Linköping Studies in Science and Technology, No. 1841
Licentiate thesis

Discrete Event Simulation of Bus Terminals

Therese Lindberg

LINKÖPING UNIVERSITY

Linköping Studies in Science and Technology. Thesis No. 1841
Licentiate Thesis

Discrete Event Simulation of Bus Terminals

Therese Lindberg

LINKÖPING UNIVERSITY

Department of Science and Technology
Linköping University, SE-601 74 Norrköping, Sweden

Norrköping 2019

Discrete Event Simulation of Bus Terminals

Therese Lindberg

LIU-TEK-LIC 2019
ISBN 978-91-7685-066-4
ISSN 0280–7971

Linköping University
Department of Science and Technology
SE-601 74 Norrköping

Printed by LiU Tryck, Linköping, Sweden 2019

Abstract

Public transport is important to society as it provides spatial accessibility and reduces congestion and pollution in comparison to other motorized modes. To assure a high-quality service, all parts of the system need to be well-functioning and properly planned. One important aspect for the system's bus terminals is their capacity. This needs to be high enough to avoid congestion and queues and the delays these may lead to. During planning processes, various suggested designs and solutions for a terminal need to be evaluated. Estimating capacity and how well the suggestions will function is a challenging problem, however. It requires analysis of complex interactions and behaviour of the vehicles. This sort of analyses can preferably be carried out using microsimulation. Furthermore, a discrete event simulation approach can make use of the fact that the path of a vehicle through a terminal can readily be described by a sequence of events (such as arriving, starting to drive to a stop etc.).

The overall aim of this thesis is to investigate how discrete event simulation can be used to evaluate bus terminal design and traffic control policies. The main contribution is the development of a method for bus terminal simulation. As a first step, a discrete event simulation model of a combined bus and tram stop is formulated. The model is tested on a real system where the current design is compared to an alternative one. The test shows that a model developed with a discrete event approach can be used to evaluate the situation at a stop and compare design alternatives. In the next step, a general discrete event simulation model of bus terminals is formulated. A modular approach is introduced, where a terminal can be constructed from a set of module building blocks. Another important contribution of the model is its spatial resolution that allows for queues and blockages to occur throughout the terminal. By applying the simulation model in a case study, it is shown that the model can be used to evaluate and compare various scenarios related to the layout, number of passengers and the outside traffic situation. Lastly, the bus terminal simulation model is used in a second case study in order to compare model output with empirical data. This study identified a number of factors that may have had an influence on differences between observations and simulation results and that is of interest to look further into. This includes the actual adherence to terminal rules and the effects of model parameters.

Acknowledgements

This thesis has taken form under the last few years with the continued support from my many colleagues and friends at Linköping university and VTI. Many are those that have had an influence on the writing and its contents. Some directly through discussions or guidance, others by making my days better through conversations, support and laughter. Some have been a constant presence from the very first day, other have come later and some have left. They have all been an important part of the process. There have been those that always listens and check in on how you do, those that always find the time to talk about everything and nothing, those that have made me better and those that just brightens the day.

No others have had such a direct influence on my work as my supervisors Andreas Tapani and Anders Peterson. Through their guidance, both I and the contents of this thesis have grown over the last few years. They have been a constant support and have always been helping me finding the way forward when needed, but also giving me the freedom to look for my own way. My main supervisor, Jan Lundgren, has also been of great importance with his guidance and by helping me see both the bigger picture and the smaller details.

The research of this thesis has been funded by K2 and Norrköping municipality and I am much grateful to both for having been given this opportunity. People from the two organizations, together with others from Östgötatrafiken, Stockholms läns landsting, Jernhusen, VTI and WSP, have also participated in the reference groups of the research projects. Their insights and understanding of public transport and bus terminals have been invaluable. K2 also deserves a special mention for having provided a space for contact with other researchers within public transport. The PhD seminars, in particular, have been both interesting and rewarding and the other K2 PhD students have broadened my understanding of public transport and the many ways to approach the subject.

Last, but never least, comes my gratefulness to my beloved and companion in life for just being awesome, to my cats for being fabulous, to my brother for being amazing and the rest of my family for just being fantastic in general.

Linköping, April 2019
Therese Lindberg

Contents

Chapter 1

Introduction

The threat of global warming is becoming ever more present in political discussions, regulations and in the minds of the world population. Like many sections of society, the field of transportation needs to make big changes to have a chance to halt this development. One way to reduce the greenhouse gas emissions of the field is to increase the share of motorized trips taken by public transport. As a more efficient means of transportation than individual cars, this can not only reduce emissions but also the congestion in a city. To make this a reality, public transport needs to be an attractive choice for transportation. It needs to have a high quality and all parts of the system need to be well-functioning. Physical infrastructure should be properly planned for the demand of the system and interchange stations and bus terminals, in particular, should be able to handle the flow of both passengers and vehicles without congestion, delays and queues. Insufficient dimensioning may lead to a terminal acting as a bottleneck where delays originate and spread through the system. Since passengers are well known to dislike waiting and transferring, delays will have a great impact on the experience of the trip (see for instance the perceived value of time of in-vehicle time versus waiting time reported in Trafikverket (2016)). It is thus of great importance that when a new bus terminal is being planned, or an existing one redesigned, proper steps are taken to assure that it can handle the traffic of both today and of tomorrow. This has not always been successful in the past, among the bus terminals in the Stockholm region in Sweden, 45 % experience capacity related problems (Al-Mudhaffar et al., 2016). At the same time, there is often a contradicting requirement of compact terminals that do not occupy large areas of land. Bus terminals are often centrally located and the land may be commercially valuable and of interest to exploit for other purposes. This conflict between terminal requirements has been seen in many cities around Sweden and is one reason why some terminals experience capacity related problems. Other reasons include bottlenecks at some point at the terminal, miscalculations of how much traffic a terminal can handle or increases in traffic over time. It is thus of great importance that the planning of the terminal layout results in a highly efficient solution with a high capacity in relation to size. Good methods are needed in this process, methods that can evaluate and compare various alternative design solutions. Not only the physical infrastructure needs to be evaluated, but also the traffic planning of the terminal in the form of timetabling and allocation of buses to stops. If this planning is poor, a terminal can be congested even if the physical design is well-planned. Good planning of the traffic can also reduce the congestion on an existing terminal, an easier measure than redesigning the infrastructure and important when changing the infrastructure is not an option. During the planning process other questions may arise that also need to be answered. How should various give-way rules and other rules of the terminal be set? Can the terminal handle replacement traffic from other modes? Good evaluation methods would be able to also answer these kinds of questions.

Simulation is an approach that can meet the described needs for methods in planning processes of bus terminals. The various alternatives, whether regarding the design, the traffic, the rules of the terminal or some other scenario, can with this approach be evaluated and compared. There are a number of simulation approaches suitable in various situations. One such approach is discrete event simulation. In this approach, the system is described based on a set of events where each event changes the state of the system. A bus terminal can from the perspectives of the buses and their movements be considered as a system consisting of a set of such events and the relationships between them. A single bus stop, for instance, has the events of arriving to the stop, starting to drive to the front of the stop and stopping at the front, dwelling to let passengers board and alight and leaving the stop. This kind of system is well-suited to be simulated using discrete event simulation. In this thesis, the overall aim is to investigate how discrete event simulation can be used to evaluate bus terminal design and traffic planning solutions on a terminal.

The following chapters will start with an overview of bus terminals in Chapter 2. This chapter describes what a bus terminal is and how it is characterized, how bus terminals are planned and how they can be evaluated. This is followed by Chapter 3 which gives an overview of analytical approaches to evaluate the efficiency of bus operations on terminals. Chapter 4 presents simulation approaches to traffic systems that share characteristics with bus terminals as well as simulation of bus stops and terminals. Chapter 5 presents the work of this thesis, which is followed by the three included papers.

Chapter 2

Bus terminals

This chapter defines and describes bus terminals, with a focus on how they can be characterized, planned and evaluated.

