A Simulation Model of Local Public Transport Access at a Railway Station

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Abstract
A high quality railway service requires that all parts of the complete journey, from door to door, are well-functioning. This includes any transfers taking place, as well as last mile transportation to and from the railway station. Since the last mile often consists of local public transport, the access to this mode at stops and terminals and how well these are functioning are of great importance. A critical aspect is the capacity of the stop or the terminal in relation to the number of departures, where a higher capacity generally means an increase in size. At the same time it is desirable to limit the use of valuable land and keeping the facility as small as possible. The trade-off between capacity and size needs to be evaluated when designing stops and terminals. In this study we have developed a discrete event simulation model of a combined bus and tram stop, which is a part of a larger multi-modal station. The objective of the study is to evaluate the modelling approach for the situation at hand. Of special interest are the complexities due to the different driving patterns of buses and trams. The developed model is capable of evaluating design alternatives and is applied in a case study of a stop at Norrköping railway station in southern Sweden. The model was found to realistically capture the various events occurring at such a stop and the case study further showed that the model is a useful tool in design evaluation.

Keywords
Microsimulation, Terminal layout, Performance evaluation, Stop capacity, Bus and tram

1 Introduction

In order to ensure a high quality railway service, all parts of the door-to-door journey are of great importance. This does not only include the railway travel mode itself, but also transfers and last mile transportation. This last mile is often conducted by local public transport, such as buses and trams, and takes the passenger between the railway station and the origin or destination. It is thus important for the attractiveness of the rail mode that all the constituents of the local services are well-functioning and properly dimensioned, including the stops along the routes and the terminals of the system. The operation of these have a great impact on the whole public transport system, not least considering that this is where transfers take place. These transfers are critical points of all trips containing them, since the time spent in transfer is valued significantly higher than the in-vehicle time, see for instance the recommended values for cost-benefit analyses by the Swedish Transport Administration (Trafikverket, 2016). This means that transfers need to be smooth and uncomplicated, fast and efficient. A stop or terminal that is not functioning properly will lead to the opposite; unreliability and longer waiting times and as a result, a reduced market share for railway and all public transport modes.

A critical aspect for a well-functioning stop or terminal is the number of scheduled departures in relation to the capacity. If the amount of incoming vehicles is too high, there will be congestion and queues resulting in delays and an unsatisfactory service level. While this would imply a need to design for a high capacity, one would also need to consider the effects of the increased usage of land that is typically the result. Interchange stations are generally located on commercially valuable land, which in contrast calls for keeping the land use as small as possible. There are also other incentives for a small, compact design, such as shorter walking distances and less impact on the surroundings. When designing stops or terminals, all of this needs to be considered in order to find an acceptable trade-off. This is a situation that calls for proper tools and methods which can be used in design evaluation, especially considering that the infrastructure is not easily changed once it has been built. Few tools of this kind are available however and there is thus a need to find a good modelling approach for the situation at hand.

Both in the case of a stop and of a terminal, the operations of the vehicles using the facility can be readily described as a number of events and the relationships between these events. Consider, for example, a bus that first arrives to a stop (one event) before it drives to a berth where it can drop off and pick up passengers (another event). The events of this one bus also depend on other vehicles. If none of the berths are free, another vehicle needs to leave before the bus can drive to a berth. There is also a time duration associated with many events, which can vary significantly. While vehicle arrival can be considered to be instantaneous, the event of dropping off and picking up passengers has a time duration that can vary between individual vehicles. A system such as this is well-suited for microsimulation, where each individual vehicle is simulated, and *Discrete Event Simulation* (DES). DES is a kind of simulation that is based on well-defined events, the duration of these events and the relations between them, just as in the present case (Banks et al., 2005). It allows a model to focus on the main events and simplify the less important parts of the system. Just like other simulation methods, DES makes it possible to test different scenarios and alternatives without doing any physical construction. It 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) and rail modelling (Berger et al., 2011; Espinosa-Aranda and García-Ródenas, 2012; Cha and Mun, 2014). It has also to some extent been used among authors addressing stop or terminal simulation, see for instance Silva (2000) and Fernández (2010). These studies are rather limited in number, especially when considering only those having a purpose of evaluating design alternatives or those combining different modes of public transport.

The objective of this study is to evaluate the suitability of using a DES approach for modelling a combined bus and tram stop at a railway station. The developed model is capable of comparing alternative designs as well as evaluating their performance in terms of the queue situation and the effects on the individual vehicles. While this is a stand-alone model it is also meant as a first building block of a complete terminal model. The contribution of this paper consists of evaluating the DES approach for this situation, combining buses and trams and to model two specific, off-street stop designs (with either one or two lanes). The model is applied in a case study of an existing bus and tram stop located at the railway station in Norrköping, Sweden.

In the following section the background of the topic is discussed. This is followed by a description of the model, the case study and the result of the case study, before the conclusions and future work are presented.

2 Simulation of Local Public Transport Access at Railway Stations

In this section simulation of local public transport access, i.e. stops and terminals, at railway stations will be discussed. First this type of access, with a focus on stops, will be presented and defined together with important aspects needed in a simulation model. This is followed by an overview of the literature concerned with microsimulation of both stops and terminals. This includes studies of stops not connected to a railway station, since large portions of such systems are similar to rail station connected stops. The survey is divided into studies using a DES approach and studies using a time-based simulation approach. The section concludes with some final remarks of the lessons learned and how this article relates to the literature.

2.1 Railway Connected Stops and Terminals

At interchange stations, railway is often connected to local public transport through terminals used by a large number of public transport lines. These will generally include not only the local public transport, but also regional and long-distance. As a part of this facility there might also be isolated single stops, separated from the terminal, which only have a few berths and are used by a limited number of lines (Transportation Research Board, 2013). Such a stop might be necessary for tram lines where the tracks restrict the access point but could also enable easier access for local lines and for lines that only drop off passengers at the station. In these cases, it is important that the stop has a high enough capacity to handle the amount of incoming vehicles and operate smoothly. Due to the railway connection, it is common that passengers arrive in large numbers at specific times, i.e. when a train has arrived. Conversely, large amounts of passengers may also want to alight at the same time in order to board a departing train. The timetables of the local lines may be synchronized in such a way that they meet this demand, resulting in a large number of vehicles arriving in a short period of time (Smart et al., 2009). If the capacity is not high enough to handle this situation, it will lead to congestion and queues and increase the average time a vehicle needs to pass through the stop together with the variability of this time. This will result in longer route travel times, longer waiting times and decreased reliability. Considering that the capacity of a particular stop depends on its layout, the design of this layout is crucial. Different designs will also vary in size, which is not only important due to the general need to limit the land use at the station, but also since it might restrict how close the stop can be to the rail platforms and thus the ease of transfers between these modes. When developing a simulation model of a stop connected to a railway station it is thus of importance that the model is able to address design evaluation. How large amounts of incoming vehicles can be handled by various designs? It should also be able to take the effects of transfers into regard. There could for instance be a large number of passengers wanting to board at specific times or many close departures due to timetable synchronization. Another important aspect is the representation of vehicle arrival times and dwell times. One way of representing these is to use probability distributions. In this study we have included distributions common in these contexts, but do not focus on statistically justifying their use.

