development, to facilitate an easier daily life for citizens, and to increase the proportion of trips made by public transportation, walking, and cycling.

The public transportation system in Gothenburg and the neighbouring municipality Mölndal is operated by Västtrafik, the public transport authority in the region, and consists of buses, trams, ferries, and trains. Buses are the most frequent form of transport in the area and provide a convenient way to reach different areas of the city and though the smaller suburban areas where rails do not exist. Trams are a popular way to get around the city center and out to the suburbs, while ferries are used to travel shorter distances across the city's waterways. The train system is also well-developed, with lines running from Gothenburg's city center to various outlying cities in the region of Western Sweden.

Buses play a vital role for the public transport infrastructure in the Västra Götaland Region and Mölndal this is since buses could be seen as less costly, more accessible and more flexible than other public transport modes e.g. metros and trams. These characteristics make buses an easy approach to raising the capacity of public transport without having to do significant changes to the current infrastructure. The Region of Västra Götaland emphasizes in its transport supply program the significance of comprehending the population's demographics, travel patterns, and requirements while devising public transportation systems (Region Västra Götaland, 2021). The traffic regulation program for the region of Västra Götaland county explains that there are challenges including capacity constraints, which are expected to worsen as a result of increased travel demand due to the rising population. As public transport expands, access to terminals and major interchanges around the region, particularly in Gothenburg, will be affected (Region Västra Götaland, 2021).

The Mölndal resecentrum is one of the bigger hubs in and around the Gothenburg are and comprises three main components: Mölndals bro, the bridge serving as the central bus terminal; Mölndal station, serving as a stop for regional trains; and Mölndal innerstad, located approximately 100 meters from the bridge, serving as a stop for trams (spårvagnar) and the recently added city bus line 25. In this report we focus on the bridge as it is the home for the bus system, but noteworthy is that when referring to the entire public transport complex/hub, we most commonly use the name Mölndal station.

As for many similar transport hubs around the world, Mölndal station is expecting an increase in travelers and the capacity of the bus system therefore has to increase. To avoid costly reconstructions, the existing public transport infrastructure has to be utilized and optimized. Therefore it is important to be able to analyze a timetable and a quantity of buses that are beneficial to people's travel habits, offer transit reliability but at the same time do not put pressure on the infrastructure and instead contribute to the opposite.

In this study, the capacity of Mölndal station's bus terminal Mölndals bro was evaluated. This was done through data analysis as well as a microscopic simulation and a mathematical model based on queue theory. The study was mostly based on the concept of queuing theory which can be applied to analyse queue formation in different systems. Additionally, the microscopic simulation program PTV Vissim was employed to visualize the behavior of buses under various scenarios with a micro simulation model.

1.1 Aim and objectives

This report constitutes an operational performance analysis of the bus system at Mölndal station, aiming to assess the capacity of Mölndals bro. To accomplish this, the analysis will be conducted in line with three primary objectives.

Firstly, a comprehensive data analysis will be carried out utilizing both provided and self-acquired data. This analysis will yield valuable insights into the influx of buses to the station and their corresponding dwell time. These findings will be instrumental in constructing both a queue model and a microsimulation, which will serve as the subsequent steps in the analysis. The second objective involves the development of a dynamic queue model for the bus terminal. The model will be based on queue theory and will play a crucial role in assessing the station's capacity through calculating the probability of queue. Lastly, a microsimulation using PTV Vissim will be created to explore and observe various scenarios. This simulation aims to provide further understanding and evaluation of the system's performance under different conditions.

The three cases that will be analysed in this report are the following

1. Scenario 1 is supposed to reflect the current state of Mölndals bro in terms of scheduling, bus stops and bus data.
2. Scenario 2 is supposed to show how the station performs when buss line 25 is added to the station as it looks today.
3. Scenario 3 is supposed to reflect how the station would perform if bus 25 was added and two additional bus berths, designated to it.

1.2 Literature review

This literature review chapter will provide an overview of pertinent theories and literature. It aims to build the foundation and to offer an understanding of existing research and theories which will be used to shape this study.

1.2.1 Bus scheduling

As explained by Wren and Rousseau (1995) transport and line planning begins with assessing the current and actual needs of the community. The key approach is to establish direct connections whenever feasible, between existing hubs or between cities or regions that experience high traffic volumes. The subsequent planning process becomes a challenging mathematical task centered around optimization. Optimization, as defined by Bunte and Kliewer (2009), entails achieving the smallest possible fleet size and/or operational costs.

The bus system should ideally meet the demand by providing services to the passenger while also minimizing one or few of the objectives; passenger waiting time, vehicle traveling time or operational costs meaning vehicle cost or passenger cost (Guihaire & Hao, 2008; Galicia et al., 2009). Public transport planning typically involves conflicting interests between users and operators. According to Guihaire and Hao (2008), authorities strive for service quality, while operators focus on cost minimization. Authorities impose route configurations and frequencies to ensure coverage, while operators adjust departure times to optimize resource utilization.

Bunte and Kliewer (2009) also provide insights into the process of transport planning, which begins at a strategic level by collecting and analyzing current or forecasted data on passenger demand. Using this data, demand models are developed to determine the required infrastructure, including route and stop configurations. The authors further suggest that the next crucial step involves determining the number of trips for each line, which serves as the foundation for creating timetables with specified arrival and departure times, as well as start and end stations. Subsequently, the planning process focuses on efficiently allocating resources to ensure the feasibility of these trips, taking into account factors such as drivers and vehicles.

A shorter process is provided by Guihaire and Hao (2008) that share the process into five steps being: route design, frequency setting, timetabling, vehicle scheduling, and crew scheduling (Ibarra-Rojas et al., 2015; Guihaire and Hao, 2008). Connected to the third step of the bus transport planning process the authors also stress the importance of bus transit synchronization in the already very complex process of timetabling. The synchronization of bus transfer is defined by the literature as a situation where the departure time of a bus is scheduled after the arrival time of another bus, accounting for the necessary time for the passenger to complete the transfer (Chu et al., 2019; Gkiotsalitis and Maslekar, 2018; Guihaire and Hao, 2008). Transferring becomes necessary when there is no direct service available for a particular origin-destination pair (OD). To create an appealing public transportation system, Chu et al., (2019) explains the importance of establishing transfer stops or hubs where buses operate with high frequency and are synchronized. For a better bus transit system the waiting times need to be shorter and buses need to have sufficient capacity to accommodate passengers without becoming overcrowded (Chu et al., 2019; Schmöcker et al., 2011). It is also crucial to avoid delays in service that can result from buses reaching full capacity when passengers attempt to board. Such delays can make the bus transit system unattractive and discourage passengers from utilizing it (Ibarra-Rojas et al., 2015). The authors point out that, despite its significance, transfer timing has not been explicitly taken into account in literature. Instead, the focus has primarily been on ensuring the efficient operation of buses and trains in meeting passenger demands (Chu et al., 2019).

There are therefore many different areas that regard the operation of bus services. The frequency, timetables and vehicle schedules of all the bus lines are all part of this. However, during the operational stage, uncertainties such as varying travel times, disruptions, vehicle breakdowns, and weather conditions often arise, possibly resulting in bus bunching. Bus bunching refers to the situation where consecutive buses on the same route arrive at stops with intervals shorter than the planned timing (Fonzone et al., 2015; Schmöcker et al., 2016; Verbich et al., 2017). This phenomenon typically occurs when the first bus is delayed due to factors like high boarding rates or traffic congestion, causing the subsequent bus to have fewer passengers and depart ahead of schedule. To address this issue, dynamic control approaches are employed, including stop skipping, holding vehicles at stops, adjusting operation speeds, and implementing traffic signal priority for buses (Ibarra-Rojas et al., 2015). These approaches rely on the availability of sufficient data and are effectively utilized to optimize operational performance. Bus bunching, schedule sliding and overcrowding occur due to spatio-temporal variation of travel times and passenger demands. An increase of the dwell time (the time that the bus stays on the station) might increase it's time headway with the proceeding trips and leads to a domino effect. The delayed bus trip in result falls behind schedule and has to serve a bigger amount of passengers (Hans et al., 2015).

With dynamic control it is possible to alleviate the effects of bus bunching, schedule sliding and overcrowding that have a big impact on the attractiveness of bus transit use (Gkiotsalitis, 2019). The author explains that this is a problem of stochastic nature and real time control is needed to react continuously to the travel time and passenger demand variation. Since these problems are stochastic, they cannot be effectively addressed in the strategic or tactical planning phases according to Gkiotsalitis (2019). Instead, they need to be managed through corrective real-time control, requiring continuous monitoring of travel time and passenger demand. To facilitate this, Automated Vehicle Location (AVL) data, Automatic Passenger Count (APC), and Automated Fare Collection (AFC) and Geographical Positioning Systems (GPS) systems are employed (Gkiotsalitis 2019; Ibarra-Rojas et al., 2015).

The availability of data is crucial for observing bus operations and implementing corrective actions in real time. It also serves as a means to oversee and assess the performance of operations. As a result, bus transit companies face greater pressure to incorporate data-driven approaches into their decision-making processes (Ibarra-Rojas et al., 2015; Gkiotsalitis, 2019).

Prior to making operational decisions, tactical planning decisions must be established. These decisions are focused on enhancing the level of service and reducing future operational costs. This phase involves fixing the fleet size and utilizing given lines' origin-destination matrices. (Gkiotsalitis, 2019; Ibarra-Rojas et al., 2015). When determining the frequency of a transport system, it is essential to align the service with the demand, recognizing that demand is a dynamic factor that undergoes changes over time. The frequency setting problem, as referred to by Ibarra-Rojas et al. (2015), entails determining the number of trips required to provide a high level of service for a given set of lines. However, due to fluctuations in passenger demand, it is expected that system usage will experience periodic increases or decreases.

Ibarra-Rojas et al. (2015) categorize transit problems in operational planning into two primary types: frequency-based operations, where a specific number of buses per hour is maintained for regular service, and timetable-based operations, where precise departure and arrival times are scheduled for each line. In the case of Gothenburg's public transportation, timetable-based operations are employed. When developing a frequency schedule, important considerations include estimating waiting times, determining fleet size, and managing transfer waiting times. Conversely, timetable-based operations require careful attention to specific operational characteristics such as meeting demand patterns, synchronizing bus lines, and optimizing well-timed transfers (Barnhart and Laporte, 2007; Ibarra-Rojas et al., 2015).

To minimize operational costs, it is crucial to align the timetables and service with the demand, ensuring that buses are neither overcapacity nor significantly underutilized. Ceder et al. (2013, as referenced in Ibarra-Rojas et al., 2015) demonstrate how to create a balanced timetable. They assume a constant passenger arrival rate in smaller planning periods and employ analytic procedures to generate departure times. In the case of the next step in transport planning, that is vehicle scheduling, F. Zhao (2006) divides the entire day into "morning" and "afternoon" problems, showing that this is a normal way to solve complex transportation problems. This approach relies heavily on data collection. While headways are typically not considered in timetabling, according to Ibarra-Rojas et al. (2015), Ceder et al. (2013) propose minimizing deviations from the desired passenger load while maintaining headways, achieved by employing buses of different sizes. Other authors recommend additional methods, including mathematical programming problems with supply-demand equilibrium constraints and the implementation of various heuristic procedures. The procedures are continually explained in Ibarra-Rojas et al. (2015) while presenting the main objectives for each procedure, varying from minimizing time to maximizing savings.

1.2.2 Queue Theory

Queue theory is an analytical technique used for evaluating delays and queue lengths, or simply explained a mathematical way to examine waiting lines (Newell, 2013). A bus stop can be regarded as a queueing system, wherein buses arrive according to a particular probability distribution, wait in a queue to enter the stop if it is occupied, dwell for a period, and leave, possibly experiencing delays due to blocking traffic or downstream traffic signals. A queuing system comprises two essential components, namely the source of the customer population and the service process (Hui, 2009). The customer (in this case, the bus) population may be finite or infinite. A finite system is one where the number of customers has a notable impact on the potential new customers, such as when buses are waiting in line for service. Conversely, an infinite population is one where the number of buses waiting in line has minimal impact on the rate at which other buses reach the service. Hui (2009) notes that customer behavior and how buses approach the bus stop can always change, depending on queue characteristics. In certain cases, customers may opt for a different line, leading to a bus entering another bus berth. However, this is not a queue characteristic to consider, as it is not a typical occurrence.

The other essential component of a queueing system is its service. This component encompasses the number of waiting lines, number of services, service arrangement, arrival and service patterns, or pre-decided priority rules. Queueing systems may be classified as either single-server or multi-server, meaning that they consist of either one queue or multiple queues, where customers can decide which line to join (Mehdi, 2003). The rate at which customers arrive and get served characterizes queueing systems. The arrival rate is a term that describes the average number of customers per time period, while the service rate refers to the average number of customers that can be served during the same period, and it governs the capacity of the service system (Shortle et al., 2018).