2.1 Bus terminal characteristics

This section describes general characteristics of bus terminals. A bus terminal will first be defined and its typical parts described. This is followed by a discussion of how bus terminals can be classified and a description of the various types of stops and terminals.

The following description of a bus terminal is based on the definitions presented in AASHTO (2002), Sveriges Kommuner och Landsting and Trafikverket (2012), and Stockholms läns landsting (2018). A bus terminal is a location where various modes and routes of public transport are connected and passenger transfers are facilitated. There are generally several stops for buses or trams as well as space allocated for passengers. Often there are also other functions on or in close proximity to the terminal, such as indoor waiting areas and toilets. While there are bus terminals where the stops are located along streets in the general road network, in most cases the terminal is separated from other modes of traffic. In this thesis, a bus terminal is assumed to be located in such separated areas with specific space allocated for the bus stops.

In general, a bus terminal can be separated into two spatial parts, one part for the passengers and one part for the buses. The bus side consist of the roadways, the stops where the buses let passengers board and alight and the entries and exits of the terminal. The passenger side includes platforms, possibly with passenger amenities such as benches and weather protection, passenger information systems, waiting areas and walking passages. There can also be various commercial functions, parking areas for bikes and cars as well as waiting areas for taxis. Here, the focus is on the bus side of the terminal. In the bigger public transport network, the bus terminal plays an important role through its connections of modes and lines. This makes the terminal a central hub were large amounts of passengers pass through. From the perspective of the buses, many lines stop at the terminal and any delays originating at the bus terminal can affect large parts of the network.

When planning for bus terminals it can be necessary to classify various types of terminals. These may have different requirements from a planning perspective. While many aspects are in common for bus terminals, others differ. It is possible to group terminals in various ways. One can focus on other functions available at the station, on the facilities that are present and whether or not there are trains stopping at the station. Another way is to focus on the role of the terminal in the network. Do most trips start or end at the station or are there mainly transfers between bus lines or between buses and trains? Other ways of grouping are to focus on the physical size of the terminal and the number of stops, the amount of traffic in the form of the number of arrivals and departures, or on the type of lines using the terminal. Are the lines passing through or are they starting or ending at the terminal? Is it local, regional or long-distance lines? Terminals can also be classified based on the layout of the terminal, the type of stops present and how these are arranged.

When it comes to the layout and the types of stops present, there is a range of varieties. Different types of terminals differ in the types of stops present and how these stops are arranged at the terminal. Different classifications of stop and terminal types are possible. Here, a new classification inspired by AASHTO (2002), Auckland transport (2013), and Stockholms läns landsting (2018) is presented.

Possible types of stops are linear, sawtooth and angle stop (drive-in, back-out), see Figure 2.1. Linear stops can be either dependent or independent, determined by the space in-between them. An independent stop can be entered or driven out from even if a stop in front or in the back is occupied. Sawtooth stops are always independent and are generally a more space-efficient alternative. They can differ

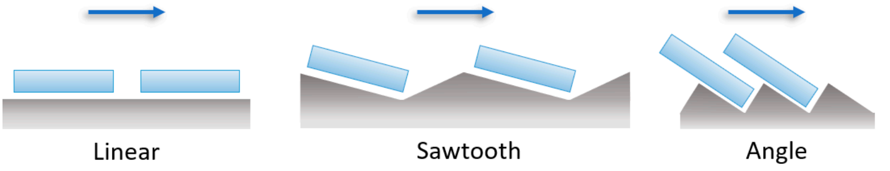

Figure 2.1: Stop types

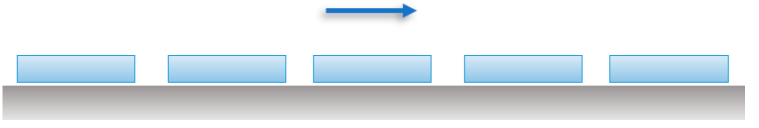

Figure 2.2: A serial arrangement of stops

in the angle of the stop, but will always have an angle small enough to allow for the buses to drive out of the stop without needing to back out. Larger angles give an angle stop, which will always require the bus to back out when leaving.

The various types of stops can be arranged in a large variety of ways. Some common arrangements include serial, laminar and parallel arrangements, angle terminal and centre platform. Added to these are also various combinations of the arrangements. In a serial arrangement, linear or sawtooth stops are simply placed one after the other, see Figure 2.2. This can be in a single row, with a bend or in a U formation. One variant of this is a bus street where there is a series of stops on both sides of the street.

Laminar stops are arranged side by side, see Figure 2.3. They are placed close enough so that no vehicle can pass directly by an occupied stop. Often there is only one stop in each parallel lamina, but it is also possible with two or more stops after one another.

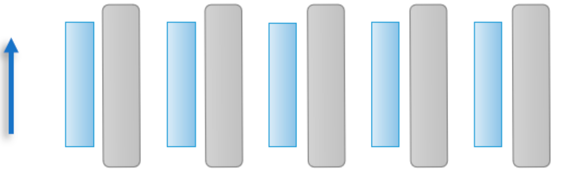

Figure 2.3: A laminar arrangement of stops

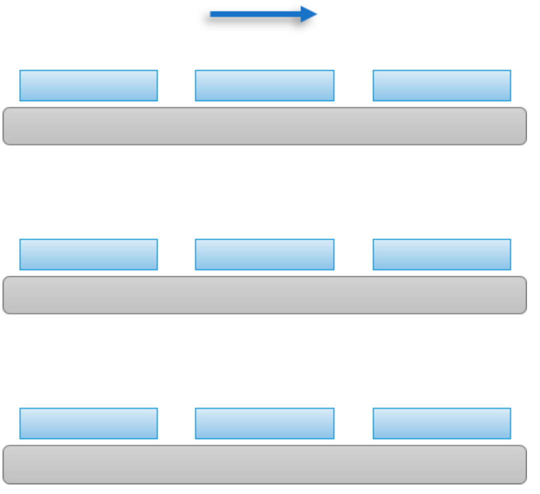

Figure 2.4: A parallel arrangement of stops

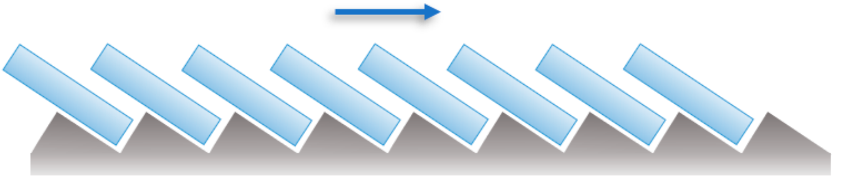

Figure 2.5: An angle terminal

An arrangement closely related to the laminar one is the parallel arrangement, see Fig 2.4. The stops are in this arrangement parallel, just as for the laminar stops. The difference lies in the fact that there is more space in-between the platforms so that buses can drive past occupied stops. There are often more stops next to each platform and the arrangement allows for both linear and sawtooth stops.

An angle terminal consists of angle stops arranged in a row, see Figure 2.5. The angle of the stops can differ and varying angles require a varying amount of space for buses to back out. There can also be platforms in-between the stops so that the passengers can reach all doors of the buses.

At a terminal with a centre platform, the stops are arranged on several sides of the platform, see Figure 2.6. The stops can be either of the linear or the sawtooth types.