2.2 Discrete Event Simulation of Stops and Terminals

Stop and terminal DES models in the literature range from small stops at the side of the road to terminals with many berths. In some cases, stops are included in a model of a larger system, such as in Ancora et al. (2012), Gunawan (2013) and Huynh et al. (2015), who all use DES to model larger bus systems. While Gunawan (2013) presents a general bus rapid transit model, the purpose of Ancora et al. (2012) and Huynh et al. (2015) is to evaluate different measures to improve existing bus systems. Campos et al. (2015) have a similar purpose as they present a DES stop model that is intended to be a part of a larger bus system model. There are also several DES models focusing on a stop or a terminal. Fernández (2001, 2010) presents a stop model that has been further developed and applied in a number of articles. This model is able to handle both buses and trams and can include several berths. Luo and Guo (2010) have developed a general terminal model and Liang and Wang (2009) a model of a particular terminal. The latter of these two attempts to improve transfer efficiency (waiting time) and reduce the operating cost by adjusting the bus dispatch schedule. Passengers in the simulations arrive to the terminal depending on train schedules. Adhvaryu (2006), finally, is to our knowledge the only study who uses a DES approach in order to evaluate design alternatives. Various designs of a small, physically constrained bus terminal in Brighton are evaluated with the purpose of not only improving the capacity, but also making the terminal more accessible to wheel-chair users. Two alternative designs are tested, both with three berths where these are either all in parallel (side by side), or where two are in serial with each other and in parallel with the third.

DES has not only been used to model stops and terminals within the field of traffic modelling. While a time-based approach is far more common in road traffic models, there are still several examples during the last few decades of models following a DES approach. In the 80's Darzentas et al. (1980), Brodin et al. (1982) and Hummon et al. (1987), for instance, developed DES models of nonurban T-junctions, two-lane rural highways and of signalized intersections, respectively. In recent years, various DES models have been developed in order to reduce the model complexity (Soh et al., 2013), decrease the computational time needed for simulations (Thulasidasan and Eidenbenz, 2009) or include heterogeneous flow (Arasan and Dhivya, 2010). This shows a second strength of DES, apart from focusing on the important events of a system; the high computational speed and limited model complexity.

2.3 Time Based Simulation of Stops and Terminals

Apart from studies using a DES approach to model stops and terminals, there are also several using a time-based approach. In such models time is progressed in discrete, constant steps and in each of these steps the state of the system is updated. This stands in contrast to the variable jumps in time between events that are used in DES. Among articles using this kind of approach, there are both studies who develop their own simulation model and others who use commercial traffic simulation software. Just as in the DES case, some include stop modelling as they model larger public transport systems. Both Fernández et al. (2010)

and Widanapathiranage et al. (2014) add public transport and stop functionality to existing simulation software programs in order to better represent public transport vehicles. Other studies focus on a single stop or terminal, such as Lu et al. (2010) and Tan et al. (2013) who use stop modelling in order to evaluate how bus lines should be assigned to the berths of a stop. We have also found a few studies evaluating design alternatives. Silva (2000) assesses traffic impacts of stop accessibility improvements by adding bus related functionality to SIGSIM2, a commercial traffic simulation software. Three stop designs of a one-berth bus stop are included in the study; a boarder stop, where the stopping area is completely in-line with the rest of the traffic, and two versions of a kerbside stop within a parking area, which is a type of stop located at the side of the road. Instead of addressing the effects on the surrounding traffic, Seriani and Fernandez (2014) focus on the operation of the buses and the effects on the passengers as they compare various designs of stops for bus rapid transit systems. Using the commercial traffic simulation software TSIS-CORSIM three alternatives of off-street, two-berth bus stops are evaluated; two versions of a serial configuration and a sawtooth design with angled berths, allowing for independent movement of the buses. Kramer (2013), finally, also uses a commercial traffic simulation software; Aimsun. The same two alternatives of a combined bus and tram stop included in this paper are evaluated, that is, either one or two lanes of an off-street stop. In the two-lane case, buses (but not trams) are able to overtake on departure. The author found that incorporating the different driving patterns of buses and trams in this situation where difficult. The limitations were due to the fact that neither trams nor overtakings at stops were included in the version of Aimsun used. The distinction between buses and trams and which of these were allowed to overtake in the various situations could not be implemented in a satisfying way. The author suggests that either manual coding or other simulation tools should be used for this kind of situation where there is a mix of buses and trams.

2.4 Findings of the Survey

The conclusions of Kramer (2013) suggest a need to explore alternatives of their modelling approach. We suggest that DES would be a good remedy to the various problems that were encountered. The time-based models tend to focus on car-following and other aspects related to road traffic, while DES allows a model to focus on the important events of a system, such as overtaking. Among the studies that have been previously presented, surprisingly few have modelled trams or a combination of public transport modes and have mostly not discussed problems that may arise. In this study we model the same stop as Kramer (2013) in order to evaluate a DES approach for this situation. We include effects from the proximity of a railway station through the timetables of the buses and the trams, something few other DES models have included. It can also be noted that of the studies presenting a DES model, few have done so with the purpose of evaluating design alternatives.

3 A Combined Bus and Tram Stop Model

In this section the developed DES model will be presented. First the combined bus and tram stop of the model will be specified, which is then followed by an overview of the model itself.

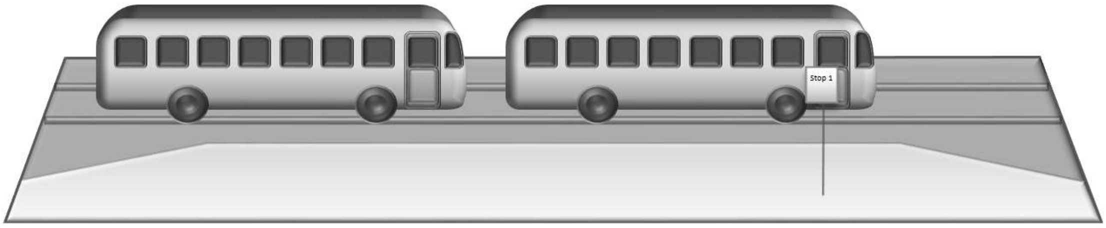

Figure 1: A one-lane, off-street bus and tram stop

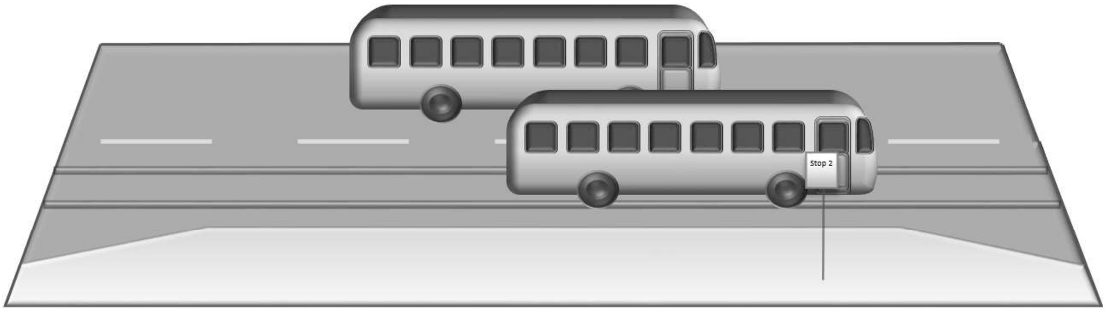

Figure 2: A two-lane, off-street bus and tram stop

3.1 The Combined Bus and Tram Stop of the Model

The model introduced in this paper is concerned with two versions of a combined bus and tram stop. It is, in both of these versions, an off-street, drive-through stop which is separated from the surrounding traffic. The difference between the two versions lies in the number of lanes, either one or two, which can be seen in Figure 1 and 2, respectively. In the one-lane case, any vehicle standing still will block the path for all vehicles behind it, which will limit the capacity of the stop. This suggests that the alternative with a second lane could improve the situation, since non-rail bound vehicles are now able to overtake vehicles in front. In other words, buses can now overtake when needed, but trams still need to wait. The two-lane version will occupy a larger area, however, and there may be other unwanted consequences. This trade-off between capacity and size is thus of interest to investigate.