In the case of the bus system, the parameters correspond to the following.

- Source: Public transport
- Server: Bus Stop
- Service facility: In a case where buses can choose between several stops.
- Customers: Buses
- Service time: How long the bus dwells at the station (follows a negative exponential distribution)
- Inter-(arrival time): The time between buses to reach the server. 2 minutes for bus 1, 4 for bus two, etc. (follows a Poisson distribution).

The fundamental single-server models, such as the one that could be assumed in the case of a bus terminal with pre-decided berths for each bus, are presumed to arrive at a Poisson arrival rate with exponential service times (Hall, 1999; Shortle et al., 2018; Wang et al., 2021). The Poisson and exponential distributions are fundamental components in queue theory. Straightforwardly described, the Poisson distribution focuses on quantifying the number of occurrences of in this case arrivals within a fixed time frame, whereas the exponential distribution characterizes the time intervals between these occurrences in an infinite time frame, which is how these two relate to one another (Cooper, 2005). The queue discipline usually follows a first-come, first-serve basis, with infinite queue lengths and an infinite calling population. Bus stops provide service in a steady-state, implying that the arrivals at the stops, over a long period, are expected to be less than the stop's capacity

(Wang et al., 2021). Literature shows that bus arrivals to a stop follow a Poisson distribution, some stops however rather follow a general distribution (Mehdi, 2003).

The Poisson process is characterized by a "memoryless" waiting time until the arrival of the next customer (Fodor, 2023). As seen in the equation below, where X is a random variable.

$$P(X > t + \Delta t \mid X > t) = P(X > \Delta t) \tag{1.1}$$

The expected time from one customer (bus) to the next, denoted by λ, implies that the probability of waiting an additional minute, second, or hour, etc., until the next arrival is independent of the amount of time that has passed since the last arrival (Fodor, 2023). This further implies that the waiting time until the next arrival follows an exponential distribution with parameter

$$P(T > t) = e^{-\lambda x} \tag{1.2}$$

Furthermore, this implies that the number of customers (buses) arriving during any time interval of length t follows a Poisson distribution with expected value $\frac{t}{\lambda}$ (Adan and Resing, 2015; Shortle et al., 2018).

Queue models are presented by a Kendall's notation in the following manner:
(1/2/3):(4/5/6)

1. Inter-arrival distribution
2. Service time distribution
3. Service Channels
4. Service Discipline
5. Max number of customers allowed in system (infinite or finite)
6. Calling source (infinite or finite) (Asmussen et al., 2003; Koko et al., 2018)

This study utilizes an M/M/1 queue model, representing a single server model, where there is one single server available for customers to choose from (Aung, 2020). The M stands for Markovian, however another term is Poissonian and stands for as previously explained memoryless or completely random with an exponential distribution (Asmussen et al., 2003). As mentioned earlier, this model entails the presence of a queue, where customers are placed in line when the server is occupied serving another customer. This concept is particularly applicable to buses, as each bus is assigned a specific berth and is restricted to serving passengers exclusively at that berth.

Although queue theory is a valuable method for analyzing bus systems, it should be noted that it may be inadequate for complex bus stops, necessitating the use of simulation in conjunction with queue theory (Lindberg, 2019). Simulations often only include the isolated station and are less good when including surrounding traffic. J. Zhao et al. (2018) means that by adding a delay, the traffic can be indirectly included while keeping the quality of the simulation.

As Mölndals bro is a terminal its important to note that bus terminals are special in the sense that they function differently than a single bus stop. Buses need to arrive according to timetables based on headways and they need to leave, possibly with a purposeful delay, or with a delay due to traffic signals (Lindberg, 2019). In this process of entering the terminal the bus will have to interact with other buses, dwell at different points and most likely dwell at a passenger crosswalk, which is also the case for Möldnals bro.

1.2.3 Dwell time modeling

The duration for which a bus occupies a station encompasses several factors. As presented by Jaiswal et al. (2007) these include the time spent waiting in a queue until the bus reaches the loading area, where it will serve passengers, the dwell time required for passengers to reach the bus door at its loading area position, the time required to serve passengers through the busiest door, and the time required to open and close the doors. Additionally, the clearance time comprises any re-entry delay due to waiting in turn for any buses at leading loading areas that are obstructing the subject bus's departure, along with any re-entry gap acceptance delay.

Dwell times, concerning the interaction between passengers and the bus, can be described as the overall time required for the bus to interact with passenger(s) at any given busway station, including the time required for door opening and closing (Pathiranage et al., 2013). In other words dwell time is defined as the time the bus spends while stopped to serve a passenger and consumes up to 26% of the total travel time of buses (Rajbhandari et al., 2003). Bus characteristics such as the number of doors, if the bus is low floor or not or if only the front door opens for alighting passengers are all factors that impact dwell time (Jaiswal et al., 2007). Those factors are however constant for the bus whereas the number of people boarding and unboarding and other instances that cannot be exactly predicted are not.

Dwell time is as said considerably impacted by any factors that impede bus from moving forward. Such factors may include queues or traffic, as well as the volume of passengers and the activities they must complete before boarding the bus, such as fare payments or entrance through the front door only. Fletcher and El-Geneidy (2013) have reported that crowding on buses notably intensifies when the bus reaches 60% of its maximum capacity (Fletcher and El-Geneidy, 2013).

Jaiswal et al. (2007) explains that apart from assessing bus delays through stations, comprehending bus dwell times is crucial in evaluating the bus handling capacity of the loading areas and consequently the bus capacity of the station platform as a whole. The bus platform capacity is of great importance as it can potentially create a bottleneck within the transportation system.

2

Site description

2.1 Mölndals bro

Mölndals bro (Mölndal Bridge) is a prominent bus terminal situated within the Mölndals station complex, centrally located within the town of Mölndal, as depicted in Figure 2.1. Mölndal resecentrum represents a key transport hub, accommodating buses, trams, and local and regional trains. The terminal is situated atop a bridge structure bearing the same name, which traverses over tramways, motorways, highways, and railroads. This bridge structure functions as a pedestrian, cyclist, car, and bus overpass, linking the eastern and western portions of Mölndal. Moreover, it serves to interconnect the train stops with other public transport stops situated within Mölndal station/ Mölndal Resecentrum. Figure 2.2 and 2.3 show more detailed maps of the area.

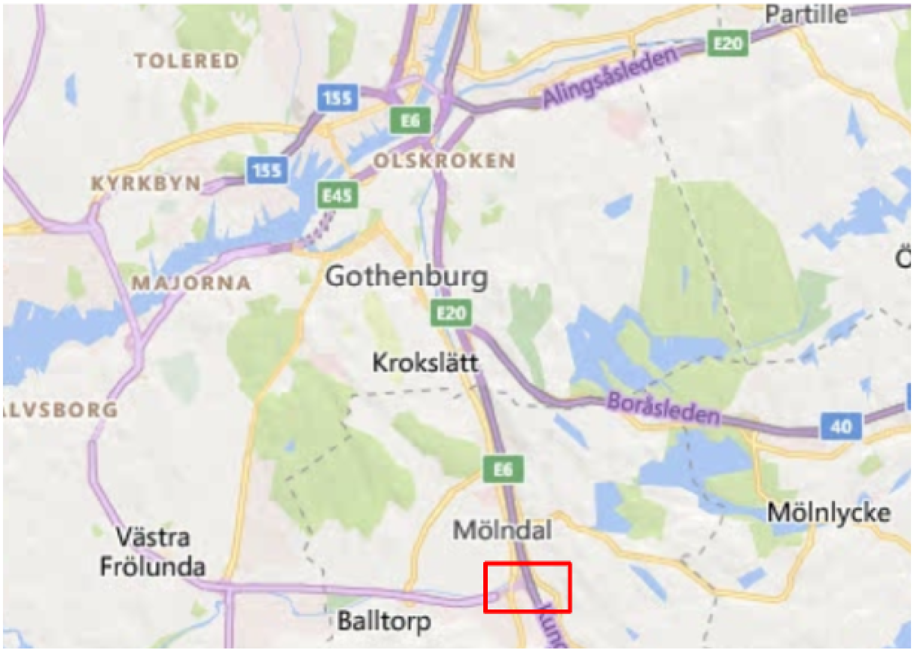

Figure 2.1: Location of the Mölndal Bro in relation to Gothenburg, (Mango map, 2023)

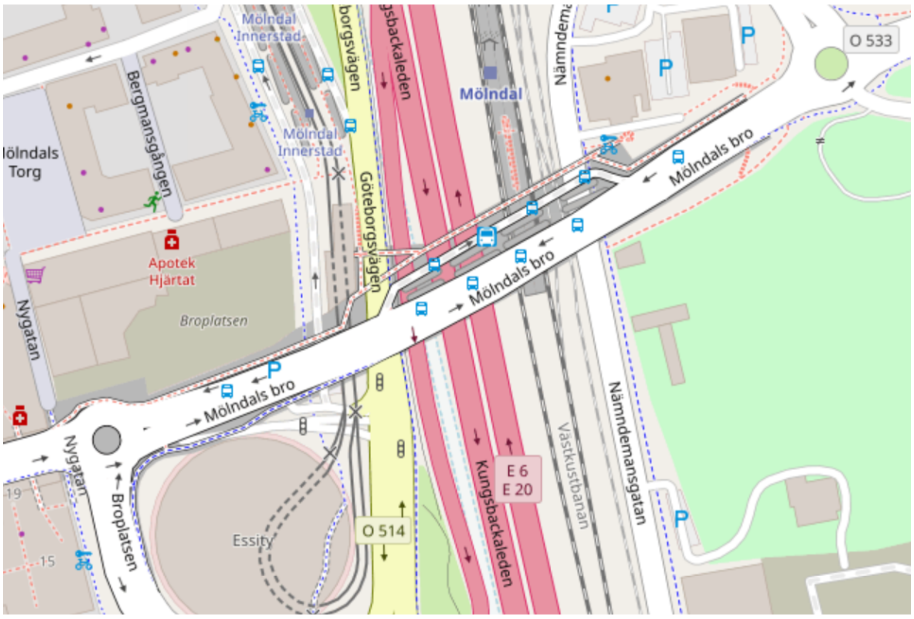

Figure 2.2: A detailed map of the area which shows the bridge, bus berths and surrounding roads (MangoMap, 2023)

Figure 2.3: A satellite picture of the bridge (Google, 2023)

The Mölndals bro bus terminal is a sawtooth bus station where there are currently nine bus berths, (see figure 2.4). Bus berths B1-B8 are used consistently by eight different buss lines in both directions while berth B9 is used as to serve replacement traffic in case of unforeseen events in the public transport system. Table 2.1 shows the bus lines that operate on Mölndals bro and which berth they stop on. Figure 2.5 and 2.6 aim to give a better visualization and understanding of the station.

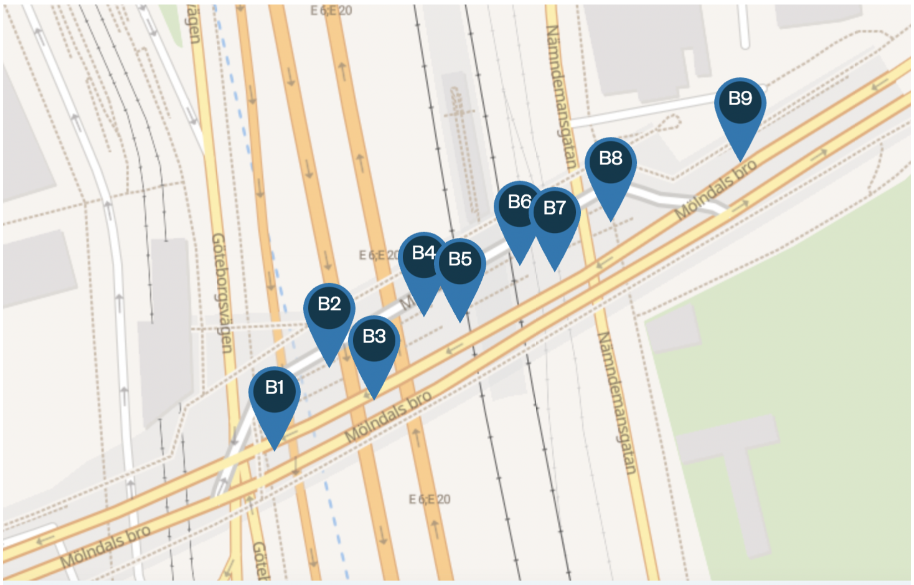

Figure 2.4: Bus berths/stops on the bridge (Västtrafik, 2022)

Figure 2.5: The middle of the station (Google Street View, 2023)

Figure 2.6: The station shown from the side (Google Street View, 2023)

Table 2.1: The different bus lines and their berths (Västtrafik, 2022)

Line	Direction code	Berth
Lila	Torslanda	B5
	Mölnlycke	B6
751	Frölunda	B5
	Mölnlycke	B6
753	Heden via Åby	B8
	Heden via Helenedal	B7
755	Kållered	B4
	Mölndal	B3
758	Heden	B2
	Marklandsgatan	B1
760	Mölndals station	B4
	Lindome	B3
761	Mölndal station	B3
	Lindome	B4
765	Mölndal	B3
	Tulebo	B4

2.2 Scheduling

As Mölndals bro serves as a terminal, buses purposely remain stationed for a longer duration than merely for boarding and alighting. Västtrafik reports that larger terminals in the city adopt this practice of prolonged bus stays to facilitate the convenience of passengers changing buses, but it may also help regulate traffic by allowing buses to remain idle for longer periods if they arrive before schedule (S.