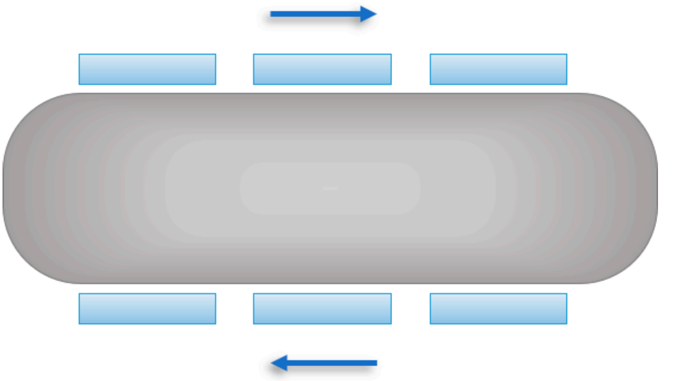

Figure 2.6: A terminal with a centre platform

2.2 Planning of bus terminals

When planning for a bus terminal, one first needs to define what quantifies as a *good* terminal. This depends on a number of factors. In this section, factors for a good terminal as well as how to choose a terminal design will be presented. This is based on a number of terminal planning handbooks, AASHTO (2002), Stockholms läns landsting (2018), Sveriges Kommuner och Landsting and Trafikverket (2012), and Auckland transport (2013). Many of these point out that a bus terminal needs to be both safe and secure for the people moving through and waiting at the terminal. It should also be accessible for people with disabilities, as well as for people with baby strollers, luggage or small children. These are all necessary requirements for the planning of any terminal. Other aspects depend on the size and type of terminal. Several guides point to the need of good information, weather protection and comfort for the travellers, aspects that should always be included to some degree, but where a bigger terminal may have higher requirements. Many guides also state the importance of a design with clear visibility where it is easy to find your way and where the walking distances are short. The environment of the terminal should be attractive, for instance through the architecture, art or plants, but also by being clean and in a good condition. Other parts of the station and the surrounding areas of the bus terminal also has an effect on the experience of the traveller, such as access to services of various kinds; toilets, vending machines, shops, and parking of bikes and possibly cars. The terminal also needs to have a good integration with the surroundings so that it is easy to move to and from the terminal.

The aspects presented so far are all from the perspective of the traveller. There are also aspects important for a good terminal from the traffic and driver perspectives. The vehicle operations need to be easy with few conflict points and enough space for manoeuvrability. The terminal also needs to be dimensioned for the amount of vehicles using the terminal so that it does not risk congestion, that is, it needs to have a high enough capacity. Since a bus terminal should last for a long time, it needs to be durable and able to handle future increases in traffic and amount of passengers. This has implications both for the terminal capacity and its flexibility. The terminal also needs to be able to operate under diverse weather conditions and there need to be appropriate facilities available for the drivers for shorter and longer breaks.

When designing the layout of a terminal, several of the listed aspects need to be taken into account. Conflicts between pedestrians and buses need to be minimized and allowed only in ways that are safe. Conflicts between buses should also be minimized since they have a negative impact on the capacity. Stop types and stop arrangements should be chosen based on the specific situation. Sawtooth stops are more space efficient than linear stops, especially for the independent variant, but less flexible for future changes. Sawtooth stops also make it easier to align the bus doors with the kerb line. Angle stops are also space efficient and non-flexible. A terminal with angle stops allows for shorter walking distances and comfortable waiting areas, but require more time for backing and are not safe if pedestrians cannot be stopped from walking behind the buses. It is not a recommended design for terminals with through-going lines and cannot be used by double-articulated buses. A laminar arrangement can be very space-efficient, but will result in many conflict points between buses and pedestrians. A parallel arrangement results in less conflict points and can be used to reduce the distance between stops for larger terminals. A serial arrangement can give long walking distances and difficulties seeing the whole area, but may fit into places other arrangements would not. Sometimes existing infrastructure can be used, such as a street used for a bus street terminal. Using existing infrastructure or fitting the terminal into small places may make it difficult to arrange passenger services such as waiting areas, however. A centre platform gives short walking distances, can allow for easy access to passenger services and can either be very safe for level separated access, or much less so if pedestrians have to cross the driving areas. The driving directions of the buses can also be perceived as confusing.

Choosing a design thus depends greatly on the situation. No definite rules can be given since each situation is more or less unique. In general, bus terminals with many transfers should have a design that facilitates fast and easy transfers. In some cases, there may even be requirements of short transfer times, such as a maximum transfer time between the rail and bus modes. If there are few bus lines, transfers direct over the platform are preferable. A central platform can then be a good choice if the transfers are only between bus lines and safety can be guaranteed. For larger terminals or for transfers between modes, a central platform can instead result in long transfer times. Designs such as this require level separated access to be safe, for instance through the use of a tunnel or a bridge. This results in travellers having to change level twice if the start and end of a transfer are located at the same level. For smaller terminals, a bus street may be an easy solution. For larger terminals that only have lines starting or ending at the terminal, an angle terminal can instead be a good solution.

Planning of terminals does not only consist of planning of the physical infrastructure, but also of the traffic. Buses need to be allocated to stops in a way that is efficient without unnecessary waiting, that reduces transfer distances and possibly also reduces the number of stops needed.

2.3 Terminal evaluation

In this section, various ways to evaluate a bus terminal from a traffic flow perspective will be described with a focus on the performance measures used. How well can the buses drive through the terminal without conflicts and queuing? This includes both direct measures and more indirect ones, such as the effects on the passengers. Evaluation of other aspects of a terminal will not be included. For evaluation of the pedestrian flow in passenger areas, see for instance Johansson (2016).

An important aspect of a well-functioning bus terminal is the capacity. This is the amount of vehicles that can use the terminal without causing congestion. It is closely correlated with the punctuality of the vehicle departures since driving through a congested terminal takes more time. To use capacity as a performance measure of a bus terminal, it needs to be clearly defined. There is no clear point when a system changes from uncongested to congested, however, since this is a gradual change. It also depends on the traffic at the terminal, how the arrivals and the departures are distributed and how late or early they tend to be. For single bus stops, a capacity formula has been formulated by the Transportation Research Board (2013). It calculates the stop capacity by using the minimum possible headway between buses for a specified probability of all berths of the stop being occupied when a bus arrives (see Section 3.2). Capacity of a bus terminal is not as clearly defined. Here, it depends not only on the individual capacity of the stops, but also on bottlenecks at the terminal and various blockages between the buses. Transportation Research Board gives only rules of thumb and suggestions on how to decide the number of stops at the terminal, but no capacity formula. If the capacity can be estimated, a related metric can be calculated for a particular terminal with a given flow of vehicles. This is the saturation, the fraction of the capacity currently used.

Other approaches for evaluating the traffic flow performance of a bus terminal includes more direct measurements. One can evaluate the congestion by looking at the presence of queues and waiting vehicles. Possible performance measures include average queue lengths in various positions or the average number of vehicles waiting somewhere at the terminal. The effects on the vehicles can also be studied. Performance measures of interest include various time measurements such as driving delay, time spent waiting in various parts of the terminal and lateness at the departure. Since a congested situation may also affect the passengers, performance measures such as passenger waiting time and transfer time can also be of interest.

Chapter 3

Analytical modelling of bus stops and terminals

In this chapter, analytical modelling of various aspects of the vehicle traffic at bus stops and terminals will be presented. The focus is on methods describing the efficiency of the operations, the usage and the capacity of the stop or the terminal. Analytical modelling can be used to calculate average dwell times, delays, occupancy and capacity. Other traffic flow performance measures of terminals are more difficult to capture. Analytical modelling can be useful in planning processes to get estimates on various factors affecting the operation of the system. They are deterministic in nature and often difficult to use for more complex systems.

3.1 Dwell time modelling

In some cases, it may be adequate to estimate only the stop dwell time, rather than the capacity or the exact effect on the flow of vehicles. This is useful when estimating the total runtime of a bus line, for instance. The dwell time can also be needed in other models. It depends on a number of factors, including the number of boarding and alighting passengers. Depending on the needed level of detail and availability of data, functional forms of varying complexity and number of parameters can be used.