The stop in question can be used by several bus and tram lines and there are two berths in which two vehicles can stop at the same time to let passengers board and alight. Any additional vehicles arriving need to wait in a queue. All bus and tram lines can stop in either of the two berths and the stop is independent of lines running in the opposite direction (due to physical separation or that all lines stop in the same place). There are also a number of assumptions and approximations used in the development of the simulation model. One of these is the assumption of fixed berths, meaning that vehicles will always stop in the same positions, regardless of the length of the vehicle in front of it. There are also several driving times in different parts of the stop, which are all approximated to be ”the same”, that is, they follow the same probability distribution. This means that the corresponding driving distances are equal in these different parts and that the driving times are treated as independent of the position in which a vehicle stops. The driving time can still vary between different types of vehicles, however. Other important assumptions of the model are that vehicles in the queue will not let passengers board or alight, but will wait for their turn, and that overtaking is only allowed for vehicles leaving the stop in the two-lane version. When entering they will have to wait in line, just as in the one-lane case. Related to overtaking is also the assumption that vehicles who are being overtaken will wait until this is completed before they leave themselves.

3.2 The Discrete Event Simulation Model

The discrete event simulation model has been developed using MATLAB SimEvents (MathWorks, 2016). This is a DES tool with an event-based simulation engine and a component library. Components such as queues, switches and servers are used to model the system at hand.

The model developed in this study can be used to evaluate and compare the two stop alternatives through a number of output performance measures. These include measures related to the queue at the stop and to the effects on the individual vehicles. Examples of the former are the fraction of the simulation time with a queue present and the fraction with a specific number of vehicles in the queue and examples of the latter are the average time through the stop and the standard deviation of this time. Next, the structure and the events of the model will be described.

The Components of the Model

As stated previously, a DES model is comprised of a number of events and the relationships between said events. At the bus and tram stop of the model, the events can be grouped into four categories of greatly varying size. These are shown in Figure 3 together with the parts of the stop where the events occur. First *vehicles are generated* at a time depending on a random variable $T_{arrival\_time}$. This will be further discussed below. After generation, or arrival, the vehicle will if necessary *wait in a queue* until the path ahead is clear. The queue follows a first in, first out principle. In the next group, *Passenger exchange*, passengers board and alight the vehicle according to a number of events controlling where and when the vehicle stops. There is a second random variable in this part, T_{dwell_time}, which is the time needed to stop, drop off and pick up passengers and be ready to leave again. This group is further described in the section Passenger Exchange below. In the last part of the model, *Departure*, vehicles are simply removed from the simulations. There is also a driving time associated with different parts of the stop; between the queue and the second berth, the second and the first berth and with overtaking manoeuvres. This driving time, T_{drive_time}, is randomly distributed according to a truncated lognormal distribution with parameters that need to be specified in simulations. The truncation is due to the fact that there exists a minimum driving time. The two larger groups of events, vehicle generation and passenger exchange, will be further described below.

Vehicle Generation

Vehicles are generated according to a timetable, specific for each line, and a probability distribution describing the arrivals in relation to this timetable. This will result in both early and late arrivals. With t_{table_time} denoting the time in the timetable and $T_{lateness}$ being a random variable describing the earliness or lateness of arrival, the actual arrival time is

$$T_{arrival\_time} = t_{table\_time} + T_{lateness}. \tag{1}$$

The choice of probability distribution for $T_{lateness}$ is not obvious and various distributions have been reported by different authors. It depends on both the drive times between previous

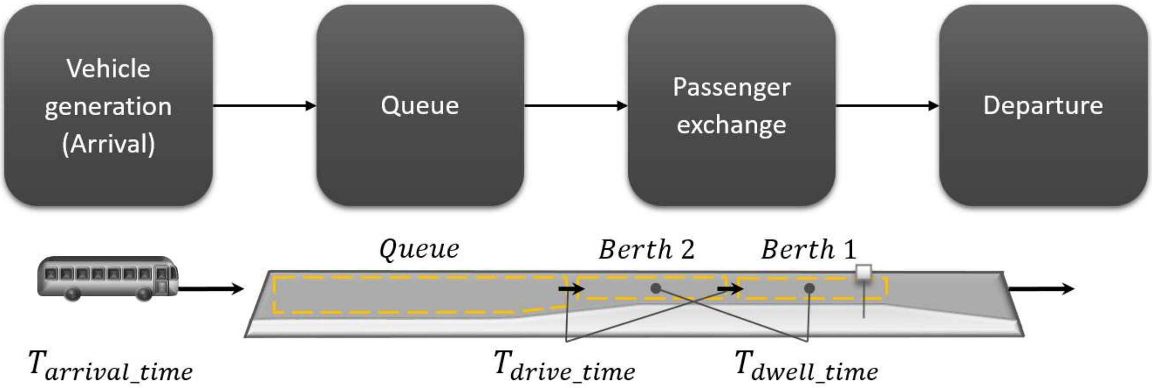

Figure 3: Four groups of events in the DES model shown together with the corresponding parts of the stop and with the random variables representing arrival, drive and dwell time

stops on the route as well as the dwell times at said stops. Wirasinghe and Liu (1995) showed that when the drive time distributions are right-skewed, then so are the arrival time distribution. Commonly used arrival time distributions of this kind are lognormal and gamma, see for instance Turnquist (1978) and Guenthner and Hamat (1988a). Rietveld et al. (2001) also found the normal distribution to be a good fit to empirical data in some cases. For this reason, all three of these distributions are available in the model. During simulations a distribution needs to be chosen for each line, together with its parameters. These can for instance be estimated from empirical data. An important characteristic of both the lognormal and gamma distributions is the fact that they are not defined for negative values. In this case negative values correspond to an early arrival and thus need to be included. A shift in the time axis is used in order to capture this effect.

Passenger Exchange

There are a number of events controlling where a vehicle stops, its exchange of passengers and how it leaves. These events will differ depending on the type of stop. Figure 4 and 5 show flow charts of these events for the one-lane and two-lane stop, respectively. Large parts of the charts are identical in the two cases, the part that differs in the two-lane design is shown in a darker colour. In both versions vehicles can only leave the queue and enter the stop if the second berth is free. If the first berth is also free the vehicle will continue directly to this one. Differences between the two types of stops will become apparent when a vehicle in the second berth has let passengers on and off and is ready to leave. In the case of a one-lane stop, any vehicle parked in front means that the lane is blocked and that the vehicle will need to wait. It will continue to the first berth when the way ahead is clear. Here a check needs to be made in order to determine if the vehicle has already exchanged passengers. If this is the case, it will simply drive through and leave the stop. Unlike the one berth-stop, the two-lane version also has the extra possibility for buses in the second berth to overtake any vehicle in front. This means that after having exchanged passengers in the second berth, there will be three possible ways to continue. If the berth ahead is free, the vehicle can drive through directly regardless of whether it is a bus or a tram. If it instead is occupied, a tram will have to wait while a bus can overtake the vehicle in front. For vehicles continuing through the first berth, rather than overtaking, a check needs to be made in order to control if passengers have already been exchanged, just like in the one-lane case.