Krafft, personal communication Västtrafik, February 24, 2023). In literature this planning of bus timetables is called transfer synchronization (Chu et al., 2019; Gkiotsalitis and Maslekar, 2018; Guihaire & Hao, 2008). Since most stations before and around Mölndals bro comprise of suburban bus stops, buses can often bypass these stations and may arrive earlier. In cases of delay, they can depart right away at Mölndals bro without waiting and still have a better chance of being on schedule. This deliberate prolongation of dwell time may impact the operational structure of the station and is often separate from the time it takes for passengers to align and board the vehicle, as observed. However, as previously stated, when buses operate on a higher frequency timetable, with intervals of 5-7 minutes, the use of prolonged waiting periods or bus synchronization is not necessary. This observation has also been corroborated by Västtrafik. Therefore, for this study, the collection of dwell time data considered only the time when the wheels stopped at the station and started moving again to exit the station, without taking passenger aligning/boarding into account, although it did have an impact.

2.3 Future plans for Mölndals station

As per the detailed development plan of the municipality, there are proposals to undertake a reconstruction of Mölndal station. This reconstruction aims to facilitate a new railway line that will connect the cities of Gothenburg and Borås, the second largest city in the County of Västra Götaland. To this end, a new train stop, along with two additional bus stops on the bridge, are slated to be constructed, which will bring the total number of bus stops on the bridge to ten. Where it is envisaged that the city bus line 25 will make stops at the newly added berths B9 and B10. This instead of under the bridge at the stop called Mölndal Innerstad as it does today. The proposed reconstruction is intended to cater to the expected surge in passenger numbers who will be utilizing the terminal. Therefore, the reconstruction project shall accommodate the needs of the increasing number of users and the new transportation systems that will operate through the station (H. Lundström, personal communication Ramboll AB, January 18, 2023.)

3
Data

This chapter contains the data collection and analysis method and results used for this project. It also contains the statistical testing of data used to validate the usage of queue theory in this report.

3.1 Data collection

In order to assess the capacity of Mölndals bro, it was necessary to collect pertinent data regarding the bus lines which stopped at the location, including the frequency of stops and the specific berths utilized by each bus line. Additionally, information regarding dwell time, entry time, and arrival rate was required. To acquire this data, numerous actual arrival and departure points were compared with estimated data for all bus lines. Two methods were employed to collect the necessary information. Firstly, data was obtained from Västtrafik, the organization responsible for public transportation in the western region of Sweden. Secondly, an independent data collection was conducted, with a focus on analyzing morning and evening rush hour periods - times during which the system experiences the greatest congestion.

Data derived from Västtrafik included both planned and actual arrival/departure times, stop duration in seconds, and stop points, as derived from GPS detectors aboard the buses from the period of February 6th, 2023 to February 10th, 2023.

The independent data collection involved analyzing time tables provided by Västtrafik to obtain estimated arrival and departure times and corresponding stop points for all bus lines. Actual arrival and departure data was obtained via two site visits. The first visit was on March 7th, 2023, during the evening peak hour period of 16:00-18:00, and the second on March 15th during the morning peak hour (7:00-9:00). In which the buses were manually timed on how long they spend on their berth, and the time they arrived.

The primary dataset utilized for this report consisted of the data received from Västtrafik. This decision was made due to the larger size of the dataset and the increased accuracy associated with automated data collection, which is less susceptible to human error. Furthermore, the independent data collection was conducted with the objective of obtaining a more comprehensive understanding of the bus terminal.

3.2 Data analysis

The collected data obtained from on-site observations and from Västtrafik were subject to separate analyses. To facilitate meaningful comparison of data, both datasets were subjected to identical visualization and analysis techniques, utilizing both Microsoft Excel and MATLAB. The analyses performed encompassed evaluations of the distributions of dwell time, entry time, and arrival times.

3.2.1 Data comparison

The site collected data set as well as the data set from Västtrafik were compared. Both the comparison of dwell time and entry time are visualized as a cumulative distribution function (cdf) plot as well as a probability density function (pdf), see Figure 3.1-3.4. Comparing the collected data from Västtrafik with the own data, it is evident that both sources corroborate each other, as evidenced by the similarities observed in the graphs. Västtrafik's sensors and data collection methods provide a realistic representation of the station's operations.

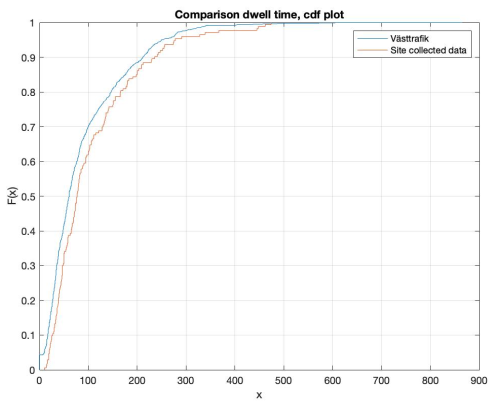

Figure 3.1: Dwell time comparison, cdf

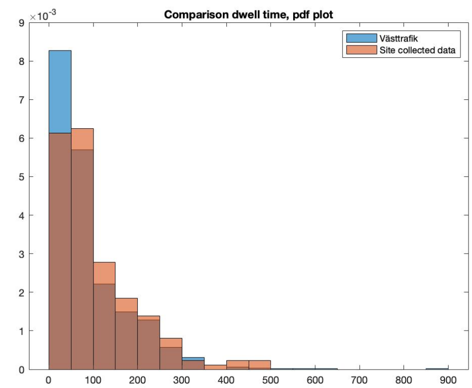

Figure 3.2: Dwell time comparison, pdf

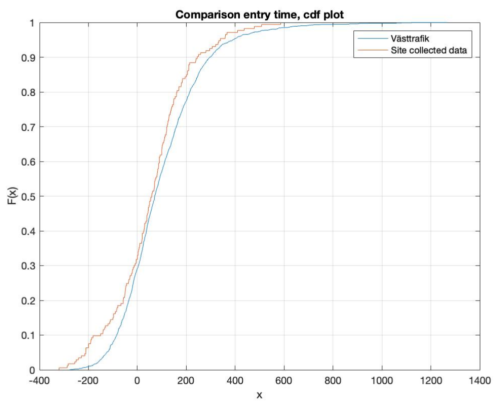

Figure 3.3: Entry time comparison, cdf

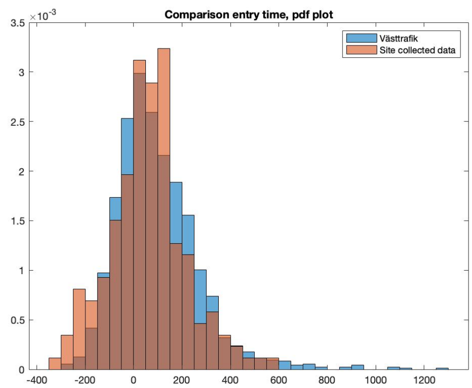

Figure 3.4: Entry time comparison, pdf

3.2.2 Dwell time

Based on the data set provided by Västtrafik, the dwell time distributions could be calculated for each of the berths, see figure 3.5. The dwell time did not include Clarence time since no data on clerence time was recorded. The figure shows cdf plots and mean dwell time for each of the bus berths as well as for bus 25. Since no data on dwell time was collected of bus 25 the data was based on the buses without scheduled stop, such as bus line 755, 760, 761 and 765. It can be seen that the dwell time differs a lot between the berths. The results reveal that berths B5 and B8 have the longest dwell times. This implies that these berths are more susceptible to queue formation, as there is a higher likelihood of another bus arriving while a bus is already occupying the berth. This data was later used in the simulation model as well as the queue model.

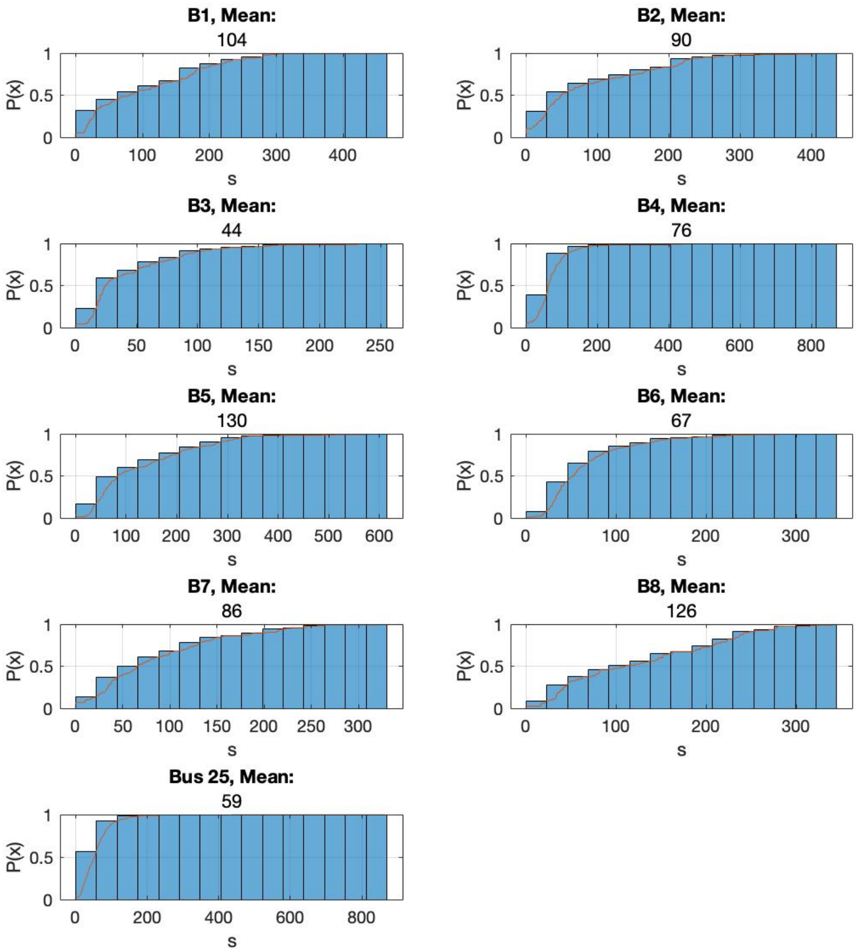

Figure 3.5: Dwell time for each berth and bus line 25

3.2.3 Entry time

Based on the data set provided by Västtrafik, the entry time distributions could be calculated for each of the berths (see figure 3.6). The figure shows cdf plots and mean dwell time for each of the bus berths as well as for bus 25. Since no data on entry time was collected of bus 25 the data was based on all buses without scheduled stop. These were as previously presented; bus 755, 760, 761 and 765. From the figure below it can be seen that the results differ significantly. Delays are commonly observed across almost all berths, with the exception of B3, where buses tend to arrive earlier. This data was later used in the simulation model.