Here, a version is presented where a set of linear equations determine the dwell time in various situations. For a bus with only alighting passengers the dwell time is calculated based on the dead time, t_0, the time per alighting passenger, t^{alight}, the number of alighting passengers, n^{alight}, and the number of doors, n^{doors}. The passengers are assumed to spread evenly on all doors except the one in the front. The dwell time, T_d, then becomes

$$T_d^{alight} = t_0 + t^{alight} \left\lceil \frac{n^{alight}}{n^{doors} - 1} \right\rceil. \tag{3.1}$$

If passengers are only boarding, the dwell time is the largest of the time until the planned departure, t^{to_dep}, and the time for stopping and letting passengers board. The latter is calculated based on the dead time, the time per boarding passenger, t^{board} and the number of boarding passengers, n^{board}. All passengers are assumed to use only the front door, which gives the dwell time

$$T_d^{board} = \max(t^{to\_dep},\ t_0 + t^{board} n^{board}). \tag{3.2}$$

If both boarding and alighting are to take place, the dwell time is the maximum of the time until planned departure and the boarding and alighting processes. This can be written as

$$T_d^{both} = \max\left(t^{to\_dep},\ t_0 + \max\left(t^{board} n^{board}, \left\lceil \frac{n^{alight}}{n^{doors} - 1} \right\rceil\right)\right). \tag{3.3}$$

Other papers use similar equations, see e.g. Luo and Guo (2010) and Seriani and Fernandez (2014), or more complex versions with for example different boarding and alighting times for individuals or for groups, as in Tirachini (2013), or other functional forms as in Fernández (2010).

3.2 Capacity formulas

Another analytical method is to use capacity formulas, as was introduced in Section 2.3. These give the capacity of a stop in the form of the maximum number of buses per hour. Adhvaryu (2006) states that the simplest version of a capacity equation for a single bus stop is

$$Q_{stop} = \frac{3600}{T_c + \overline{T_d}}, \tag{3.4}$$

where T_c is the clearance time and T_d the dwell time. This is simply the inverse of the average time the stop is occupied by a vehicle, converted from buses per seconds to buses per hour.

Other versions of Equation (3.4) have also been introduced. These include more factors affecting the capacity. One of the most widely used versions is the one formulated by the Transportation Research Board (2013). An important addition to the simpler equation is the fact that instead of calculating the capacity using the average time the stop is occupied, it uses the minimum headway between buses for a chosen failure rate a, that is the probability of all loading areas being occupied when a bus arrives to the stop. It also includes factors accounting for the number of loading areas, traffic blockage and the effects of a downstream traffic light. The stop capacity in the form of the maximum number of buses per hour is

$$Q_{stop} = N_l f_{tb} \frac{3600(g/C)}{T_c + \overline{T_d}(g/C) + Z_a c_v \overline{T_d}}, \tag{3.5}$$

where N_l is the effective number of loading areas accounting for the fact that each added loading area results in a reduced increase in the capacity, f_{tb} is a factor accounting for traffic blockage, g/C is the fraction of time a downstream traffic signal allows bus movements and $Z_a c_v \overline{T_d}$ is the operating margin, which is the maximum time the average dwell time can be exceeded without a large risk of a queue forming.

Other stop capacity formulas have also been formulated. Some use simpler versions of Equation (3.5) with modifications to their specific circumstances. Widanapathiranage et al. (2014) present a version for a BRT station that includes bus-bus interference within the station area and Al-Mudhaffar et al. (2016) add a correction factor based on local measurements. Hisham et al. (2018) develop Equation (3.5) further by better representing traffic blockage, interference between buses and signalised intersections. Another stop capacity formula has been formulated in Szasz et al. (1978) specifically for buses running in convoy operations. There are also non-analytical approaches where the parameters of the functions are found from simulation (Fernández, 2010).

While there are a number of stop capacity formulas, few bus terminal capacity models have been formulated. Al-Mudhaffar et al. (2016) state that if the terminal is constructed in such a way that the buses do not interfere with each other, the capacity of the individual bus stops can simply be summarised. Otherwise, which is usually the case, a reduction factor would need to be used and the capacity becomes

$$Q_{term} = \sum Q_{stop} F_{term}, \tag{3.6}$$

where F_{term} is a reduction factor depending on bus to bus interference, limited exit capacity, interference from pedestrians and other situations arising at bus terminals. This factor is in general not known and difficult to estimate.

3.3 Queuing theory

A third analytical method is queueing theory. This can be used to analyse delays and queue lengths of simpler bus stops and may make use of formulas from previous sections. A bus stop can be considered a queuing system where buses arrive with a particular probability distribution, wait on entering the stop if it is occupied before dwelling and leaving, possibly with a probability of needing to wait on blocking traffic or a downstream traffic light. Huo et al. (2018), for instance, use queuing theory to estimate bus delay at a multiple berth bus stop. For more complex systems with many stops, vehicle interactions and rules governing when and how buses can enter and leave stops, queuing theory is more difficult to use, however.

Chapter 4

Microsimulation of bus stops and terminals

This chapter will present microsimulation of bus stops and terminals, as well as discrete event simulation approaches to related traffic systems that also consists of vehicles moving within a bounded area.

4.1 Introduction

In traffic microsimulation, individual vehicles and their movements are simulated (for an introduction to the field, see e.g. Barceló (2010)). There are primarily two simulation approaches used, time-based and event-based simulation. These differ in their strengths and limitations and are suitable in different situations. In time-based simulation, the state of all vehicles is updated at discrete time steps. This stands in contrast to event-based simulation, generally referred to as discrete event simulation, where calculations are only carried out at positions in time when an event occurs that changes the state of the system.

For simulation of road traffic, the time-based approach is most common with a number of commercial software available. The state of the vehicles is in this approach determined based on a number of sub-models describing the behaviour in various situations. The acceleration behaviour, for instance, is determined in a car-following model where the acceleration is based on the gap to the vehicle in front, both vehicles' speed and a number of other factors and parameters (Barceló, 2010). Other models describe lane-changing and various discrete-choice situations such as junctions. Time-based microsimulation of public transport often uses the presented models together with public transport specific ones. The specific models can for instance add public transport routing, timetabling and the behaviour at bus stops.

Discrete event simulation has been used in a variety of fields over the years, such as production scheduling (Rodammer and White, 1988), resource allocation in health care (Jun et al., 1999; Steins, 2017) and rail modelling (Berger et al., 2011; Espinosa-Aranda and García-Ródenas, 2012). It is a less common approach to road traffic simulation, however, with time-based simulation being the dominant approach. Some examples where discrete event simulation is still being used in traffic simulation will be given in the next section.

4.2 Discrete event simulation of traffic

In this section, various applications of discrete event simulation to traffic systems will be presented, both examples of road traffic simulation and simulation of other transport systems that share similar characteristics to bus stops and terminals. The latter examples consist of simulations of various kinds of vehicles (trucks, planes, ships etc.) moving within a bounded area between clearly defined positions, just like buses at a terminal move within the terminal area between various types of stops and entries and exits.

For road traffic, an event-based approach is far less common than a time-based one. Even so, there are several examples in the literature of this approach being used. In the 1980s Darzentas et al. (1980), Brodin et al. (1982) and Hummon et al. (1987), for instance, presented discrete event simulation models of nonurban T-junctions, two-lane rural highways and of signalized intersections, respectively. In recent years, an event-based approach has been used in various circumstances utilizing the strengths of the approach. It has been used to reduce the model complexity (Soh et al., 2013), decrease the computational time needed for simulations (Thulasidasan and Eidenbenz, 2009) and include heterogeneous flow (Arasan and Dhivya, 2010). There are also examples of discrete event simulation being used in mesoscopic traffic simulation, a less detailed approach than microscopic simulation. Cats et al. (2010), for instance, presents such a model that can be applied to public transport systems.

Traffic systems with similar characteristics with bus stops and terminals include intermodal freight terminals, airport terminals, car parking areas and mining systems. In all of these some sort of vehicle moves within a bounded area. At intermodal freight terminals, goods are transferred from one mode to another. This can be at ports where goods are moved between ships and railway or trucks, or at an inland terminal where the transfer is between railway and trucks. Several studies have simulated the processes associated with this transfer of goods between modes (Rizzoli et al., 2002; Bielli et al., 2006). These simulations include generating arriving vehicles according to some particular pattern, activities carried out in specific locations and a service time associated with the activities.