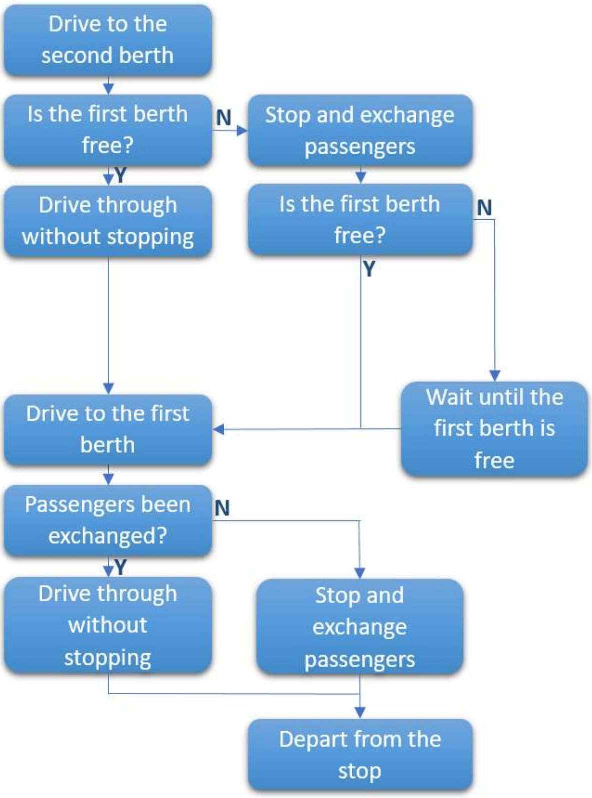

Figure 4: The events related to passenger exchange at the one-lane stop

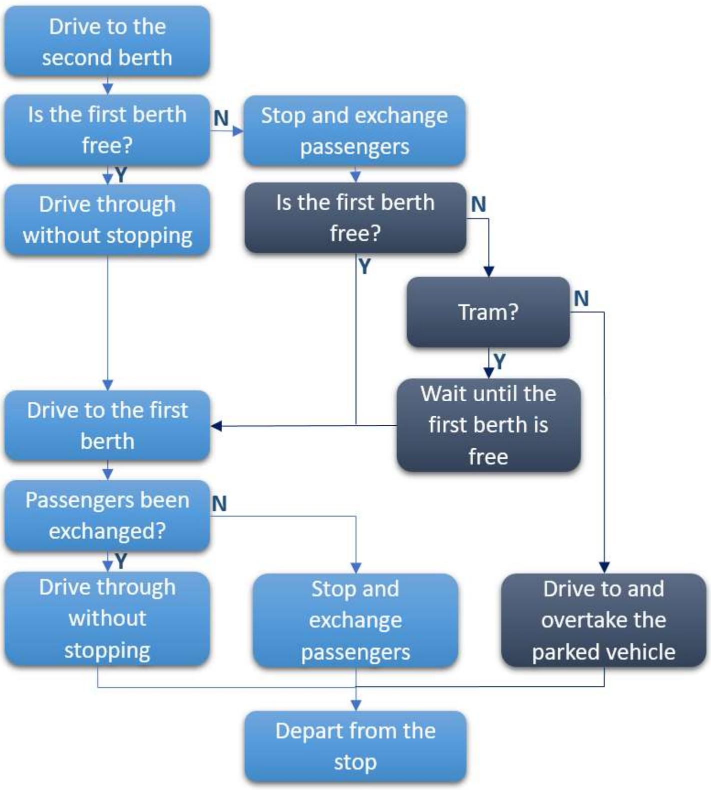

Figure 5: The events related to passenger exchange at the two-lane stop

Figure 6: The case study bus and tram stop located at Norrköping railway station. The station building can be seen in the background (the railway tracks are on the other side).

The dwell time needed for passenger exchange depends on a number of factors such as the number of alighting and boarding passengers and the time needed to open and close the doors. Here this is modelled in a simple manner with a random variable T_{dwell_time} following a lognormal probability distribution. Guenthner and Hamat (1988b), among others, found that such a distribution did not deviate significantly from empirical data. The parameters of the distribution need to be specified in simulations.

4 Case Study

The model has been applied to a bus and tram stop located at Norrköping railway station in southern Sweden during a morning peak, 07.00 - 08.30. A photo of the stop can be seen in Figure 6. It is a one-lane version of the stop described in Section 3.1 and the study thus enables comparisons between the current design and the effects of adding a second lane. The stop is the main connection between the railway and the local public transport and is used by two tram lines and five bus lines, of which 2 are local and 3 are regional. While the two stopping positions are not fixed, the second vehicle simply stop a few meters after the one in front, they are approximated as fixed berths in this study. The effects of varying vehicle lengths, which can be from 12 m to 30 m, are thus not included. In reality there will in some cases be enough space for three vehicles at the stop platform, but regulation dictates that vehicles always need to stop in the first or second position from the front. In order to run simulations of the stop, timetables for each line are needed together with distribution parameters for the arrival, dwell and drive time distributions. While the choice of distribution is pre-determined for the dwell and drive times, it needs to be specified for the arrival times. The distribution parameters need to be estimated from measurements of arrival, departure and driving times of individual vehicles. In the rest of this section, the data used in the case study will be presented, followed by a description of the case scenarios.

4.1 Timetables

Timetables from early 2016 are used in the simulations. These are presented in Table 1. Both of the tram lines and the two local bus lines have regular arrivals with a headway of either 10 minutes (tram) or 20 minutes (bus). The regional buses are commuter lines with only a few departures each during the simulation period. For two of these, 412 and 430, the stop is the last of the line while for the third it is the first. It can be noted that the departures are not evenly spread during the time period, which is to an extent related to the arrival and departure times of trains at the railway station. Some lines have departures very close to one another and one of the regional lines, 430, have three buses with departures at the exact same time. These are buses carrying people for the start of school and the working day.

Table 1: Timetables of the lines using the stop in the case study

Type	**Line**	**Departure time**			
Tram	2	07.09	07.19	....	08.29
	3	07.08	07.18	....	08.28
Bus local	115	07.16	07.36	....	08.16
	117	07.06	07.26	....	08.26
Bus regional	412	07.11	07.56		
	430	07.12	07.47 (3 vehicles)		08.17
	458	07.05			

4.2 Dwell Time Distribution

In order to estimate the parameters of the dwell time probability distributions, empirical dwell time data is needed. The access to such data varied between the lines. For the tram and local bus lines, arrival and departure data was retrieved for a period of almost 4 weeks, 29/02/2016 - 24/03/2016, from the public transport agency Östgötatrafiken. These arrival and departure times are given with a precision down to the second and were used to calculate the empirical dwell times. From these the parameters of the lognormal distribution could be estimated for each line individually, using maximum likelihood estimation. For the regional bus lines only departure times were available however and we had no empirical data of the dwell times. To work around this shortage, the regional lines were assumed to behave similarly to the local bus lines and their dwell time parameters were set to an average of the local distribution parameters. Table 2 lists the dwell time distribution parameters of both the local and the regional lines, where the unit of the dwell time is in minutes.