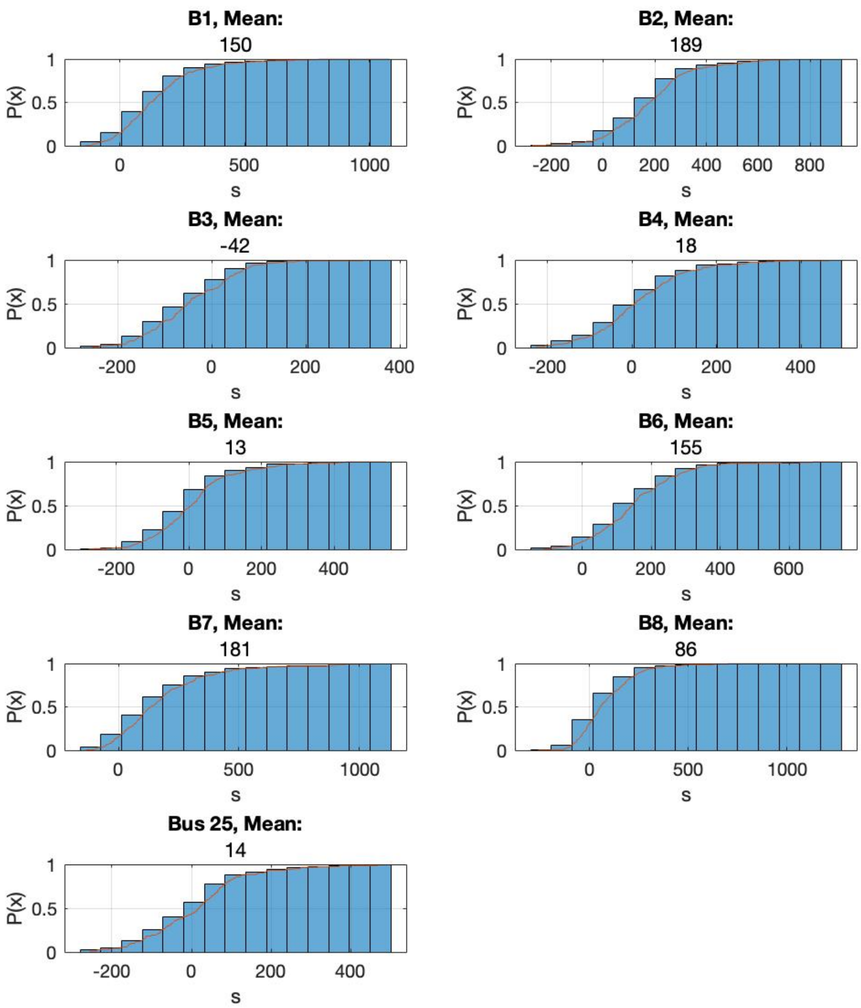

Figure 3.6: Entry time each berth

3.3 Validation of queue theory usage

In order to use the queue theory equations, the dwell time distribution had to follow exponential distribution and the arrival rate distribution had to follow Poisson distribution. For the validation, chi squared (χ^2) goodness of fit tests were performed for dwell time and arrival rate. The tests were done for the entire station in both cases. The following hypothesis were formulated for both tests:

- Null hypothesis (H0): There is no association between the data and the distribution.
- Alternative hypothesis (Ha): There is association between the data and distribution.

The level of significance was set to 0.05 and the degrees of freedom was calculated through equation 3.1 for both tests. Where P is number of parameters and DF is degrees of freedom.

$$DF = P - 1 \tag{3.1}$$

The chi distribution table (see Figure 3.7) below, was then used to find the critical value for both tests.

Chi-square Distribution Table

d.f.	.995	.99	.975	.95	.9	.1	.05	.025	.01
1	0.00	0.00	0.00	0.00	0.02	2.71	3.84	5.02	6.63
2	0.01	0.02	0.05	0.10	0.21	4.61	5.99	7.38	9.21
3	0.07	0.11	0.22	0.35	0.58	6.25	7.81	9.35	11.34
4	0.21	0.30	0.48	0.71	1.06	7.78	9.49	11.14	13.28
5	0.41	0.55	0.83	1.15	1.61	9.24	11.07	12.83	15.09
6	0.68	0.87	1.24	1.64	2.20	10.64	12.59	14.45	16.81
7	0.99	1.24	1.69	2.17	2.83	12.02	14.07	16.01	18.48
8	1.34	1.65	2.18	2.73	3.49	13.36	15.51	17.53	20.09
9	1.73	2.09	2.70	3.33	4.17	14.68	16.92	19.02	21.67
10	2.16	2.56	3.25	3.94	4.87	15.99	18.31	20.48	23.21

Figure 3.7: Critical value (Zablotski, 2019)

The observed and expected data was gathered and evaluated through equation 3.2. Where O_i is the observed values, E_i and χ^2 being the chi square value.

$$\chi^2 = \sum \frac{O_i - E_i}{E_i} \tag{3.2}$$

The χ^2 value was compared with the critical value to see whether the data follows the distribution in both cases.

3.3.1 Dwell time and exponential distribution

The dwell time distribution for the entire station was fitted with an exponential distribution, see figure 3.8. The dwell time data and the exponential distribution was split into eight intervals, the probability for each interval being shown in Figure 3.9. It can be seen that both distributions are similar.

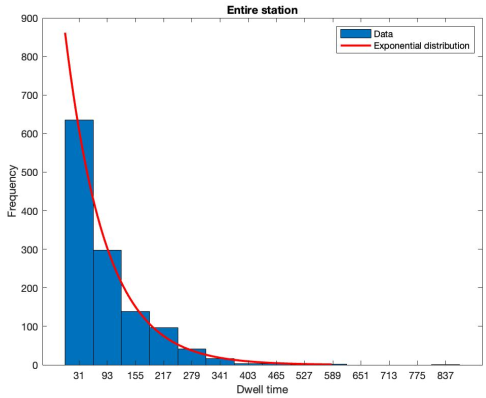

Figure 3.8: Dwell time and exponential distribution

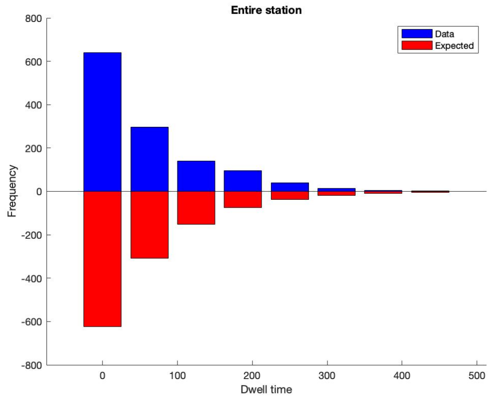

Figure 3.9: Dwell time and exponential distribution divided in 8 segments

The results of the chi-square (χ^2) test can be observed in Table 3.1, revealing that the calculated χ^2-value is lower than the critical value. Consequently, the null hypothesis cannot be rejected, indicating that the dwell time adheres to an exponential distribution.

Table 3.1: χ^2goodness of fit test

Dwell time	
Degrees of freedom	7
Critical value	14,0671
χ^2	12,4335

3.3.2 Arrival rate and Poisson distribution

The arrival rate distribution for the entire station was subjected to a fitting process using a Poisson distribution, as depicted in Figure 3.8. Subsequently, the dwell time data, along with the exponential distribution, was divided into six intervals, and the corresponding probabilities for each interval are illustrated in Figure 3.9. It is evident that both distributions exhibit a similar pattern.

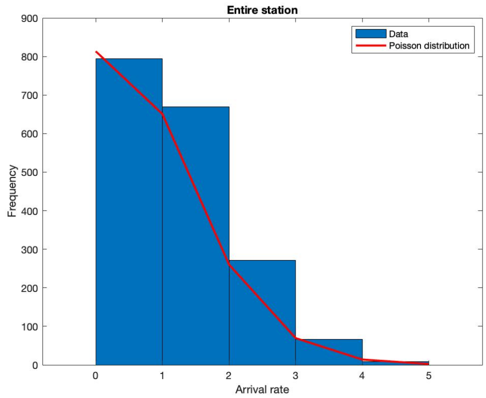

Figure 3.10: Arrival rate and Poisson distribution

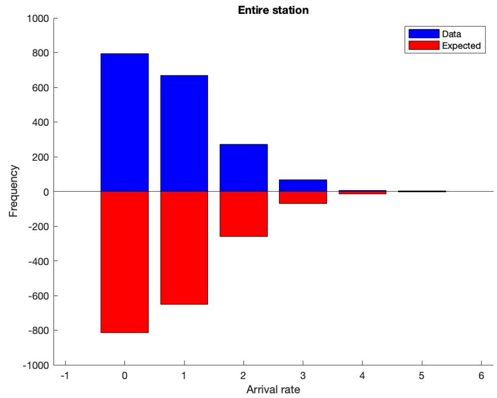

Figure 3.11: Arrival rate and Poisson distribution divided in 6 segments

The outcomes of the χ^2 test for the arrival rate are presented in Table 3.1. The analysis reveals that the calculated χ^2-value is lower than the critical value. Consequently, the null hypothesis cannot be rejected, indicating that the arrival rate conforms to a Poisson distribution.

Table 3.2: χ^2 goodness of fit test

Arrival rate	
Degrees of freedom	5
Critical value	11,0705
χ^2	7,5156

4
Method

This chapter provides an overview of the methodology used in this study. It outlines the research design, the use of the microsimulation software PTV VISSIM as well as the method of analysing capacity based on queue theory.

4.1 Queue model

A mathematical model utilizing queue theory was created to assess the capacity of the bus terminal. By examining various scenarios and calculating the probability of queue occurrence, the station's capacity could be evaluated.

Given that multiple bus lines utilize the same bus berths and only one bus can be seved at a time, a M/M/1/3 system was used to represent each berth, assuming a maximum queue length of three buses. By determining the arrival rate and average dwell time, the probabilities ($P_0 - P_3$) of having 0, 1, 2, and 3 buses at each berth could be calculated. The service rate per hour (v) was computed using Equation 4.1, where T_d denotes the average dwell time.

$$v = \frac{3600}{T_d} \tag{4.1}$$

The utilization factor(ρ) was calculated through equation 4.2, where α is arrival rate.

$$\rho = \frac{\alpha}{v} \tag{4.2}$$

The probability of having 0, 1, 2 and 3 buses at once could be calculated through equations 4.3-4.6.

$$P_0 = \frac{1}{1 + \rho + \rho^2 + \rho^3} \tag{4.3}$$

$$P_1 = p_0\rho \tag{4.4}$$

$$P_2 = p_0\rho^2 \tag{4.5}$$

$$P_3 = p_0\rho^3 \tag{4.6}$$

The average amount of buses could be calculated from equation 4.7.

$$L = \sum_{i=0}^{3} iP_i \tag{4.7}$$

The probability of having queue was defined as having more than one bus at one bus berth. It was calculated from equation 4.8.

$$P(\geq 2) = 1 - P_0 - P_1 \tag{4.8}$$

Once the probabilities for each berth were computed, probability theory was employed to determine the probability of a queue, the probability of having a specific number of buses, and the average number of buses for both the eastern and western directions, as well as the entire station. This analysis was performed and visually presented for various scenarios.

4.2 Microscopic simulation

The microscopic simulation was created in PTV Vissim. A detailed model of Mölndal Station provided by RAMBOLL were used in this project, see figure 4.1 and 4.2. The model was stripped down and additional parameters had to be modified. Input data such as dwell time, entry time and bus scheduling were applied in the model for all of the scenarios. The model was validated through comparing the simulation run with Data from Västtrafik as well as the queue model. The microscopic simulation was used as a tool to evaluate the accepted probability of queue.
The PTV Vissim software was used to construct a microscopic simulation of Mölndals bro, using a detailed model of the station provided by RAMBOLL (refer to Figure 4.1 and 4.2). The model was adapted and additional parameters were adjusted accordingly. Input data, such as dwell time, entry time, and bus scheduling, were integrated into the model for all scenarios. To validate the model, simulation results were compared against data from Västtrafik and the queue model. The microscopic simulation served as a valuable tool for assessing the accepted probability of queue.

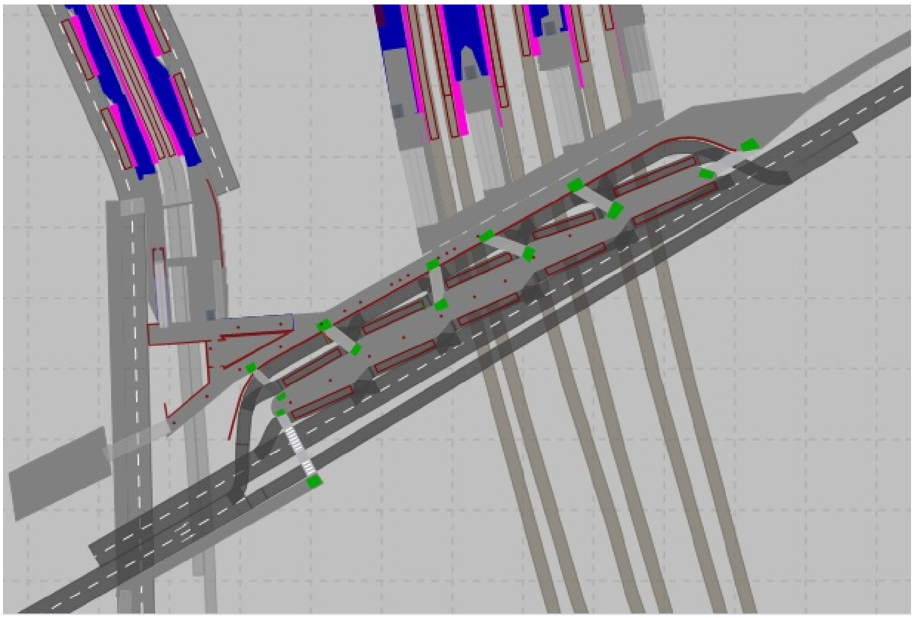

Figure 4.1: Simulation model from above, (Ramboll, 2022)

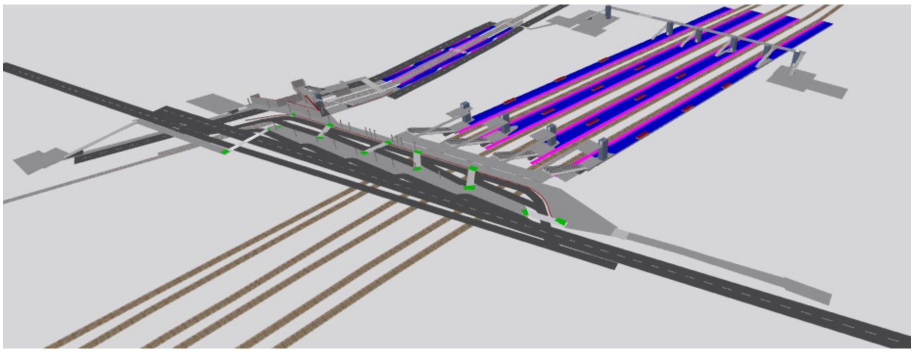

Figure 4.2: Simulation model in 3D perspective, (Ramboll, 2022)

4.2.1 Modified parameters

The simulation model involved modifications to these following parameters.