At airport terminals, discrete event simulation has been used to sequence arrivals and departures as well as assigning runways (Andreussi et al., 1981). Such models require generation of arriving and departing planes and includes some simple priority rules for how the planes can use the runways.

Car parking areas also share several characteristics with bus terminals. Here, vehicles are to drive to and from a parking space. Various strategies to reduce car circling time or improve parking space availability have been evaluated. The arrivals of vehicles are generally simulated together with rules for finding a parking space, driving times and parking time (Harris and Dessouky, 1997; Surpris et al., 2014). A closely related area is that of curb-side parking for dropping off or picking up passengers, for example in connection to an airport. The parking times are here much shorter and there may be several modes as well as mode restricted parking areas. Interactions and blockages between vehicles can have a bigger impact and simulation models may include a more detailed description of the vehicle movements, as in Tunasar et al. (1998).

Mining systems, both under and above ground, can also be evaluated using discrete event simulation. Trucks or other vehicles can be simulated as they transport mining materials through the mining system. This includes simulating the loading times, transport times and possibly vehicle interactions at meetings and intersections (Lizotte and Bonates, 1987; Greberg et al., 2016).

Due to the similarity of these systems to bus stops and bus terminals, several aspects that are also needed for stops and terminals have been modelled. This include arrival and service time processes, routing to specific locations, priority rules and vehicle interactions. While there are articles including a spatial resolution with a more precise representation of the vehicles' positions and a more detailed modelling of vehicle movements, this is still uncommon, however.

4.3 Simulation of stops and terminals

There are a number of studies presenting simulation models of bus stops and a few presenting models of bus terminals. Some use discrete event simulation, while others have a time-based approach. Bus stop studies range from those modelling a larger system where the stop is only one part, to studies focusing on the stop itself. When a larger system is modelled, not only the bus stop is included, but also road segments and possibly stop lights in-between. Examples of such models can be found in Ancora et al. (2012) and Spek et al. (2017). These simulation models are often used to evaluate various operational schemes or ways to improve the performance of the bus system.

Studies modelling a bus stop without a larger system can still include the immediate surroundings and other motorized vehicles, see for instance Tan et al. (2013) and Qian and Hu (2014). Often stop types in close contact with the road traffic are modelled. Similar to models of larger systems, these smaller models are often used to improve the operations of the system, but here focusing on either the stop itself or the effects of the stop on the surrounding traffic. Possible improvements include both various operational principles, such as assignment of lines, and stop design.

Simulation models that only model the stop itself and not the surrounding traffic put more focus on the stop operations. Examples of such models can be found in Fernández (2010) and Zhao et al. (2018). Surrounding traffic can still be included indirectly by adding delay as vehicles leave the stop. The stop types modelled in these kind of studies vary, but are often more or less separated from the surrounding traffic system. Common applications of these models are similar to applications of models including surrounding traffic, with the exception of not evaluating the effect on the surroundings.

While models of bus stops can generally be simpler than those of bus terminals due to fewer points of conflicts, less interactions between the vehicles and a shorter, more direct way through the system, there are still several parts of stop models that can be used also for terminals. This includes modelling of bus arrivals, passengers, dwell time and effects of outside traffic on exit times. An early example of bus terminal simulation is the study presented in Jennings and Dickins (1958). In this paper, a time-based approach is taken as a large bus terminal in New York is simulated. The model includes blockage rules between vehicles and modelling of arrivals of both vehicles and passengers. It is used to evaluate the effects of varying platform lengths on bus queue lengths and passenger waiting times.

A much smaller terminal in Brighton consisting of three stops is studied in Adhvaryu (2006). In this, a discrete event simulation model originally developed for bus stops is used to simulate the whole bus terminal. This stop model is presented in more detail in Fernández (2010). It includes bus and passenger arrival modelling, modelling of delay at the exit and of the dwell time at the stop. In Adhvaryu (2006), this model is used to evaluate a number of alternatives to the current design of the terminal based on the performance measures stop capacity and saturation. Liang and Wang (2009) also have a discrete-event approach which is combined with optimization as the bus dispatching scheme of a small, five stop terminal is optimized by maximizing profit per day. The model includes modelling of buses, trains and passengers.

Unlike other terminal model papers, Fernández et al. (2010) do not focus only on bus terminals. Instead they integrate the bus stop model of Fernández (2010) into a commercial time-based traffic simulation software that also simulate the passengers. This is applied in several experimental examples, including evaluating the transfer operations of a ten stop terminal partly integrated with road traffic. In this, the effects of various operational conditions on the passenger waiting time are evaluated. Seriani and Fernandez (2014) also have a time-based approach as they use commercial simulation software programs to simulate both vehicles and pedestrians at two stop bus rapid transit stations. These models include dwell time modelling. Various pedestrian traffic management measures are evaluated with regard to bus delay and transfer delay and dissatisfaction of passengers. Figueras Jové and Casanovas-García (2018) also include both buses and passengers as well as taxi cars, as they model a shuttle bus system at a cruise terminal. The system consists of two bus terminals where passengers are shuttled from one to the other, where they continue to board taxis. A discrete event approach is used and the terminal side includes modelling of passenger arrivals and dwell time. Based on passenger lead times, the number of needed stops is decided upon, among other design factors.

The presented terminal simulation models in this section include many of the parts and processes needed for a complete terminal model. Most of these model specific bus terminals and systems and may be difficult to adapt to another system. Furthermore, only the time-based approaches using commercial software include a spatial resolution where vehicle interactions can occur throughout the terminal. These may, on the other hand, have difficulties adapting the software programs to bus terminals. This is due to the differences in behaviour and rules between terminals and the road traffic for which the software was originally developed. There is thus a lack of dedicated terminal simulation models that can be adapted to various terminals and that can capture the vehicle interactions throughout the terminal.

4.4 Processes needed for a terminal simulation model

Based on the studies of the previous sections, a number of processes that can be included in a terminal simulation model have been identified. These are presented in Figure 4.1. Vehicles needs to arrive to the terminal, for instance according to a timetable or based on headways, and they need to eventually leave, possibly with delay due to traffic or traffic signals. In-between these processes a vehicle needs to drive and interact with other vehicles, dwell at one or more stops and possibly wait at for example a pedestrian crossing. A terminal model may also include modelling of the passengers in more or less detail, for instance in the form of an arrival distribution. Vehicle arrivals, dwell times and exit always need to be included in a terminal simulation model in one form or another. The other three processes, on the other hand, can be omitted for simpler models.

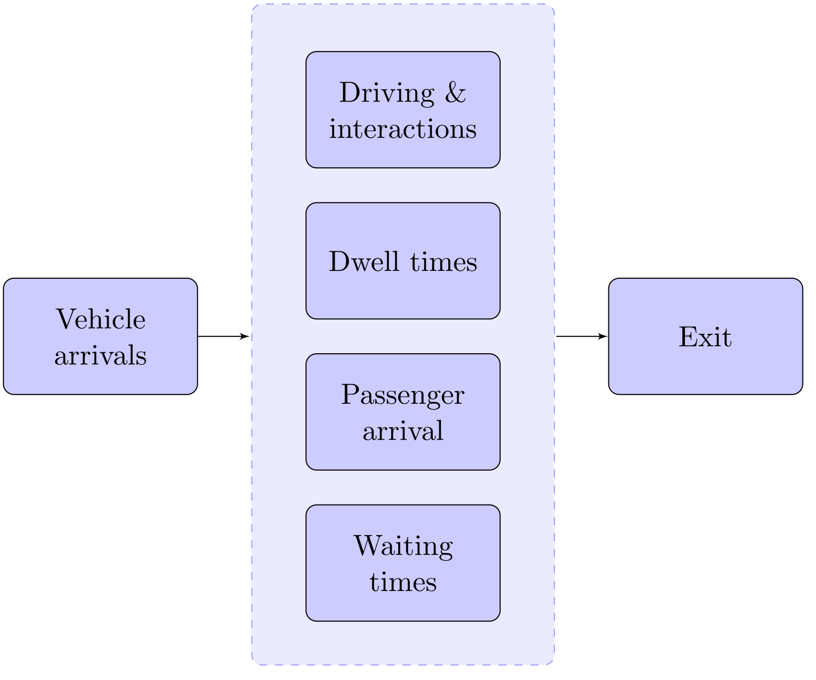

Figure 4.1: The processes that can be included in a bus terminal simulation model

Chapter 5

The present thesis

Previous chapters have shown the complexity of bus terminal planning and the need for good methods that can be used in this process. For this purpose, there are several handbooks describing the requirements for a good bus terminal and that give some general advice how to choose a design in various situations. There are also analytical methods that can analyse the efficiency of the bus operations at smaller bus stops from various perspectives. Neither of these approaches are suitable to analyse the operations of larger bus terminals, however. Microsimulation, on the other hand, has been used for this purpose and is able to do more detailed analyses. Few simulation models have been able to capture the terminal specific rules and behaviour and the detailed movements and interactions of the buses. This thesis aims to fill this gap.