Table 2: Lognormal distribution parameters (location μ and scale σ) of the vehicle dwell times in the case study

Line	**2**	**3**	**115**	**117**	**412**	**430**	**458**
μ	-0.7123	-0.4871	-0.6349	-0.7679	-0.7	-0.7	-0.7
σ	0.5468	0.5284	0.5417	0.5351	0.54	0.54	0.54

4.3 Arrival Distribution

The gamma distribution was chosen as the distribution controlling vehicle arrivals. For the tram and local bus lines, the arrival distribution parameters could be estimated from the previously described empirical arrival data. The times from the timetables were subtracted from the empirical arrival times in order to get a relative arrival time. An extra time shift was also added in order to avoid negative values. From these relative arrival times, the gamma distribution parameters could be estimated using maximum likelihood estimation. For the regional bus lines the lack of data again posed a problem. Empirical departure times with a minute precision were available for a period of almost 3 weeks, 13/05/2016 - 01/06/2016. In order to get approximate arrival times from these, the expected value of the dwell time distribution was subtracted from the departure times. The arrival distribution parameters were then estimated from the approximate arrival times in a similar manner to the estimation of the tram and local bus lines. A separate distribution was also added for the 430 bus line, in order to include a spread in arrivals of the three buses with identical departure time in the timetable. Only the first of these three followed an arrival distribution in direct relation to the timetable. The other two instead arrived according to a distribution set in relation to the arrival of the previous bus. This was a gamma distribution with shape parameter $k = 0.3405$ and scale parameter $\theta = 0.4496$. All other parameters of all the lines are presented in Table 3 together with the used time shifts in minutes.

Table 3: Gamma distribution parameters (shape k and scale θ) of the vehicle arrival times together with the time shifts used in order to avoid negative values

Line	**2**	**3**	**115**	**117**	**412**	**430**	**458**
k	120.2351	12.0825	6.2909	3.633	4.5592	103.1213	4.5592
θ (min)	0.0922	0.2555	0.5132	0.8598	1.6913	0.0907	1.6913
Shift (min)	10	3	3	2	10	10	10

4.4 Drive Time Distribution

The three driving times of the model (queue to second berth, second to first berth and overtaking) are assumed to follow the same lognormal distribution. Two versions of the distribution have been used, one for buses and one for trams. In order to estimate the parameters, measurements of driving times have been collected at the stop during one morning peak. From these the parameters have been estimated using maximum likelihood estimation. Since there exists an (unknown) minimum driving time the distributions have been truncated at 0.06 min, a value slightly below the minimum value observed in the measurements. The distribution parameters can be found in Table 4.

4.5 Scenarios

Five scenarios have been included in the study, all related to the number of scheduled departures from the stop, that is, the amount of vehicle arrivals. The first scenario, *x1*, corresponds to the present situation and is based on the timetables described previously. The other four

Table 4: Lognormal distribution parameters (location μ and scale σ) of the driving times

Type	Bus	Tram
μ	-1.9933	-2.1649
σ	0.1580	0.2589

scenarios have a proportional increase in the number of departures, from twice the amount of the present situation, *x2*, to five times the amount, *x5*. In these scenarios extra departures are added to the existing timetable. For the regular headway lines (trams and local buses) the increase in the number of vehicles has been done in such a way that there are still regular headways. Bus line 115, for instance, goes from one departure every 20th minute in scenario x1, to one every 10th minute in scenario x2. As a result, some departure times will start to coincide. The dwell time distributions are not changed, which means that the increase in number of passengers is assumed to be proportional to the increase in departures so that the number of passengers on each vehicle remains constant. How to increase the number of regional bus line departures is less obvious than the regular headway ones. Here the extra departures have been distributed during the time period using a uniform probability distribution. An alternative could have been to group them together in order to simulate synchronization with train timetables.

5 Numerical Results

In this section the results of the case study will be presented together with the conclusions that can be drawn from these. The result is separated into two parts; results describing the queue situation and how well the stop is operating and results related to the effects on the individual vehicles. Also presented is the effects of trams in comparison with a situation where only buses are using the stop.

5.1 Queue Situation

How well the two versions of the stop layout function under varying amounts of incoming vehicles can be seen in Figure 7 and 8, where the former shows the fraction of the simulated time with at least one vehicle in queue and the latter goes into more detail by looking at the fraction of the time with a specific number of vehicles in the queue. In both figures the fractions of time have been averaged over the number of repetitions of the simulation. As can be seen in Figure 7, the fraction of time with a queue having formed at the stop goes from close to 0 at x1, to 0.05-0.1 at x2, close to 0.2 at x3, around 0.5 at x4 and almost 0.9 at x5. While a queue being present 20% of the time might be acceptable, the same can hardly be said about a queue at 50% or 90% of the time. When studying the queues in more detail in Figure 8, the untenable situations for these two scenarios are made even more evident. At x4, 10 vehicles can be in the queue at the same time and at x5 the queue lengths can be more than 20 vehicles. This is true for both stop alternatives, even if the two-lane version has shorter maximum queue lengths than the one-lane version in both scenarios. Looking closer at the differences between the two stop layout alternatives, it is evident that the differences are very small for the three scenarios with lower amounts of incoming vehicles. In the other two scenarios, with the long queues, the differences are somewhat more noticeable.

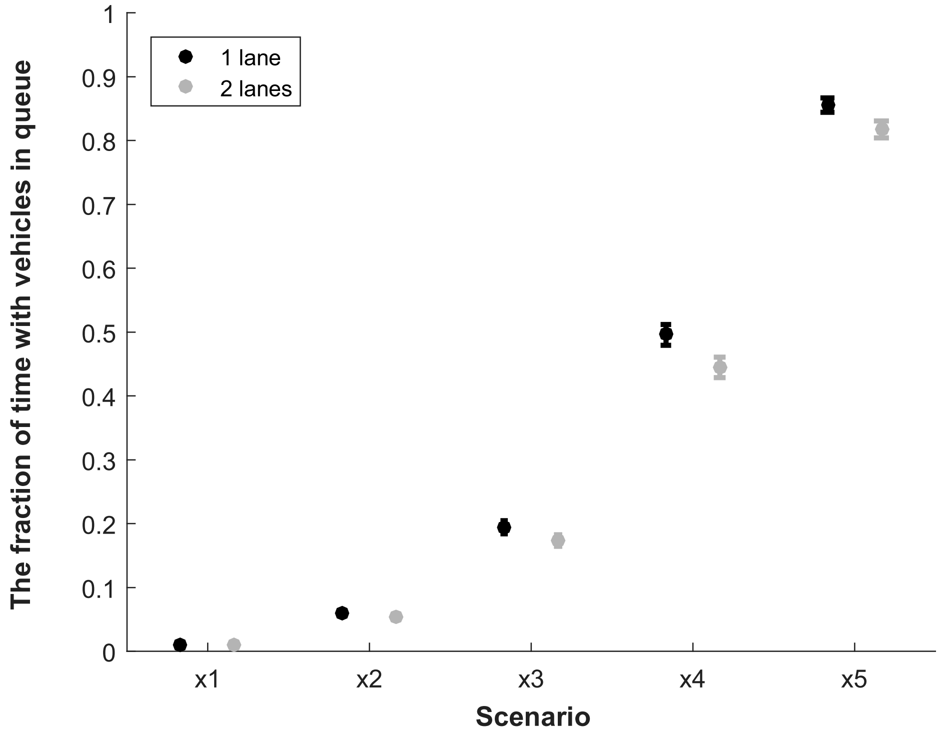

Figure 7: The fraction of the simulated time with at least one vehicle in the queue. Error bars correspond to 95% confidence interval of the average over the repetitions of the simulation.