4.2.1.1 Bus Data

The entry time and dwell time distribution from the data analysis as well as the scheduling were inserted into the model.

4.2.1.2 Passenger car traffic Data

The exclusion of passenger car traffic data from this analysis was motivated by a desire to maintain simplicity in the modeling process. It is at the same time assumed in this report that the impact of surrounding traffic on the bus system will not be significant, particularly given the expectation and plan for a decrease in car traffic in the future.

4.2.1.3 Pedestrian Data

The maximum pedestrian data was provided by Ramboll. Since the busses had priority at the crosswalks, the pedestrians were assumed to have low impact, thus the pedestrian flows stayed the same for each of the scenarios.

4.2.1.4 Signaling

Since the initial model did not include the traffic signals that are present at Mölndal bro, it was necessary to integrate them into the model. In reality, the signaling system on Mölndals bro is regulated by sensors that grant priority to buses travelling in the eastward direction (Ö, Nordlinder, personal communication Mölndal Stad, February 28, 2023). However, due to time constraints, these sensors were configured to operate on a fixed cycle. The signal heads that were inserted are pointed out by the blue and green arrows in Figure 4.3. The color indicates which signal group the operate with. Figure 4.4 shows the the cycle for signal group 1 and 2.

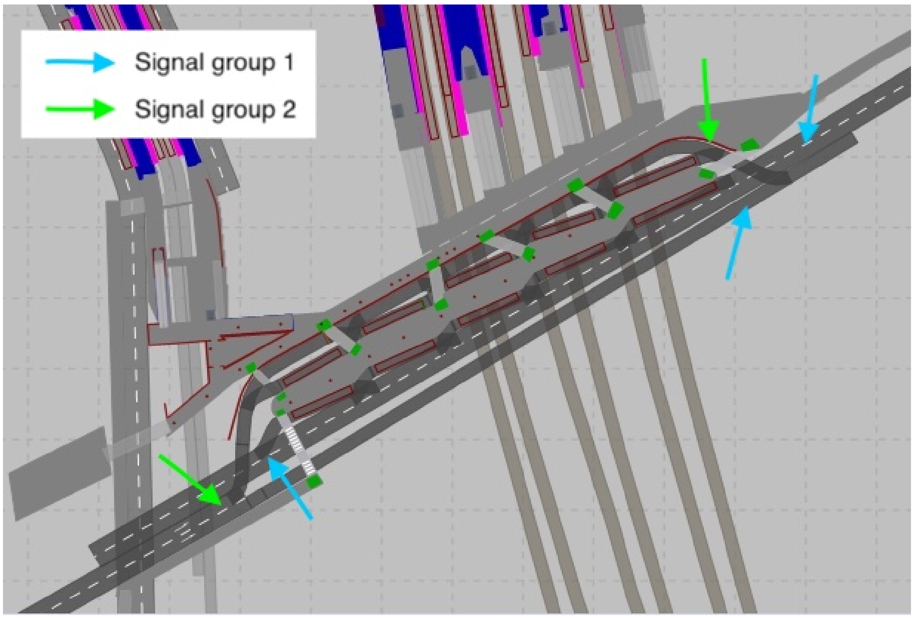

Figure 4.3: Location of signal head and their signal group

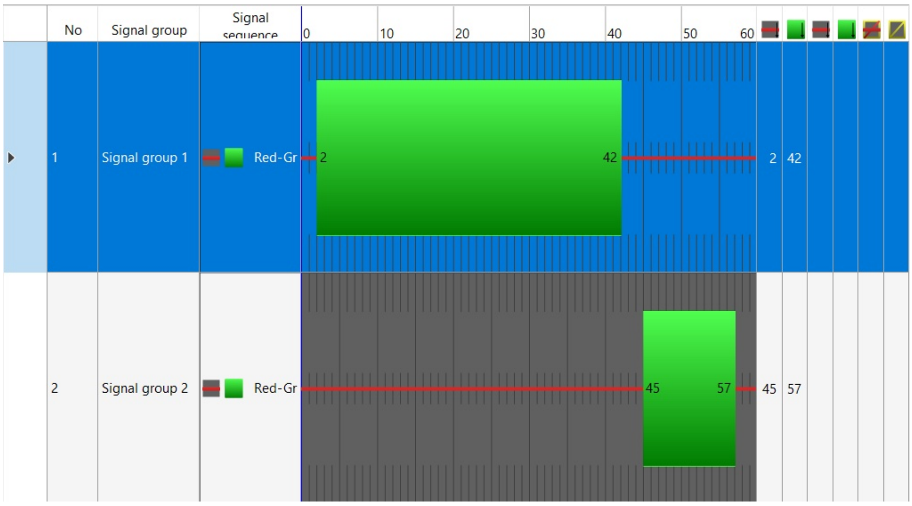

Figure 4.4: Fixed cycles for signal groups

4.2.2 Validation of Simulation model

In order to validate the model, a comparison was made between the base case simulation and the queue model. The simulation was equipped with several data collection points that measured when the bus entered and exit the station. The simulation was conducted over a duration of 10 hours, and the collected data was analyzed using both Excel and Matlab. The analysis focused on evaluating the average number of buses present at the station, as well as the probability of having n buses at the station. These two parameters were then compared to the queue model. Additionally, the arrival rate was analyzed and compared to the data provided by Västtrafik.

4.2.3 Risk of queue threshold evaluation

The risk of queue was investigated in order to establish a reference threshold, i.e. how large risk of queue that could be accepted at a station. This was done because there were no general thresholds since all stations are different. To evaluate the threshold, several simulations with 10-30% risk of queue were tested. Through varying the arrival rates for all bus lines proportionally in the base case, five scenarios with 11%, 15%, 20%, 25% and 30% risk of queue in the west direction could be calculated through the queue model. In the evaluation of a 20% risk of queue, the arrival rates were incrementally increased until the queue risk reached 20%. Thereafter, the scheduling for this specific scenario was incorporated into the simulation model. Each scenario was simulated and analyzed by observing congestion and collecting data such as average delay and the number of buses at the station. The simulations were conducted for a duration of 10 hours, with data collected at one-minute intervals. Based on the analysis, a reference threshold was established.

4.3 Max capacity evaluation

When the risk of queue threshold was established, the maximal capacity could be calculated through the queue model. This was done through increasing the capacity for each of the scenarios until the risk of queue became equal to the threshold value. The increase of scheduling was assumed to be proportional to the present scheduling and the dwell time was assumed to stay the same. The maximal capacity was analysed and visualized.

In order to see how sensitive the model was to changing input parameters, the maximal capacity was tested with 50%, 40%, 30%, 20% and 10% decrease of dwell time as well as a 10% increase. One example is when the dwell time is decreased with 20%, the arrival rates are increased until the risk of queue reaches the threshold. The maximal capacity was analysed and visualized for the changes in dwell time.

4.4 Assumptions

As part of the methodology a few assumtions had to be made in order to proceed the methodology. The study is anchored on the assumptions that:

- Surrounding traffic does not have a big impact on the bus traffic since it is not included in the mathematical model. This situation may not fully reflect the truth, as the bridge currently experiences an amount car traffic, which does have an undeniable impact on the bus traffic. However, there are future plans in place to mitigate the car traffic further.
- Pedestrian flow does not have an impact on the bus system. It is challenging to definitively state that pedestrians do not impact bus traffic, as there are specific areas of the station where pedestrians pass through to access different parts of the station. With an increased volume of pedestrian traffic, it will inevitably lead to crossings occurring at various times, causing buses to make frequent stops. This issue was also brought to attention by Ramboll but for simplicity reasons was chosen to be overlooked.
- Dwell time distribution is assumed to stay the same when increasing scheduling at the bus station. More passengers increase the dwell times while more frequent scheduling decreases the dwell times. These were assumed to balance each other out making the dwell time constant.
- The scheduling for different bus berths is assumed to change proportionally to the base scenario when evaluating max capacity.
- The dwell time is assumed to change proportionally to the base scenario when evaluating the effect of dwell time.
- The signal heads were put to a fixed cycle in the model instead of being operated by sensors to allow priority for buses as they are in real life. Simplicity reasons.

4.5 Sources of error

To provide a proper analysis, it is important to acknowledge and discuss potential sources of error that may have influenced the results of the study. The following sources of errors that are believed to have an effect on the results are outlined below.

- The pedestrian flows used in the simulation model were not changed when increasing the scheduling of buses. This might not be realistic since an increase of bus traffic realistically would mean more pedestrians.
- The queue model does not consider that busses can be blocked by other busses stopping at other berths. This could potentially result in more queue.
- The data on dwell time did not include clearance time which would further decrease the capacity. This choice was partly done since there were no recorded clearance time in the data set and partly done since the clearance time is rather low in comparison to dwell time.
- Some data points were missing from the data obtained from Västtrafik. Table 4.1 has been included below to display the percentage of missing data points within the dataset. The effects of this data gap have been observed within the evaluation of arrival rate.

Table 4.1: Percentage of missing data from Västtrafik

Data	Actual Arrival Data	Actual Departure Data
Percentage of missing data	20%	14%

5
Results

This chapter presents the results of this study. The scheduling of the scenarios were introduced and each of the scenarios were evaluated using the queue model. The results from the microscopic simulation was used to evaluate a threshold of the risk for queue. The maximal capacity was then evaluated for all of the scenarios.

5.1 Scenarios

This section introduces the three scenarios that were used for evaluating capacity in this study. It presents the scheduling for all of the buses that were used for each scenario. It also contains summarised scheduling for all berths for each scenario as well as the average dwell time and service rate. It is worth mentioning that the service rate is not a representative measure of how many buses that can operate at the station, but is rather used as a modeling/approximation parameter when evaluating capacity.

5.1.1 Scenario 1

The first scenario reflects the current state of Mölndals bro during morning peak hour. The bus lines and their schedules were based on the actual time schedule of the time of the study (January-March 2023). The dwell time, entry time and arrival rate distributions were based on the data collection. The scheduling of each bus in scenario 1 is demonstrated in Table 5.1.

Table 5.1: Scheduling of each bus line in scenario 1

Scenario 1		
Line	Berth	Arrival rate (veh/h)
Lila, Torslanda	B5	4
Lila, Mölnlycke	B6	4
751, Frölunda	B5	4
751, Mölnlycke	B6	4
753, Heden via Åby	B7	4
753, Heden via Helenedal	B8	4
755, Kållered	B4	2
755, Mölndal	B3	2
758, Heden	B2	6
758, Marklandsgatan	B1	4
760, Mölndals station	B4	2
760, Lindome	B3	2
761, Mölndal station	B3	2
761, Lindome	B4	2
765, Mölndal	B3	2
765, Tulebo	B4	2

Based on the Table 5.1 and Figure 3.5 the arrival rate, dwell time and service rate for scenario 1 could be summarised in Table 5.2.