5.1 Aim and research questions

The overall aim of the thesis is to investigate how discrete event simulation can be used to evaluate bus terminal design and traffic planning solutions on a terminal. To contribute to this aim, the objective of the thesis is to develop a discrete event simulation model that describes vehicle movements and interactions at bus terminals.

The following research questions are formulated for the development of the model:

1 How can a discrete event microsimulation model of a bus terminal be formulated?

2 What are the advantages and challenges of using discrete event simulation for bus terminal simulation?

3 For what type of terminal planning and traffic control related questions can a discrete event simulation approach be useful?

5.2 Method and delimitations

The implementation of the modelling of this thesis is carried out using the discrete event simulation modelling software SimEvents. This was chosen due to ease of use and its access to MATLAB functionality (MathWorks, 2019a). SimEvents is a discrete event simulation engine and component library developed by Mathworks (MathWorks, 2019b). The activities of a terminal can be described by combining various components of the library. A vehicle arrives by being generated in an *entity generator*, can wait in an *entity queue* and spend time in an *entity server*, for instance. This is complemented with MATLAB functions that are used for complex calculations of the time spent in entity servers representing various activities, such as driving or waiting at the exit. This makes it possible to have a big freedom in modelling these activities, while still making use of the simplicity of using library components.

Any simulation model is dependent on input data and in the case studies of this thesis, several automatic data sources are used. Vehicle arrivals and departures data is captured through automatic vehicle location systems on the buses. The number of boarding passengers is gathered either through smartcard data or automatic passenger counting at the doors. The latter method has also been used to get the number of alighting passengers. This has been complemented by manual collection of data. Analysis of simulation output in the case studies is carried out using various statistical methods, including confidence intervals and t-tests.

This thesis aspires to not restrict the type of terminal considered, but rather to find a general way to model bus terminals. Some delimitations are still needed. Terminals considered are separated from other modes of traffic, have clearly defined areas for various purposes (boarding, alighting etc.) and no or negligible number of pedestrians walking in the driving areas outside of pedestrian crossings. The modelling focuses on the terminal itself and its driving areas and does not include outside traffic or other parts of the station. The modelled entities consist of the vehicles located within the terminal. It is their movements and interactions throughout the terminal that are modelled and the output of the model is based on these bus operations. Other actors, such as pedestrians, bicycles or taxis, are generally not included. An exception is how the number of pedestrians affect dwell times at stops and waiting times at pedestrian crossings. Other aspects of a bus terminal not related to the efficiency of the bus operations, such as safety and accessibility, are not considered.

5.3 Contributions

The main contribution of this thesis is the development of a method for simulating bus terminals. The papers of the thesis present two discrete event simulation models, one for a smaller stop and one for larger terminals. These have been tested and used in case studies and shown to be able to analyse and compare various scenarios and design alternatives. The stop model was used as a first step to a terminal model and its development and application showed the suitability of the discrete event approach for the smaller system. The terminal model uses the same approach for a general bus terminal. It is able to capture interactions and queuing throughout a terminal by having a spatial resolution that is uncommon for discrete event models. Another important feature of the model is its modular structure, which allows for easy applications to various terminal layouts. Each module represents a section that can be found on a terminal and models the events and actions associated with this part. This modelling of terminal events and actions is in itself an important contribution of the thesis.

The discrete event approach has been evaluated also for the larger system of a bus terminal and shown to indeed be a good approach for terminal simulation. Comparisons with previous time-based simulation approaches of the same systems considered in case studies have shown that the event-based approach can easier incorporate various decision points in the processes, such as different routing of buses and trams or routing in general on the terminal where different decisions may be taken depending on the situation.

By applying the simulation models in several case studies, examples of for what kind of problems the simulation approach is useful have been shown. In these case studies, insights into the systems studied have also been gained. This includes increased understanding of operations of the bus and tram stop and the bus terminal at Norrköping interchange station and the Slussen bus terminal in Stockholm.

5.4 Outline of papers

In this section, the papers included in the thesis will be presented. In Paper I, a model is developed for a combined bus and tram stop and it is shown that the discrete event approach is able to describe and simulate the vehicle movements of a smaller stop. This is expanded upon in Paper II, where the approach is used on general bus terminals and a modular terminal simulation model that can be adapted to various layouts is presented. This model is further expanded upon in Paper III where one of the output metrics is validated against empirical data.

Paper I

A simulation model of local public transport access at a railway station

In this paper the discrete event modelling approach is tested on a smaller system. A combined bus and tram stop located at Norrköping interchange station is chosen as a case study. The stop serves as the main access for local public transport to the station. One of the two sides of the stop with vehicles going in one direction is modelled and the events and activities of this smaller system are identified. In doing this, extra caution is taken to the differences between the behaviour of buses and trams. The current layout of the stop is compared with an alternative where a second lane allows buses to overtake vehicles in front when ready to leave the stop. The results show that while this alternative design improved the operations of the stop, the differences where small unless there is a substantial increase in the amount of traffic using the stop (more than 4 times the current amount of traffic). In the case of these large increases, the improvement of the design alternative was larger, but not enough to stop a situation with a long queue forming at the stop. The paper also discusses reasons for the small improvement of the alternative design, focusing on the occupation of the two berths. We could conclude that the discrete event modelling approach was appropriate for the system, able to capture the related events as well as able to evaluate the stop and compare design alternatives and various scenarios. An important lesson from the study presented in this paper is the need of a more precise modelling of the vehicles' positions. Here, this was simplified to fixed positions of the berths with a preceding queue. For a more complex system where the positions of vehicle interactions cannot be completely determined beforehand, a more detailed modelling is needed.

The paper is co-authored with Anders Peterson and Andreas Tapani. The author of this thesis has contributed by doing the majority of the design and implementation of the modelling, collection and processing of data, adaptation to the case study and analysis of the results, as well as being the main author of the paper.

Paper I is published in:

- Proceedings of the 7th International Conference on Railway Operations Modelling and Analysis, Lille, France, 2017

The content of Paper I has been presented at:

- Nationell konferens i transportforskning, Lund, 2016
- Transportforum, Linköping, 2017
- RailLille2017, the 7th International Conference on Railway Operations Modelling and Analysis, Lille, France, April 4-7, 2017

Paper II

A simulation model for assessment and evaluation of bus terminal design

Paper II continues the work of Paper I by increasing the size of the modelled system and presents a discrete event simulation model of bus terminals. By having a modular structure, the presented simulation model can be adapted to different terminals of varying size. Included modules in the model are entry, driving section, stop (independent linear/sawtooth stop with an adjacent driving lane) and exit. These can be combined in an endless number of ways and represent most terminals with this particular kind of stop. The model describes the movements and interactions of individual vehicles as they drive through the terminal. It is discrete in space and divides the driving areas into cells. One vehicle generally occupies several cells at once and by keeping track of the occupation of these cells, interactions between vehicles can be modelled. The main contribution of this paper is the development of a bus terminal simulation model with spatial resolution and vehicle interactions, together with the fact that it can easily be adapted to various terminals and layouts. In the paper, we model one such layout as the model is adapted to the bus terminal at Norrköping interchange station. This terminal serves regional and long-distance traffic, where most buses either start or stop at the station. The case study showed that the terminal has more capacity than needed today and could handle an increase in the number of passengers or a reduction in the number of stops without a significant effect on the operations. Similar to Paper I, these conclusions show how the larger simulation model of this paper can be used to evaluate and compare terminals and scenarios.