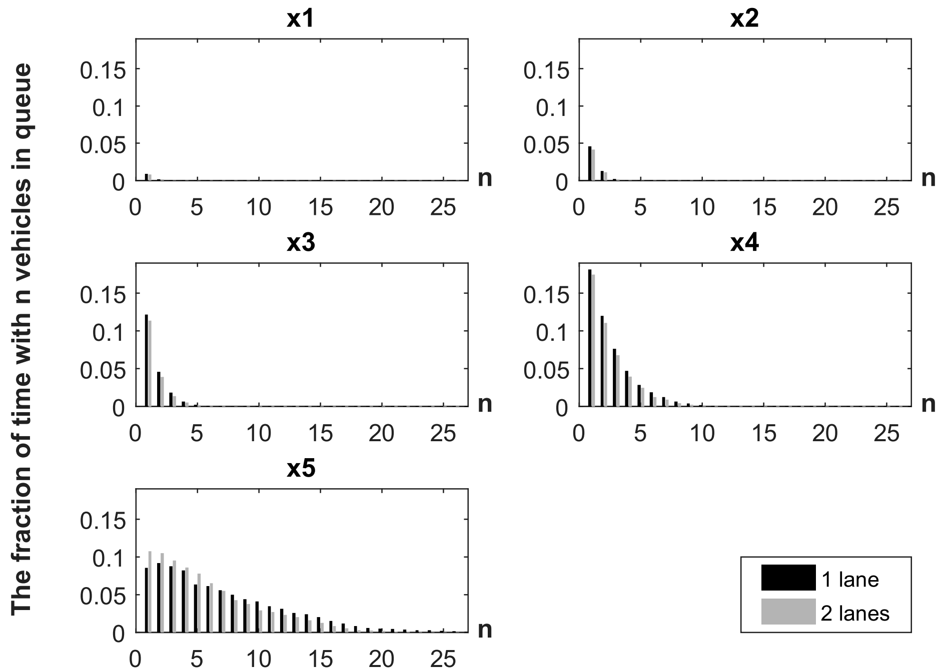

Figure 8: The fraction of the simulated time with a specific number of vehicles, n, in queue (shown on the x axis)

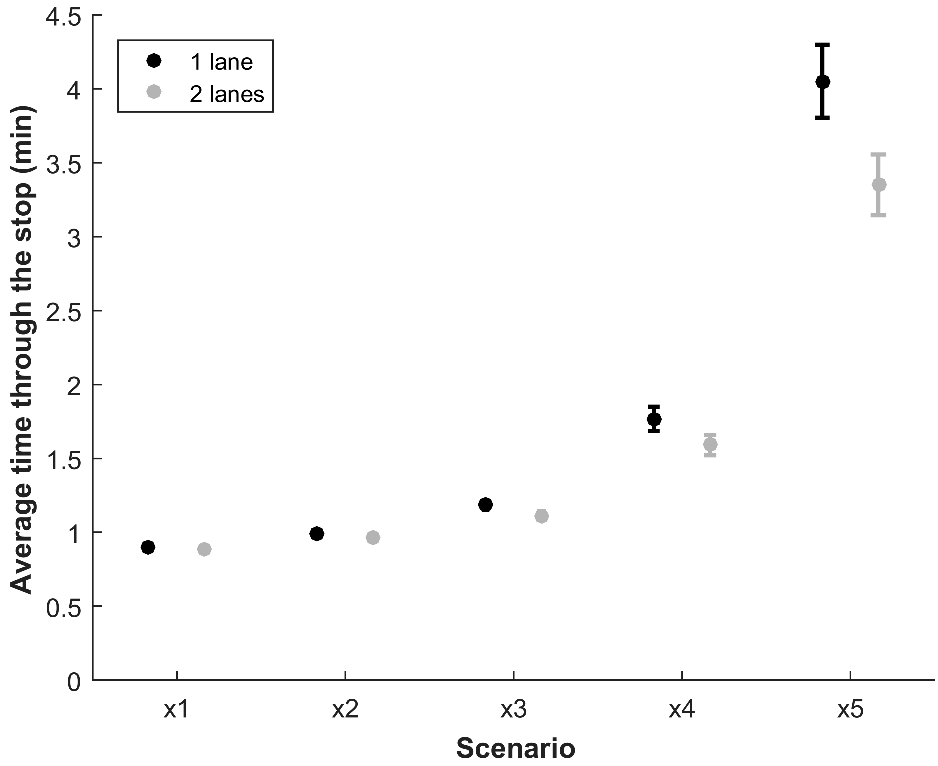

Figure 9: The average time needed to pass through the stop. Error bars correspond to 95% confidence interval of the average over the repetitions of the simulation.

5.2 Effects on the Individual Vehicles

While information about queue lengths is important in order to establish the feasibility of a situation, it tells little of how large the impact is on the actual service and on each individual vehicle. Figure 9 shows the average time needed to pass through the stop for each vehicle, averaged over the number of repetitions of the simulation. At scenario x1 it takes almost 1 minutes on average to pass through the stop. The difference between the two layouts is in this case too small to be read from the graph. As the amount of incoming vehicles doubles and triples, the time through the stop increases slightly and a very small difference in favour of the two-lane design can be observed. The difference becomes more pronounced as the number of vehicles increases further, landing at about 0.7 min at x5. It can also be noted that it is possible to find the average delay at departure by relating the average time through the stop to the arrival and timetable times. This will follow a similar trend as the average time through the stop.

Just like the average time to pass through the stop could be seen to increase with an increase in the amount of incoming vehicles, so does the variation between vehicles. This can be seen in Figure 10, which shows the replication average of the standard deviation of the time to pass through the stop. This variation means that the service becomes less reliable and more difficult to plan. Just as in the case of the previous measures, the differences between the layout alternatives are very small in the scenarios with a lower amount of incoming vehicles and more pronounced for x4 and even more so for x5.