Table 5.2: Arrival rate, average dwell time and service rate for scenario 1

Scenario 1								
Berth	B1	B2	B3	B4	B5	B6	B7	B8
Arrival rate (veh/h)	4	6	8	8	8	8	4	4
Average dwell (s)	105	90	44	76	131	68	86	126
Service rate (veh/h)	34	40	81	47	28	53	42	28

5.1.2 Scenario 2

In the second scenario, bus line 25 was added to the system. This was done to test how adding a new line would affect the risk of queue at the terminal. The scheduling of the bus lines were based on the current scheduling on Mölndals bro and the scheduling of bus 25 was based on the current scheduling at Mölndal Innerstad. The assigned bus berth of some bus lines were rearranged to get more even scheduling of the bus berths. Bus 25 is added to bus berth B7 and B10 and bus 753 is moved from bus berth B7 and B8 to B1 and B2. This was done to achieve a more balanced timetable, as it would be unrealistic to have a significant imbalance in the number of buses arriving at different berths. The scheduling of each bus in scenario 2 is shown in Table 5.3.

Table 5.3: Scheduling of each bus line in scenario 2

Scenario 2		
Line	Berth	Arrival rate (veh/h)
Lila, Torslanda	B5	4
Lila, Mölnlycke	B6	4
751, Frölunda	B5	4
751, Mölnlycke	B6	4
753, Heden via Åby	B1	4
753, Heden via Helenedal	B2	4
755, Kållered	B4	2
755, Mölndal	B3	2
758, Heden	B2	6
758, Marklandsgatan	B1	4
760, Mölndals station	B4	2
760, Lindome	B3	2
761, Mölndal station	B3	2
761, Lindome	B4	2
765, Mölndal	B3	2
765, Tulebo	B4	2
25, Länsmansgården	B7	12
25, Balltorp	B8	6

Based on Table 5.3 and Figure 3.5 the arrival rate, dwell time and service rate for scenario 2 could be summarised in Table 5.4.

Table 5.4: Arrival rate, average dwell time and service rate for scenario 2

Scenario 2								
Berth	B1	B2	B3	B4	B5	B6	B7	B8
Arrival rate (veh/h)	8	10	8	8	8	8	12	6
Average dwell (s)	95	105	44	76	131	68	59	59
Service rate (veh/h)	38	34	81	47	28	53	61	61

5.1.3 Scenario 3

In the third scenario, two new bus berths (B9 and B10) were added to the bus terminal. This was done to test how the risk of queue is affected when adding two new bus stops in the system. The scheduling is based the same way as in scenario 1 with the exception that bus 25 now occupies the newly added berths B9 and B10. The dwell time, entry time and arrival rate were based the same way as scenario 2. The scheduling of each bus in scenario 3 is shown in Table 5.5.

Table 5.5: Scheduling of each bus line in scenario 3

Scenario 3		
Line	Berth	Arrival rate (veh/h)
Lila, Torslanda	B5	4
Lila, Mölnlycke	B6	4
751, Frölunda	B5	4
751, Mölnlycke	B6	4
753, Heden via Åby	B7	4
753, Heden via Helenedal	B8	4
755, Kållered	B4	2
755, Mölndal	B3	2
758, Heden	B2	6
758, Marklandsgatan	B1	4
760, Mölndals station	B4	2
760, Lindome	B3	2
761, Mölndal station	B3	2
761, Lindome	B4	2
765, Mölndal	B3	2
765, Tulebo	B4	2
25, Länsmansgården	B9	12
25, Balltorp	B10	6

Based on Table 5.5 and Figure 3.5 the arrival rate, dwell time and service rate for scenario 3 could be summarised in Table 5.6.

Table 5.6: Scheduling of each bus line in scenario 3

Scenario 3										
Berth	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10
Arrival rate per hour	4	6	8	8	8	8	8	10	12	6
Average dwell (s)	105	90	44	76	131	68	86	126	59	59
Service rate (veh/h)	34	40	81	47	28	53	42	28	61	61

The total arrival rate for each scenario is shown in Table 5.7.

Table 5.7: The total amount of buses occupying the station for all the scenarios (veh/h) also known as the arrival rate.

Arrival rate scenarios			
Scenarios	Scenario 1	Scenario 2	Scenario 3
Arrival rate (veh/h)	50	68	68

5.2 Queue model results

The queue model could with the previous input be calculated. Therefor the probability of having n busses in the west and east directions for scenario 1, 2 and 3 can be depicted in Figure 5.1 and 5.2.

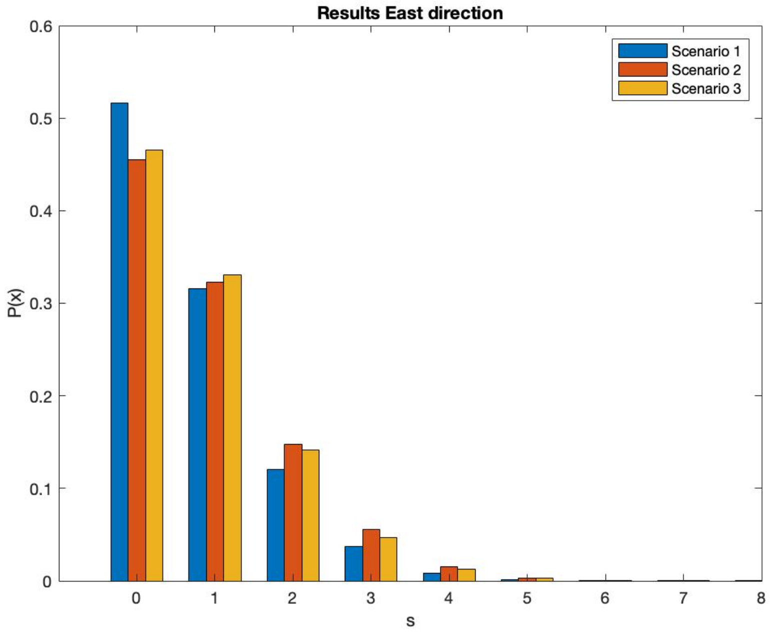

Figure 5.1: Results for scenario 1, 2 and 3 in the east direction

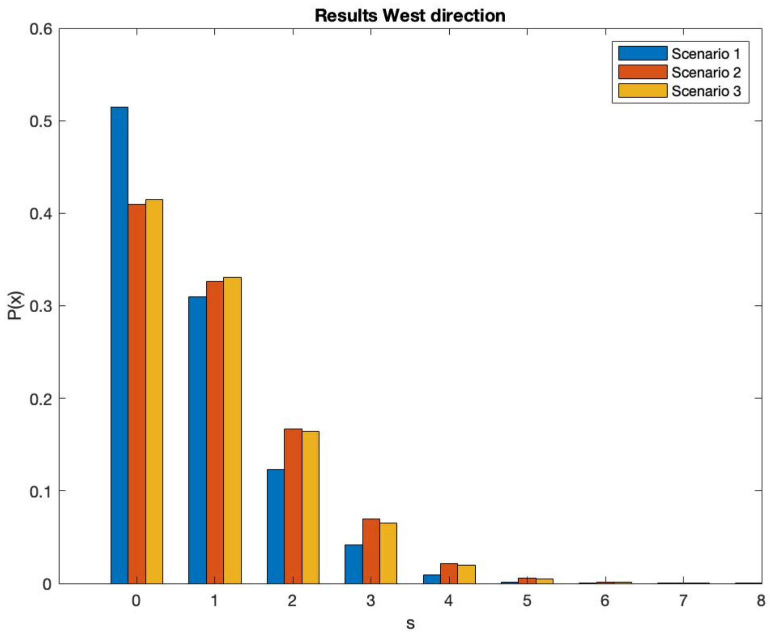

Figure 5.2: Results for scenario 1, 2 and 3 in the west direction

The probabilities for both directions exhibit similarities across all scenarios, with low probabilities of having 4 or more buses at the station. This suggests that none of the scenarios pose a significant risk of extensive queues and congestion. However, it is evident that scenario 2 carries the highest probability of exceeding 4 buses, indicating a higher likelihood of congestion. In contrast, scenario 3, which includes five berths in the west direction, exhibits a low probability of failure. The table presents the risk of queues, indicating that scenario 2 has the highest likelihood of experiencing queues, followed by scenarios 3 and 1. It is evident that the inclusion of bus 25 at the station increases the risk of queues. On the other hand, the addition of two more bus stops would mitigate this risk of queues. The risk of queue is presented in Table 5.8 below.

Table 5.8: Risk of queue

Risk of queue			
Scenarios	Scenario 1	Scenario 2	Scenario 3
West	11%	16%	14%
East	9%	13%	10%

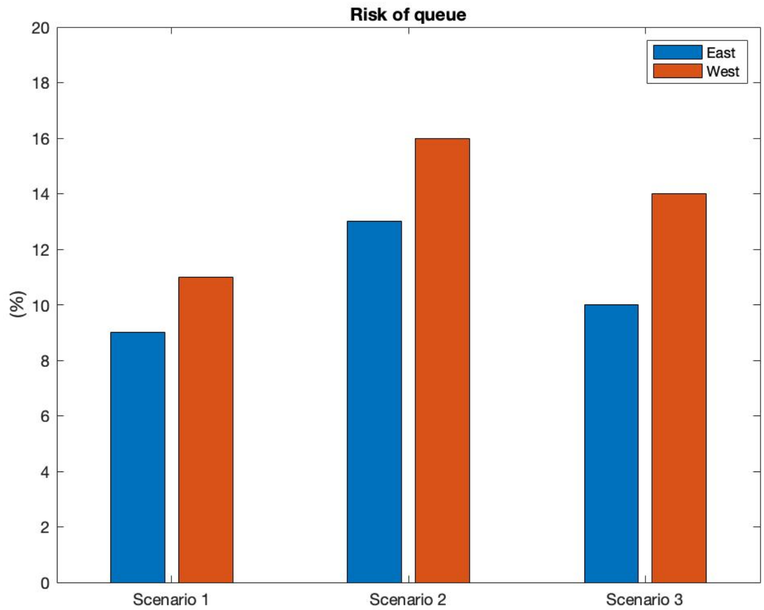

Figure 5.3: Risk of queue for each scenario in west and east direction

Table 5.9 shows the probability of queue for each of the berths. Bus berth B5 is identified as the most critical bus stop for scenarios 2 and 3, while B2 stands out as the most critical bus stop for scenario 2 specifically. These findings highlight the recurring occurrence of a few critical berths that significantly impact the overall capacity of the station.

Table 5.9: Risk of queue for each of the berths

Risk of queue berths										
Berths	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10
Scenario 1	1,3%	2,2%	1,0%	2,8%	7,8%	2,2%	0,9%	1,9%	-	-
Scenario 2	4,3%	7,8%	1,0%	2,8%	7,8%	2,2%	3,7%	1,0%	-	-
Scenario 3	1,3%	2,2%	1,0%	2,8%	7,8%	2,2%	0,9%	1,9%	3,7%	1,0%

5.3 Simulation model

This section includes the validation of the simulation model as well as the evaluation of risk of queue threshold.

5.3.1 Validation of simulation model

The comparison of the simulation run and and data from Västtrafik is showed for both directions in Figures 5.4 and 5.5 below. It can be seen that the simulation reflects the data which implies that the data input was done in a correct way.

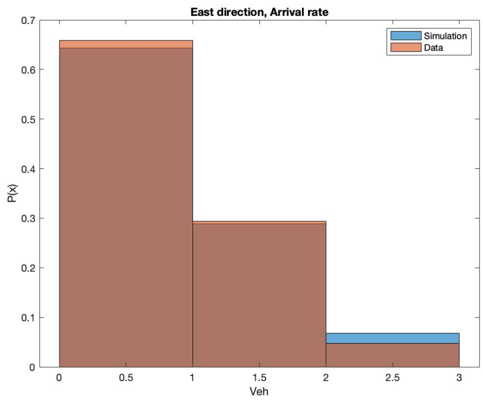

Figure 5.4: Data vs simulation in east direction

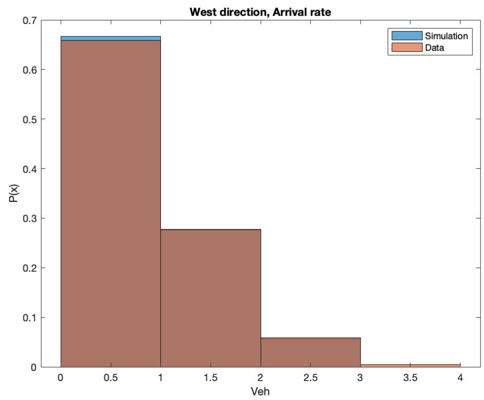

Figure 5.5: Data vs simulation in west direction

The simulation is compared with the queue model for the entire station, see Figure 5.6. Table 5.10 demonstrates the average number of buses for west direction, east direction as well as the entire station. These results show that the model and simulation show a reasonably close match in terms of the number of buses at the station, although there are slight differences. These differences are however considered acceptable for practical purposes. The simulation and queuing model reveal similar average number of buses in both directions.