The paper is co-authored with Anders Peterson and Andreas Tapani. The author of this thesis has contributed by doing the majority of the design and implementation of the modelling, collection and processing of data, adaptation to the case study and analysis of the results, as well as being the main author of the paper. Paper II is to be submitted.

An earlier version of Paper II is published in:

- Proceedings of the Conference on Advanced Systems in Public Transport and TransitData, Brisbane, Australia, 2018

The content of Paper II has been presented at:

- CASPT2018, the Conference on Advanced Systems in Public Transport and TransitData, Brisbane, Australia, July 23-25, 2018

Part of the content of Paper II has been presented at:

- Nationell konferens i transportforskning, Stockholm, 2017
- Transportforum, Linköping, 2018

Paper III

Microsimulation of bus terminals: A case study from Stockholm

This paper continues the work from the previous papers by further developing the model of Paper II and validating one of the output metrics against empirical data. To this end, the Slussen bus terminal in Stockholm, Sweden, is used in a case study. In the process of adapting the simulation model to the Slussen bus terminal, several new modules are added to the model. Previously, only one type of stop was included and in this paper three more types are added. The Slussen bus terminal is a new, temporary bus terminal that has been experiencing capacity related issues from the start. This congested situation allows for testing and validation of the model in the type of situation that is important for the simulation model to capture. The time per boarding passenger is used as a calibration parameter and the average lateness at departure is used for comparisons with empirical data in both calibration and validation. We discuss differences between simulated and empirically measured average lateness at departure and identify a need to further investigate the effects of parameters and terminal rules.

The paper is co-authored with Anders Peterson and Andreas Tapani. The author of this thesis has contributed by doing the majority of the design and implementation of the modelling, collection and processing of data, adaptation to the case study and analysis of the results, as well as being the main author of the paper.

Paper III is submitted to:

- The 2019 Winter Simulation Conference

Part of the content of Paper III has been presented at:

- Nationell konferens i transportforskning, Göteborg, 2018
- Transportforum, Linköping, 2019

5.5 Conclusions and future research

This thesis presents a discrete event simulation model of bus terminals and introduces the concept of modules representing typical sections found at terminals. The model includes modelling of important terminal processes, vehicle arrivals, dwell times, driving and vehicle interactions, waiting times and exit delay. It has a spatial resolution that allows for vehicle interactions and queueing to occur throughout the terminal. This is necessary in order to get a proper representation of the congestion at a terminal.

During modelling and model applications, the discrete event modelling approach has been evaluated and a number of advantages and disadvantages have been identified. Advantages include the fact that the chain of events a vehicle goes through as it progresses through a terminal forms the basis of the modelling. This makes for a straightforward modelling process of the overall model structure and an easy way to include various decision points in the routing of vehicles. Disadvantages of the approach include the fact that much modelling effort has been needed to get a spatial resolution. Much effort would also be needed to improve upon the simplified modelling of vehicle speed and acceleration.

In case studies, the simulation model has been shown to be useful to evaluate various layouts and scenarios. It can be used to analyse the effects of increases in number of vehicles or passengers, as well as changes in the traffic planning of the terminal or the situation outside. In more details, the case studies of the combined bus and tram stop and the bus terminal at Norrköping interchange station have indicated their respective capacity reserves and the case study of the Slussen bus terminal in Stockholm have contributed to the description and explanation of the congested situation at the terminal. Since the bus terminal in Norrköping has substantial overcapacity, parallels and differences between this terminal and the congested Slussen terminal have been observed. The operations are in many ways the same with similar events and activities being carried out. The congested terminal is much more sensitive to the details of the modelling, however.

There are many ways to continue the work of this thesis. A first step is to continue the validation of the terminal simulation model. This would start from paper III, which discusses several factors that may explain differences between simulation output and empirical measurements. In further validation, these factors can be looked into. Using more calibration parameters and output metrics for comparisons is of particular interest, and so is investigating to what extent the bus drivers follow the rules of the terminal. After this first step, two main directions for future research have been considered. The first is to apply the model to various situations in order to give advice on design and terminal traffic planning. The second direction is to consider how buses and lines can optimally be allocated to stops.

For the first direction, many research questions can be considered for model application. For instance, what is a good design in various situations and can general advice be given, or is each terminal too different from one another? There is also a need to further develop the performance measures for bus terminals. Today there is an uncertainty among practitioners as how to tell in a planning process that a suggested solution is sufficient. In this context, the capacity concept could be extended to terminals or other metrics formulated.

For the second direction, allocation modelling of buses and lines to stops would aim to formulate a method that gives an optimal stop assignment. For this purpose, optimization is the logical approach. This kind of modelling could cover both static allocation planning where buses always use the same stop and dynamic planning where the allocation is decided upon during daily operations.

Other than these two main directions, several other possibilities can be considered. One direction is to include pedestrians in a more direct manner in the model. Combining stop allocation and modelling of pedestrians, one could also model and study the reactions of the pedestrians due to dynamic allocation where they do not know where to go beforehand. Other parts of the station or the surroundings could also be included, such as train arrivals or outside road traffic.

Modelling pedestrians and train arrivals open up the possibility to study transfers between the bus and rail modes. If also doing stop allocation, transfer times could be an important factor to minimize in the optimization.

The model could also be applied in a number of situations where the application of a simulation model could give important insights. This includes how deregulation affects the operation of the terminal and the effects of disruptions of various kinds, such as replacement traffic from the rail mode. New types of vehicles may also lead to new problems and new solutions. Electric buses may need charging equipment at the terminal and automatic buses and vehicles may introduce a number of changes, such as planning for a more taxi-like service.

Bibliography

AASHTO (2002). *Geometric Design Guide for Transit Facilities on Highways and Streets – Phase I*. American Association of State Highway and Transportation Officials.

Adhvaryu, B. (2006). "Design of bus station: A case study in Brighton". In: *Traffic Engineering and Control* 47.5, pp. 182–186.

Ancora, V., Nelli, C., and Petrelli, M. (2012). "A Microsimulation Model for BRT Systems Analysis". In: *Procedia - Social and Behavioral Sciences* 54, pp. 1250–1259.

Andreussi, A., Bianco, L., and Ricciardelli, S. (1981). "A simulation model for aircraft sequencing in the near terminal area". In: *European Journal of Operational Research* 8, pp. 345–354.

Arasan, V. and Dhivya, G. (2010). "Simulation of highly heterogeneous traffic flow characteristics". In: *Proceedings - 24th European Conference on Modelling and Simulation, ECMS 2010*, pp. 81–87.

Auckland transport (2013). *Public Transport Interchange Design Guidelines*.

Barceló, J. (2010). *Fundamentals of traffic simulation*. International series in operations research & management science: v. 145. New York, Springer.

Berger, A., Hoffmann, R., Lorenz, U., and Stiller, S. (2011). "Online railway delay management: Hardness, simulation and computation". In: *Simulation* 87.7, pp. 616–629.

Bielli, M., Boulmakoul, A., and Rida, M. (2006). "Object oriented model for container terminal distributed simulation". In: *European Journal of Operational Research* 175, pp. 1731–1751.

Brodin, A., Carlsson, A., and Bolling, A. (1982). *VTI trafiksimuleringsmodell*. Tech. rep. The Swedish National Road and Transport Research Institute.