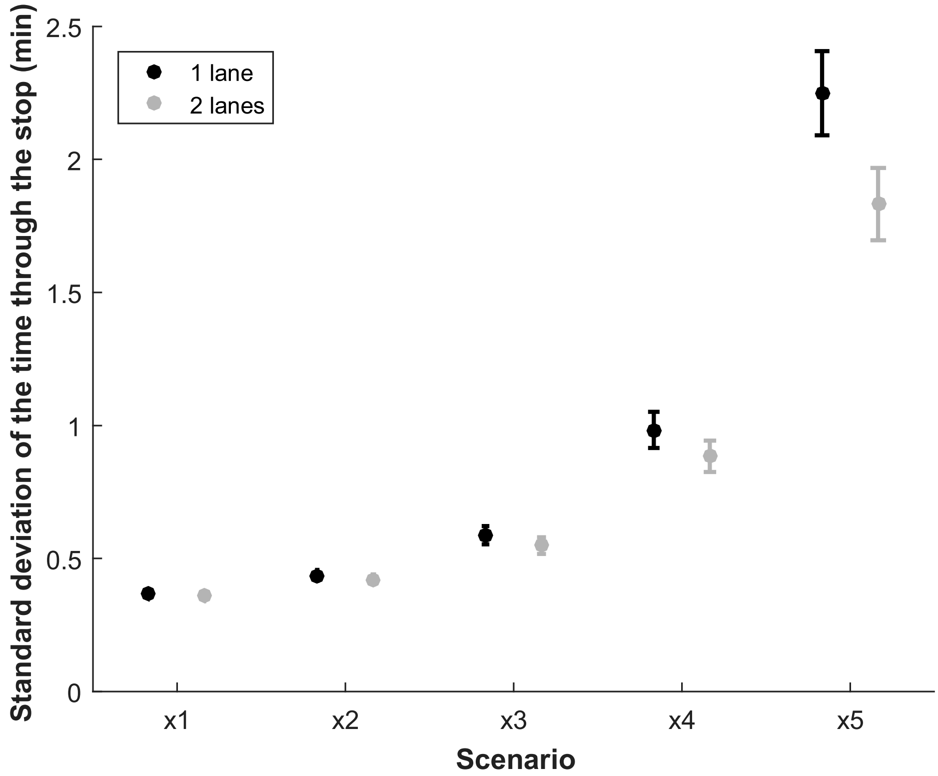

Figure 10: The standard deviation of the time needed to pass through the stop. Error bars correspond to 95% confidence interval of the average over the repetitions of the simulation.

5.3 Effects of Trams

It can also be of interest to investigate whether the result would look similar if only buses would be using the stop. This means that all vehicles, rather than just a sub-set, are able to overtake vehicles at departure. In order to get comparable result, the timetables, dwell times and arrival times are the same as previously. Only the ability to overtake, together with the distribution parameters of the drive time, have been changed. These parameters are now set to the ones for buses given in Table 4 for all vehicles. The effects of trams in the two-lane design alternative is illustrated through the average time needed to pass through the stop, see Figure 11. The figure shows the result for both the case of only buses and for a combination of buses and trams, where the latter is the same result previously shown in Figure 9. As previously, the differences between the cases are very small for the three scenarios with a lower number of scheduled departures. At x1, the new case with only buses performs slightly better than the one with a mixture of buses and trams, while in x2 and x3 being somewhat worse. This situation continues in x4 and x5, where the case of only buses using the stop has an average time longer than the corresponding time for the combination of both buses and trams. When comparing the result with the one-lane case in Figure 9, it is evident that the one-lane version of the stop performed worse than both cases of the two-lane stop. This means that while it was better to have a two-lane design with a combination of buses and trams in most scenarios, the two-lane alternative also performed better in a bus only situation. The results of this subsection will be further discussed below.

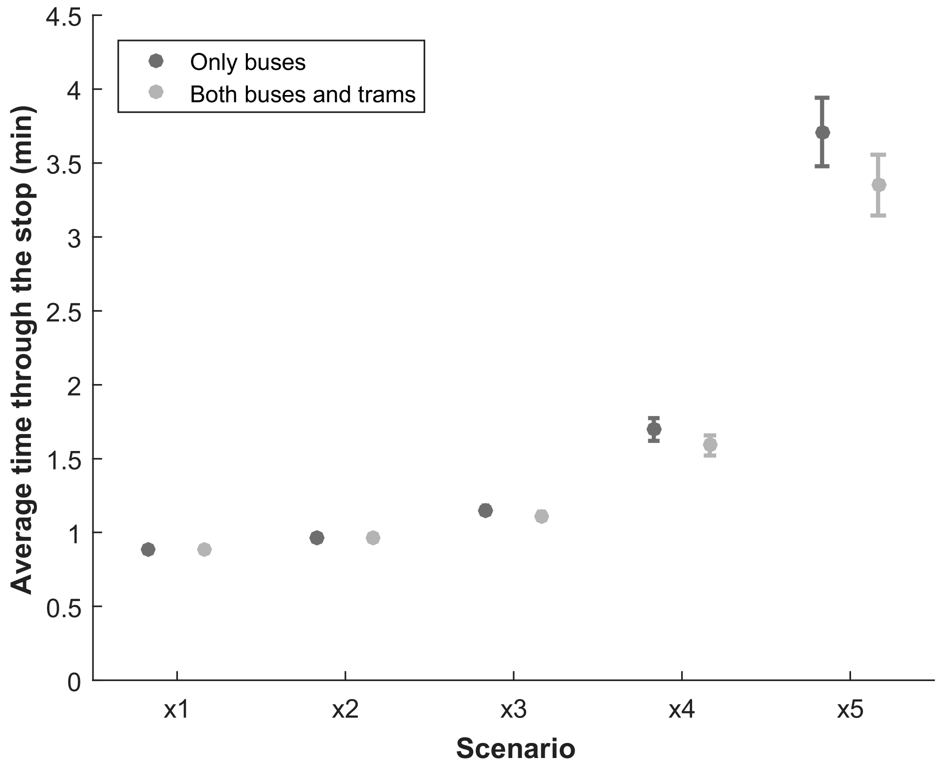

Figure 11: The average time needed to pass through the stop. Includes both a combination of buses and trams and the case of only buses, both for the two-lane design. Error bars correspond to 95% confidence interval of the average over the repetitions of the simulation.

5.4 Discussion

As has been shown, the differences between the two layout alternatives were very small for the x1 and x2 scenarios in particular. First at x4 and x5 the differences were noteworthy, but these scenarios had very long queues instead. Adding a second lane was thus not enough and a totally different solution needs to be found, such as adding more berths or stops. It should also be noted that the model operates under the assumption that there is enough space for any queue forming at the stop, which is hardly reasonable when the queue contains 27 vehicles. In reality, the queue would likely propagate out from the terminal area and interfere with car traffic in the surrounding road network. The model is clearly not valid in this situation. This does not affect the conclusion of the stop not being enough to handle the situation, however. Considering the small effects at the lower amounts of vehicles and the infeasibility at higher amounts, adding a second lane would not be advisable for this stop. It should be noted, however, that the model has not been validated with an independent dataset and such conclusions should for this reason be treated with caution. While it is reasonable that the approximations of the model would not affect the general patterns of the result, without validation this cannot be known with certainty.