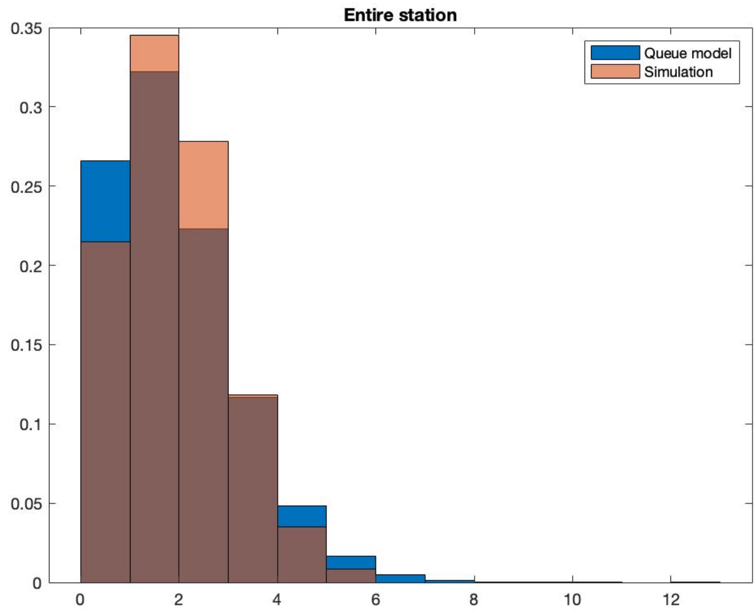

Figure 5.6: Model vs simulation

Table 5.10: Average number of busses comparison queue model and simulation

Average number of busses	Queue model	Simulation
West Direction	0,726	0,763
East Direction	0,713	0,677
Total	1,439	1,440

5.3.2 Risk of queue acceptance

Five simulations were conducted where 11% (Scenario 1), 15%, 20%, 25% and 30% risk of queue were tested on the west direction. The different risk of queue levels were obtained by changing the arrival rate for scenario 1, see Table 5.11.

Table 5.11: Effect of different risk of Queue in west direction

Risk of queue	11%	15%	20%	25%	30%
Total arrival rate (veh/h)	50	60	71	82.5	92.5

Figure 5.7-5.10 shows the the worst congestion observed during 1 hour of simulation for 15%, 20%, 25% and 30% risk of queue.

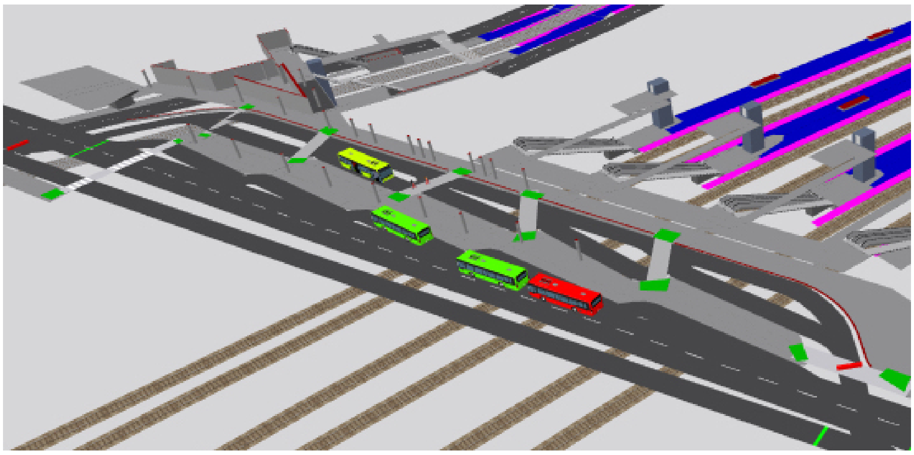

Figure 5.7: 15% risk

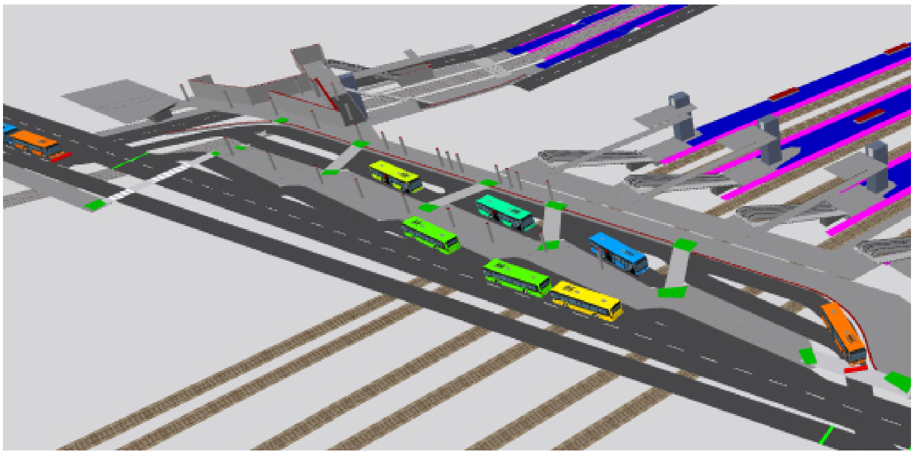

Figure 5.8: 20% risk

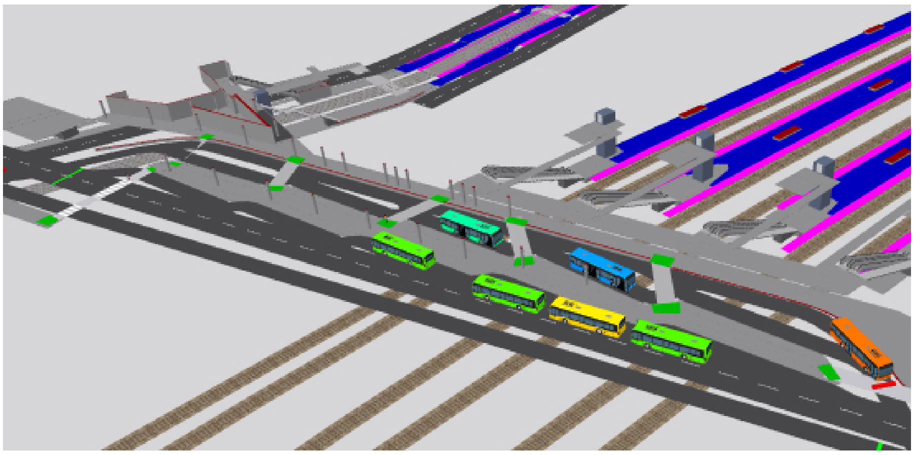

Figure 5.9: 25% risk

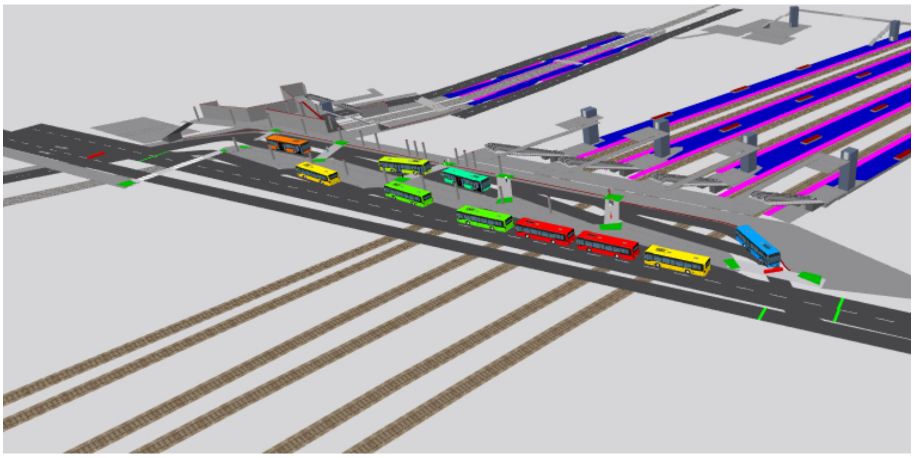

Figure 5.10: 30% risk

When observing the west direction it can be seen that increased risk of queue increases the severity of the congestion. Although, comparing 15% and 20% risk of queue no significant difference is observed. The probability of having n number of busses at the station for different risk of queue is shown in Figure 5.11

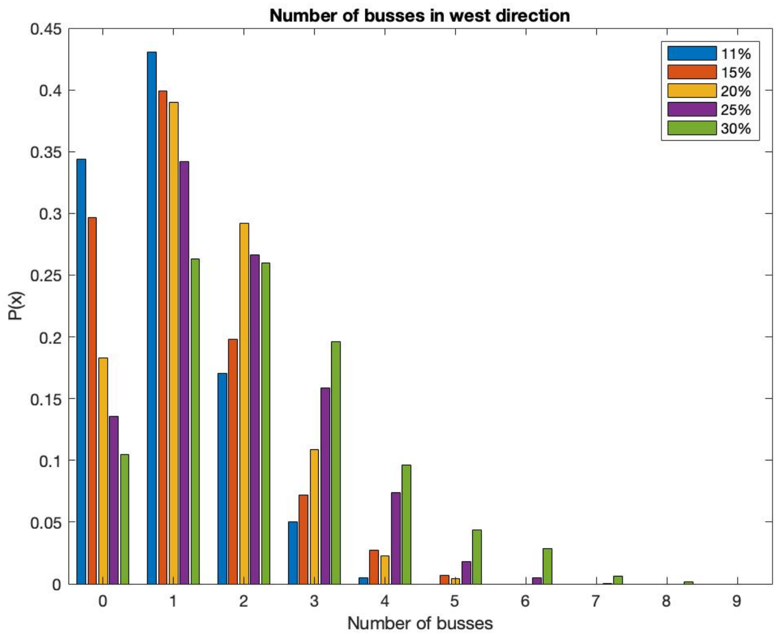

Figure 5.11: Probability of having n number of busses in west direction

Through data collection from the simulation, the analysis reveals the frequency of having a certain number of buses at the station for each risk percentage. The results indicate a high probability of encountering congestion at the station when the risk levels reach 25% and 30%. Specifically, these levels show a significant likelihood of having five or more buses at the station, which exceeds the available berths. Among the risk percentages considered (11%, 15%, and 20%), there is relatively little variation observed. The average delay was colected from the simulation and is shown in Figure 5.12.

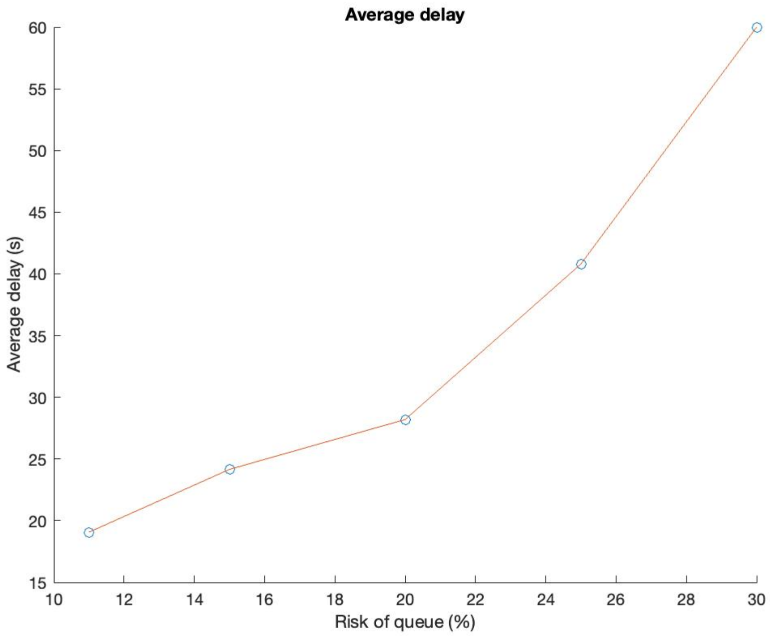

Figure 5.12: Average delay and risk of queue correlation

Furthermore, the average delay for all scenarios was examined, during a 10 hour running of each simulation. At an 11% risk level (base case), a delay of 18-20 seconds was noted, which increased to 23-25 when the risk level was raised to 15%. However, beyond a 20% risk level, there was a significant escalation in the average delay, indicating a steep upward trend. This suggests a substantial increase in bus queues when the risk threshold exceeds 20%. Nonetheless, a 20% risk level appears acceptable, as it did not result in severe congestion in the simulation, with a low probability of having more than four buses present. Beyond the 20% threshold, the delay increases considerably. These three justifications support the selection of a 20% risk level as reasonable.

5.4 Maximal capacity evaluation

The arrival rate for each scenario was gradually increased to their maximum limit, and the results are presented in Table 5.12. Additionally, Table 5.13 displays the maximal increase in arrival rate and the corresponding threshold for the Mölndal bro bus terminal.