Cats, O., Burghout, W., Toledo, T., and Koutsopoulos, H. N. (2010). "Mesoscopic Modeling of Bus Public Transportation". In: *Transportation Re-*

search Record: Journal of the Transportation Research Board 2188, pp. 9–18.

Darzentas, J., Cooper, D., Storr, P., and Mcdowell, M. (1980). "Simulation of road traffic conflicts at T-junctions". In: *Simulation* 34.5, pp. 155–164.

Espinosa-Aranda, J. L. and García-Ródenas, R. (2012). "A discrete event-based simulation model for real-time traffic management in railways". In: *Journal of Intelligent Transportation Systems: Technology, Planning, and Operations* 16.2, pp. 94–107.

Fernández, R. (2010). "Modelling public transport stops by microscopic simulation." In: *Transportation Research Part C* 18.Special issue on Transportation Simulation, pp. 856–868.

Fernández, R., Cortes, C. E., and Burgos, V. (2010). "Microscopic simulation of transit operations: policy studies with the MISTRANSIT application programming interface". In: *Transportation Planning & Technology* 33.2, p. 157.

Figueras Jové, J. and Casanovas-García, J. (2018). "Modelling and analysis of intermodal passenger operations in a cruise terminal". In: *Proceedings of the 2018 Winter Simulation conference*. Ed. by M. R. et al. Piscataway, New Jersey: IEEE, pp. 1515–1526.

Greberg, J., Salama, A., Gustafson, A., and Skawina, B. (2016). "Alternative Process Flow for Underground Mining Operations: Analysis of Conceptual Transport Methods Using Discrete Event Simulation". In: *Minerals* 6.3.

Harris, J. M. and Dessouky, Y. (1997). "A simulation approach for analyzing parking space availability at a major university". In: *the 1997 Winter Simulation Conference*, pp. 1195–1198.

Hisham, F., Bunker, J. M., and Bhaskar, A. (2018). "Development of a Modified Bus Capacity Model". In: *Transportation Research Board (TRB) 97th Annual Meeting*.

Hummon, N., Bryer, T., and Nekmat, R. (1987). "Evipas: A computer model for the optimal design of a vehicle-actuated traffic signal". In: *Transportation Research Record* 1114, pp. 103–110.

Huo, Y., Li, W., Zhao, J., and Zhu, S. (2018). "Modelling bus delay at bus stop". In: *Transport* 33.1, pp. 12–21.

Jennings, N. H. and Dickins, J. H. (1958). "Computer Simulation of Peak Hour Operations in a Bus Terminal". In: *Management Science* 5.1, pp. 106–120.

Johansson, F. (2016). “Microscopic Simulation of Pedestrian Traffic”. Linköping Studies in Science and Technology. Dissertations: 1767. Department of Science and Technology, Linköping University.

Jun, J. B., Jacobson, S. H., and Swisher, J. R. (1999). “Application of Discrete-Event Simulation in Health Care Clinics: A Survey”. In: *The Journal of the Operational Research Society* 50.2, p. 109.

Liang, J. and Wang, Y. (2009). “Research on bus dispatch of city passenger traffic hubs based on simulation technology”. In: *16th International Conference on Industrial Engineering and Engineering Management*. Tianjin, China.

Lizotte, Y. and Bonates, E. (1987). “Truck and shovel dispatching rules assessment using simulation”. In: *Mining Science and Technology* 5.1, pp. 45–58.

Luo, Y. and Guo, X. (2010). “Arithmetic Research of Computer Simulation of the Bus Junction Stations”. In: *Advanced Materials Research* 108.1, p. 441.

MathWorks (2019a). *MATLAB*. https://mathworks.com/products/matlab .html (available 2019-04-12).

MathWorks (2019b). *SimEvents*. https://mathworks.com/products/ simevents.html (available 2019-04-12).

Al-Mudhaffar, A., Nissan, A., and Bång, K.-L. (2016). “Bus stop and bus terminal capacity”. In: *6th Transport Research Arena*.

Qian, J. and Hu, Y. (2014). “Research on Bus Stop Based on Cellular Automaton Model”. In: *Advanced materials research* 2, pp. 1484–1488.

Rizzoli, A. E., Fornara, N., and Gambardella, L. M. (2002). “A simulation tool for combined rail/road transport in intermodal terminals”. In: *Mathematics and Computers in Simulation* 59, pp. 57–71.

Rodammer, F. and White, K. (1988). “A Recent Survey of Production Scheduling”. In: *IEEE Transactions on Systems, Man and Cybernetics* 18.6, pp. 841–851.

Seriani, S. and Fernandez, R. (2014). “Bus and pedestrian traffic management at BRT stations. A case study in Santiago de Chile”. In: *European transport conference 2014*. Association for European Transport.

Soh, A. C., Marhaban, M. H., Khalid, M., and Yusof, R. (June 2013). “A discrete-event traffic simulation model for multilane-multiple intersection”. In: *Control Conference (ASCC), 2013 9th Asian*, pp. 1–7.

Spek, T. van der, Stein, B. van, Holst, M. van der, and Bäck, T. (2017). “A multi-method simulation of a high-frequency bus line”. In: *2017*

IEEE 20th International Conference on Intelligent Transportation Systems (ITSC).

Steins, K. (2017). "Towards Increased Use of Discrete-Event Simulation for Hospital Resource Planning". PhD dissertation. Linköping university.

Stockholms läns landsting (2018). *Riktlinjer Utformning av terminaler.* Trafikförvaltningen.

Surpris, G., Liu, D., and Vincenzi, D. (2014). "How Much Can a Smart Parking System Save You?" In: *Ergonomics in Design* 22.4, pp. 15–20.

Sveriges Kommuner och Landsting and Trafikverket (2012). *Kol-TRAST - Planeringshandbok för en attraktiv och effektiv kollektivtrafik.*

Szasz, P. A., Carvalho Montana, L. de, and Ferreira, E. O. (1978). *Comonor: Coordinated bus convoy.* CET technical bulletin nbr. 9. São Paulo: Companhia de Engenharia de Tráfego.

Tan, J., Li, Z., Li, L., Zhang, Y., and Lu, L. (2013). "Berth assignment planning for multi-line bus stops". In: *Journal of advanced transportation* 48.7, pp. 750–765.

Thulasidasan, S. and Eidenbenz, S. (Dec. 2009). "Accelerating traffic microsimulations: A parallel discrete-event queue-based approach for speed and scale". In: *Proceedings of the 2009 Winter Simulation Conference (WSC)*, pp. 2457–2466.

Tirachini, A. (2013). "Bus Dwell Time: The Effect of Different Fare Collection Systems, Bus Floor Level and Age of Passengers". In: *Transportmetrica A: Transport Science* 9.1, pp. 28–49.

Trafikverket (2016). *Analysmetod och samhällsekonomiska kalkylvärden för transportsektorn: ASEK 6.0.*

Transportation Research Board (2013). *Transit Capacity and Quality of Service Manual, Chapter 10 Station Capacity.* 3rd. Transit Cooperative Highway Research Program (TCRP) Report 165.

Tunasar, C., Bender, G., and Young, H. (1998). "Modeling curbside vehicular traffic at airports". In: *the 1998 Winter Simulation Conference.*

Widanapathiranage, R., Bunker, J. M., and Bhaskar, A. (2014). "Modelling the BRT station capacity and queuing for all stopping busway operation". In: *Public Transport* 7.1, pp. 21–38.

Zhao, J., Chen, K., Wang, T., and Malenje, J. O. (2018). "Modeling loading area effectiveness at off-line bus stops with no clear-cut separation of berths". In: *Transportmetrica A: Transport Science*, pp. 1–21.

Papers

The papers associated with this thesis have been removed for copyright reasons. For more details about these see:

http://urn.kb.se/resolve?urn=urn:nbn:se:liu:diva-156646

FACULTY OF SCIENCE AND ENGINEERING

Linköping Studies in Science and Technology, Licentiate Thesis No. 1841, 2019
Department of Science and Technology

Linköping University
SE-581 83 Linköping, Sweden

www.liu.se