A question arises as to why the effects of adding the second lane is not larger and why it was better to allow overtaking for only a subset of the vehicles, rather than all of them. An important factor in answering these questions lies in the assumption that buses are only allowed to overtake at departure and not when they are arriving to the stop. This gives rise to two competing effects. On one hand we have the positive effect of not having to wait on

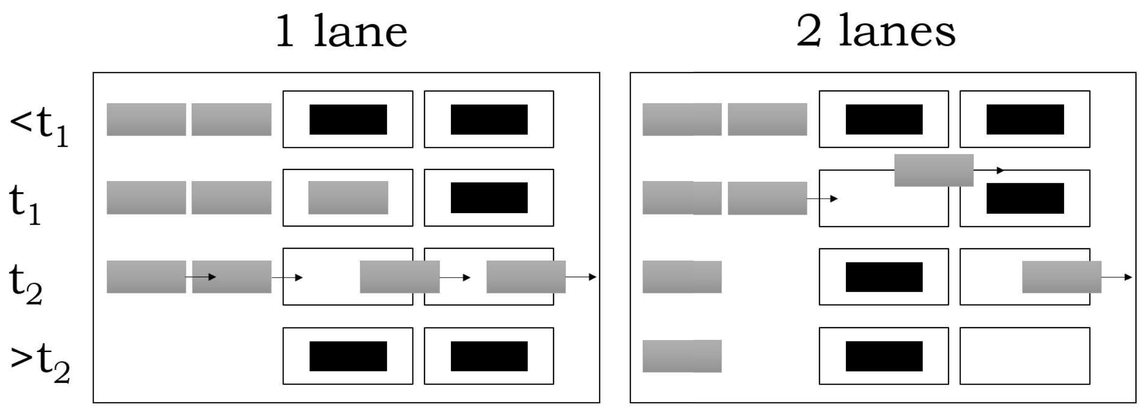

Figure 12: Illustration of the blocking effect that can arise due to allowed overtaking at departure. At t_1 a bus in the second berth is ready to leave the stop and at t_2 a vehicle in the first berth is ready to leave. This will have different consequences depending on the number of lanes.

the vehicle in front, which reduces the time at the stop for the overtaking vehicle and frees the second berth for another vehicle, reducing its queuing time. On the other hand, there can also be a negative side effect of freeing this second berth. This is illustrated in Figure 12 where vehicles letting passengers board and alight are represented by black rectangles and vehicles that are waiting or driving are represented by grey rectangles. Assume that both berths are occupied at some time before t_1, the second berth by a bus, and that there are at least two vehicles in the queue. At t_1 the bus in the second berth is ready to leave. In the one-lane case it has to wait until t_2, when the vehicle in front is ready to leave as well. Both berths will in this case be filled immediately by vehicles from the queue. In the two-lane case the bus in the second berth will leave directly when it is ready at t_1 and the second berth will be filled by a vehicle from the queue. At t_2 the vehicle in the first berth leaves, but in this case no vehicle will be able to fill this berth since the lane is blocked by the vehicle behind of it. First when that vehicle is ready to leave as well, both berths can be filled. Looking at the situation from the point of view of berth productivity, i.e. when a vehicle in a berth is exchanging passengers, it can be seen that in the one-lane case the second berth will be unproductive between t_1 and t_2. In the two-lane alternative the first berth will instead be unproductive between t_2 and the point in time t_3, when the vehicle who entered from the queue is ready to leave. How large the negative effect will be in the two-lane case mainly depends on how soon the vehicle in the first berth is ready to leave after the one in the second berth, that is, the difference between t_1 and t_2. It can be noted that this negative effect will only occur if there are vehicles wanting to enter a berth. For this reason, the effect would not be noticeable at low amounts of vehicles using the stop, where queues will rarely form. Considering that the two-lane version of the stop showed a better result, the positive effect can be deemed to be larger in this case than the negative effect. It would also seem that the negative effect can be reduced by not letting all vehicles overtake, as could be seen in Figure 11. This needs to be studied further.

There is also a similar blocking effect that is present at both layouts. Even if overtaking is not allowed, there is always the possibility of the vehicle in front leaving before the vehicle in the back is ready, blocking the path for vehicles in the queue. This effect would

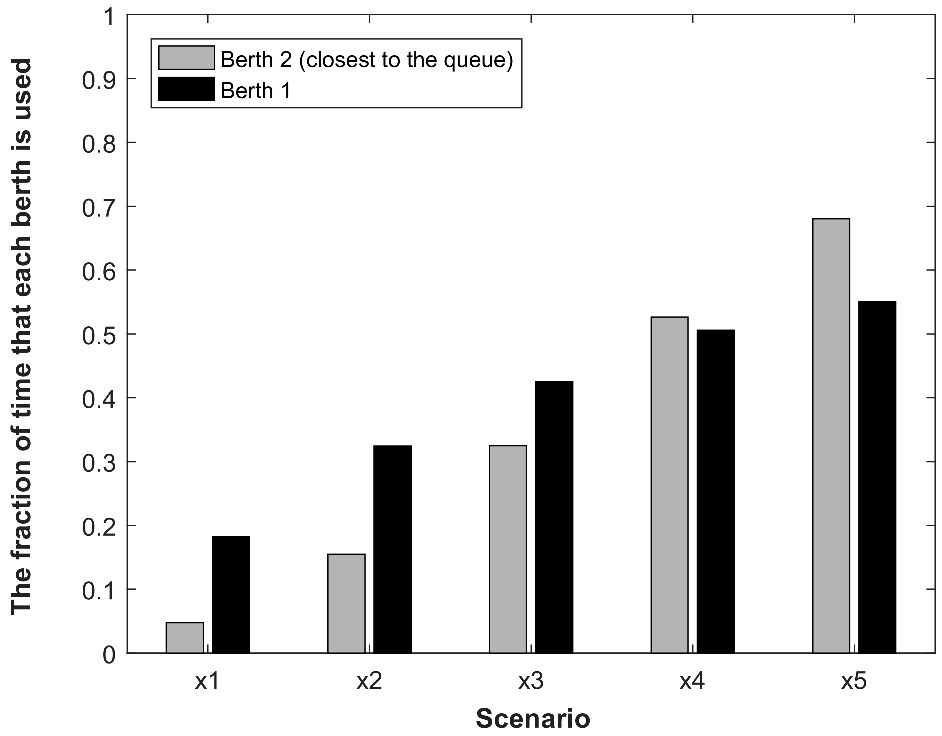

Figure 13: The average fraction of the simulation time that each berth is used

also be more noticeable at higher amounts of vehicles using the stop. Figure 13 shows the occupancy of each berth (grey/black) for the one-lane design (the two-lane design would look similar). As expected, the first berth is used more often for lower amounts of incoming vehicles. In these cases, vehicles will often arrive to an empty stop where they can drive directly to the first berth. At x4 and x5 the second berth is used more often, which would be a result of the blocking effects that have been discussed.

6 Conclusions and Future Work

In this study a discrete event simulation model of a railway connected bus and tram stop was developed. The model was able to compare two alternative stop designs, either with one or two lanes, and was applied in a case study of an existing stop at Norrköping railway station. The various events occurring at the stop, including the overtaking manoeuvres and the differences between buses and trams, were captured in a realistic way. Due to the event based approach, the focus could be on the important parts of the system, such as vehicle arrival and when and where the vehicles should stop. The case study also showed that the model could be used in design evaluation. In this particular case, adding a second lane to the studied stop would not be advisable, for example. The modelling approach has thus been deemed successful and as a good basis for further studies.

In ongoing work, the size of the model will be increased to a complete terminal with many stops and many tram and bus lines (local, regional and long-distance). This will include a generalized version of the bus and tram stop of this study. We also intend to find procedures for model verification and validation. Another direction, that would be interesting to study further, comes from the observation of the case study, that the control of the stop matters. If buses were allowed to overtake when entering the stop and not just when leaving, the conclusions might have been different (as the discussion in the previous section indicates). It would also be of interest to strengthen the connection to the railway. The bus and tram dwell times could for instance vary depending on train arrival times and the induced variety in passenger volumes. The amount of passengers could be included more directly, with an equation governing the dwell time depending on the number of boarding and alighting passengers. Lastly, the probability distributions included in the case study simulations could be chosen with greater certainty using statistical tests with a second data set.

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