Table 5.12: Maximal increase of scheduling for scenario 1,2 and 3

Risk of queue	Scenario 1		Scenario 2		Scenario 3	
Sheduling	Normal	43%	Normal	15%	Normal	22%
West	11%	20%	16%	20%	14%	20%
East	9%	17%	13%	17%	10%	14%

Table 5.13: Maximal increase and arrival rate

Increase and arrival rate			
Scenario	Scenario 1	Scenario 2	Scenario 3
Max increase	43%	15%	22%
Arrival rate (veh/h)	71,5	78,2	83,0

It is evident that scenario 1 exhibits the highest potential for increase, followed by scenarios 3 and 2. In terms of arrival rate, scenario 3 operates at the highest frequencies, which is reasonable considering its two additional bus berths compared to scenarios 1 and 2. Comparing the maximum arrival rates of scenarios 1 and 2, significant differences can be observed despite both scenarios having the same number of berths. This emphasizes the significance of scheduling and dwell time in determining the capacity. Table 5.14 provides an overview of the queue risk for all berths in each scenario, revealing that individual berths often impose limitations on capacity. Notably, bus berth B5 exhibits a considerably higher risk of queue compared to the other berths.

Table 5.14: Risk of queue in each berth with max capacity

Risk of queue berths max capacity										
Berths	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10
Scenario 1	2,7%	4,4%	2,0%	5,5%	14,7%	4,4%	1,8%	3,9%	-	-
Scenario 2	5,6%	10,1%	1,3%	3,6%	10,0%	2,9%	4,9%	1,3%	-	-
Scenario 3	2,0%	3,3%	1,4%	4,1%	11,1%	3,3%	1,4%	2,8%	5,4%	1,4%

5.4.1 Effect of dwell time

In order to gain an understanding of the effect of dwell time on the maximal capacity, various tests with changed dwell times were conducted, see Figure 5.13.

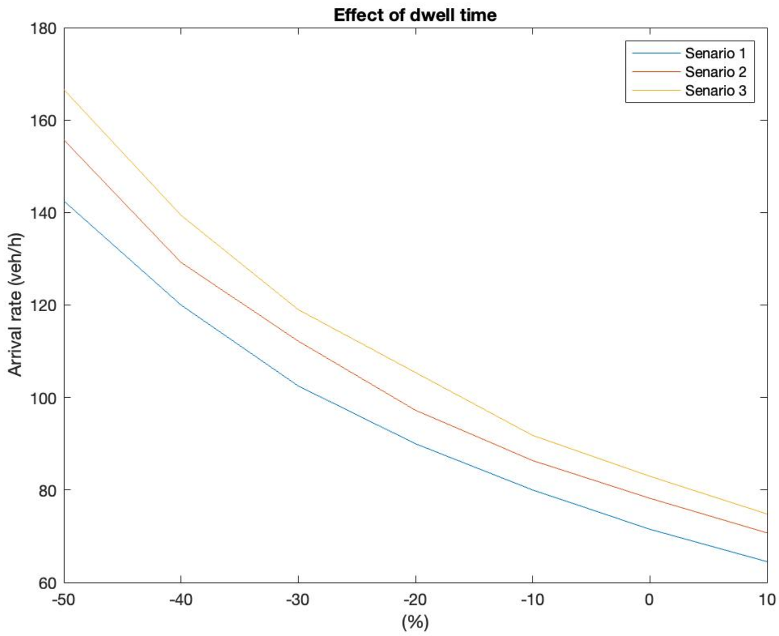

Figure 5.13: Effect that dwell time has on max arrival rate

Under normal dwell time conditions, it is possible to operate 70-80 buses per hour. However, reducing the dwell time by 50% allows for an increased capacity of 140-170 buses for the different scenarios. When increasing the dwell time the maximal capacity was reduced. The dwell time could not be increased with more than 10% for scenario 2 since the risk of queue surpassed 20% for the initial bus scheduling. It is important to note that it is not always feasible to uniformly reduce all bus berths dwell times by 50%, as certain buses require a specific amount of time for passenger loading and unloading. Nevertheless, these results highlight the significant influence of dwell time. Some buses may currently experience extended dwell times, resulting in substantial waiting periods. However, in the future, with a higher number of buses, the need for prolonged dwell times may decrease. However, this raises the issue of increased bus congestion at the station, potentially leading to longer dwell times for the affected line as a whole. Consequently, the overall impact may remain relatively unchanged.

6 Discussion

6.1 Discussion of results

Analyzing the results obtained from the queue model for different scenarios, it can be seen that the probability of having fewer than 4 buses at the station is relatively low for all scenarios (<5%), indicating a minimal likelihood of congestion. However, since queues can be influenced by various uncontrollable factors, this result does not automatically imply that Mölndals bro will never experience queues. Scenario 2 had the highest probability of having congestion as well as the highest risk of queue (16%), followed by scenario 3 (14%) and lastly 1 (11%). This was expected since this scenario had higher bus frequencies compared to scenario 1 and less bus berths compared to scenario 3. These results therefore indicate that capacity would be increased when adding two extra berths.

When evaluating the risk of queue, a guideline of 20% was set. This value was based on data collection (data obtained from the simulation model) and the observed congestion when simulating different levels of risk of queue. Data was collected of the number of buses in the system as well as the average delays due to the queuing of the buses. It was obvious that risks above 20% caused an increase in the number of buses at the station and also had a large impact on the average delays due to queuing. It is worth mentioning that the risk of queuing is subjective and may differ depending on the bus operators.

When the maximum bus flows were evaluated, the result showed that scenario 1 could be increased the most by 43%, followed by scenario 3 with 22% and scenario 1 with 15%. Since the buses had different frequencies from the start, the maximum bus flow per hour was also compared. This showed that scenario 3 could operate at highest capacity with 83.0 veh/h. Followed by scenario 2 with 78.2 veh/h and scenario 1 with 71.5 veh/h. It is reasonable that scenario 3 has the highest capacity as it has 10 bus berths compared to the 8 in scenarios 1 and 2. The fact that scenario 2 manages higher capacity than scenario 1 is partly due to the fact that the designated bus berths were rearranged in order to make room for bus 25. This made the distribution of buses more even between bus berths, which resulted in the capacity increasing further. Another reason is that the average dwell time for bus 25 was rather low which enables large increase of bus flows. This proves the great impact scheduling and dwell time have on the capacity. When the effect of dwell time was tested, it could be stated that it had a very large impact on the maximum capacity.

In all scenarios, the maximum capacity was doubled when the dwell time was reduced by 50%. When increasing the dwell time the maximal flows decreased quickly.

6.2 Limitations and challenges

Transportation systems are complex and influenced by various internal and external factors. Thus, accurately modeling and giving conclusive statements regarding the systems is and has been challenging. There were cases where the study did not directly reflect reality. One of those instance was that the queue model did not account for situations where buses from different berths blocked the path of a bus heading to its designated berth. The model is structured in separate systems where the buses do not affect or interact with each other, and the discussion arises as to whether this accurately reflects reality.

Another instance is that bus schedules in reality do not always increase proportionally when bus operators want to increase the bus traffic in an area. Bus frequency is highly adjusted based on demand and specific requirements (Gkiotsalitis, 2019; Ibarra-Rojas et al., 2015) which was something the models did not fully consider. With more data and a stronger model this could however be added as a future search. Nevertheless, implementing frequency adjustments based on demand could pose challenges, particularly in larger cities where demand fluctuates due to factors like construction projects and other variables influencing travel patterns. It would be impractical to expect a study of this magnitude to cater to every conceivable demand scenario. Instead of trying to account for every possible demand scenario, it would be more practical to use estimated counts as a reasonable approach which is what is already done in the industry. Connected to the instances where the model differs from reality it is worth noting that the introduction of the new bus line 25 at Mölndals bro was incorporated in the model/simulation in a slightly unconventional manner. This was done to achieve a more balanced timetable, as it would be unrealistic to have a significant imbalance in the number of buses arriving at different berths, meaning having one berth serving 14 buses while another berth only serves 4 per hour.

Furthermore, the model fails to account for bus drivers making logical decisions, such as diverting to another bus stop during heavy congestion. Additionally, bus drivers would not spend the same amount of time at a station when there is a large queue behind them which the model also did not always account for.

Lastly, pedestrian and car traffic were assumed to have a relatively minor impact. It is essential to address the potential implications of this assumption on the study results, as it was primarily made for the sake of simplicity. While a more comprehensive model incorporating all aspects of infrastructure, traffic, and the new railway line would provide increased realism and potentially more visually appealing outputs, focusing on bus traffic allows for a deeper examination of this study. The strategic plan to reduce car traffic on the bridge, at Mölndal, and throughout the region justifies the decision to overlook car traffic to some extent. However, it should be noted that pedestrians constitute a significant portion of Mölndal station's users, and their presence within the terminal area can impact bus movement and dwell times. In future studies, it would be vital to include pedestrian data and a simulation where pedestrians are included such as the PTV Viswalk extension and conduct further research on the expected volume of public transport users. This additional information could offer insights into the preferences and behaviors of public transport users at the terminal, providing a valuable foundation for potential redesigns aimed at reducing dwell times and alleviating passenger congestion on the bridge.

Furthermore, as mentioned previously, increasing each bus line separately in the micro simulation/model would yield more realistic outcomes. Not all bus lines require an equal increase in frequency; it depends on the demand for each specific line. By adjusting the frequency of individual lines based on their respective demand, the simulation can provide more accurate and practical results. Additionally incorporating the theory of bus bunching and investigating the stations around the hubs would give valuable information since a bus terminal is not ever an isolated entity but highly affected by the bus traffic before and after.

6.3 General discussion and observations

During the study, several key aspects and thoughts emerged that contribute to an interesting discussion. Considering the future plans to reduce car traffic and increase pedestrian activity (due to greater utilization of public transportation and the construction of the new railway station), these factors may potentially counterbalance each other to a certain extent in comparison to the model of today, now only regarding their effects on bus traffic. The impact that pedestrians will have on buses in the future could potentially be offset over time as buses will experience improved accessibility to the station, facilitated by the reduction in car congestion. Which could mean that the problems do not grow in the future but stay at a similar level.

Considering the frequent service of buses (e.g. having buses entering the station every 7 minutes or less), it is impractical for them to remain stationary for extended periods, as observed in certain scenarios. This is since the passengers could wait for that amount of time for the next bus to arrive without it affecting the attractiveness of the system all to significantly, this is however different if buses arrive every 20 minutes. Thus, the likelihood of encountering queues under such circumstances appears unrealistic as the buses with high frequency would load, unload and leave. This observation aligns with the theory that higher bus frequencies eliminate the need for synchronized operations. When buses operate at intervals shorter than 5-7 minutes, extended dwell times are unnecessary as passengers can simply wait for the next bus.

It should also be noted that two site visits cannot fully validate the realism of the data and its representation of real-life conditions, the observations made during these visits however provided valuable insights into pedestrian behavior. These insights can be instrumental in improving future models. Humans are complex beings, but their behavior can be reasonably understood. Factors such as avoiding standing in areas exposed to rain or seeking seating areas can significantly influence their movements within the station. Therefore, there are instances where pedestrians cross roads more frequently, leading to buses having to wait and dwell longer.

6.4 Significance and Contributions

This study could serve as a valuable resource for informing decision-making processes within the municipality regarding future traffic and public transport planning. It could also offer a methodological framework that could be applied to forthcoming projects. This is particularly significant considering the projected population growth and the development of new infrastructure, notably in Gothenburg and surrounding areas. It is worth acknowledging that the study conducted in this context involved a very detailed approach, which may be perceived as time-consuming and potentially costly for companies and municipalities embarking on new projects. However, the significance of robust and efficient traffic planning should not be underestimated.

7 Conclusion

This report concludes that Mölndals bro is operating far from its capacity. Neither one of the scenarios tested would experience congestion or large queues since the probability of having a full station in each direction were below 5%. It can be concluded that scenario 2 is most prone to experience congestion with its 16% risk for queue. Followed by scenario 3 and 1 with risk for queue of 14% and 11%.

Based on the results microscopic simulation model it can be concluded that a 20% risk of queue should be used as a threshold when evaluating maximal capacity. Based on this threshold it could be concluded that scenario 1 could be increased the most with 43% followed by scenario 3 with 22% and scenario 2 with 15%. When looking at maximal capacity the report concludes that scenario 3 could operate at highest capacity with 83 veh/h followed by scenario 2 with 72.2 veh/h and scenario 1 with 71.5 veh/h. Futhermore, it can be concluded that dwell time and scheduling have large effects on the operational capacity of Mölndals bro.

This method can be a useful tool for decision makers when evaluating future plans at large bus stations. Since the bus network is very complex and is affected by several factors it is hard to perfectly represent a system through a model. Therefore, decision makes should not base decision entirely on this model, it should be used as guidance.

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