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# A simulation model for assessment and evaluation of bus terminal design

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**Abstract** Interchange stations with their connections between modes and lines are central for a high quality public transport system. Bus access at the station needs to operate reliably and efficiently in order to prevent congestion and queues. Here, a discrete event simulation model of vehicle movements and interactions at bus terminals is developed and implemented. The model has a modular approach, where common spatial sections at terminals are represented by modules that can be combined into various terminal layouts. These modules describe the events a vehicle may go through in a particular section of the terminal, such as arriving to a bus stop or stopping at a traffic light at the exit. The model can be used in planning processes, both for new terminals and redesign of existing ones, and is able to describe the detailed movements and interactions between vehicles that occur at larger terminals. The model is tested in a numerical experiment representing Norrköping interchange station in Sweden. The experiment shows that the model is able to evaluate and compare different scenarios and can thus be a useful tool in planning processes.

**Keywords** Bus terminal · Microsimulation · Discrete event simulation · Performance evaluation · Capacity

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## 1 Introduction

For a high quality public transport system, all of its transfer nodes need to be well functioning with a reliable and efficient operation. Interchange stations and bus terminals have a high impact on the system as a whole since they connect the various lines and modes of the system, facilitate transfers and make it possible to achieve a high degree of connectivity within a city or a region. While this is highly important, it is also a vulnerability. Delays originating at a station may propagate through the system due to the many intersecting lines, reducing both punctuality and reliability. Added to this is the fact that while transfers between lines are important to the connectivity and quality of the system, travellers tend to dislike them. It has been shown repeatedly that the time spent in transfer is perceived as significantly less comfortable than in-vehicle time, see e.g. Wardman (2004).

An important factor for a reliable and punctual service that facilitates fast transfers is the capacity of the station's bus terminal. Too low capacity causes congestion and queues, which may result in delays and an unreliable service. In practice, however, terminals are not always planned with sufficient capacity. This is the case in many metropolitan regions, such as Stockholm in Sweden (Al-Mudhaffar et al, 2016). This can be due to an increase in demand, but can also be a result of the common requirement of compact terminals that do not occupy large areas; a requirement that is often in conflict with that of a high capacity. Besides the bus terminal, there are typically also train platforms, waiting areas and commercial facilities competing for the limited space, as has been observed by e.g. Auckland Transport (2013). Compact terminals with short walking distances are also in the interest of the travellers, since this reduces the time spent in transfer.

In order to evaluate the trade-off between capacity and size and plan for efficient terminals, good tools are needed. Terminal design guidelines and capacity handbooks, such as Auckland Transport (2013), AASHTO (2002) and Transportation Research Board (2013), give analytic capacity formulas for individual bus stops and small stations as well as approximate estimates on the number of stops needed at a terminal. These methods are less suitable for larger terminals and cannot be used to study the variations inherent to the systems. Al-Mudhaffar et al (2016) state that such deterministic methods can only be used for very simple cases and not for larger bus terminals. We believe that a highly suitable alternative for terminal capacity analysis is microsimulation due to its inherent capability to test various situations and make detailed analyses. It is commonly used and have proven to be highly useful in analysis of road traffic systems, see e.g. Barceló (2010). For microsimulation of bus terminals, it is important to be able to capture terminal specific properties and behaviour, such as allocation of lines to stops and interactions between vehicles at the terminal. These interactions may follow different rules than the ones of standard road traffic. Available traffic simulation software tools focus on road traffic and these vehicles' interactions, such as car-following and lane-changing. This focus can make them difficult to use for terminal simulation with the behavioural aspects inherent to such systems. These limitations have been discussed by Kramer (2013) and Askerud and Wall (2017), who used Aimsun and VISSIM (Barceló, 2010, chapter 5 and 2), respectively. Typically, simplifications are needed and it may be time consuming to implement the required

functionality. The literature shows a few examples where traffic simulation software is still used for terminal simulation, see e.g. Fernández et al (2010) who does not specify any terminal specific rules and behaviour. In studies using dedicated terminal simulation models, the considered terminals are generally small with a low number of stops, see e.g. Adhvaryu (2006) and Liang and Wang (2009). Nevertheless, these examples still show the potential of this approach.

In this study, a dedicated bus terminal simulation model has been formulated. The model is based on discrete event simulation, an approach well-suited for a system such as this with clearly defined events, for example driving to a stop and dwelling. The focus of the developed model is on the vehicles, their movements and when and where blocking between vehicles takes place. The latter is an important aspect that will have an effect on the capacity since queues may block entrances to stops and various sections of the terminal. Less focus is given to the acceleration and car-following behaviour typically associated with road traffic. The model is delimited to the terminal itself and does not include the surrounding traffic network or any other parts of an interchange station. While no other entities than vehicles are simulated directly, passengers are still included by affecting dwell times at stops and waiting times at pedestrian crossings. The objective of the study is to develop a microsimulation model describing vehicle movements and interactions at bus terminals of various kinds. This model is implemented in a simulation environment and tested in a real-world example. The model is able to evaluate terminal designs and traffic scenarios by having a modular approach where modules representing spatial parts of a terminal can be combined into various constellations. The contribution consists of the development and implementation of a modular model that can be used in planning processes of new terminals or reconstructions of existing ones. The model is able to describe detailed movements and capture the vehicle interactions occurring at larger terminals.

The rest of this paper is organised as follows. Section 2 presents the background and previous work in terminal simulation. This is followed by a presentation of the model in section 3 and of the numerical experiment in section 4. Conclusions and future work concludes the paper in section 5.

## 2 Simulation of bus terminals

In this section simulation of bus terminals and the components required for terminal simulation will be discussed. In this paper, we define a terminal as having two or more stops and being separated from other modes of traffic. The few studies modelling bus terminals vary in size and modelling approach. Seriani and Fernandez (2014) use existing software programs both for traffic and pedestrian simulation in order to evaluate two BRT bus stations with two stops each. Another approach can be found in Fernández et al (2010) and Adhvaryu (2006), who both use a dedicated stop simulation model developed by Fernández. This model has been presented in a number of studies, e.g. Fernández (2010). In Fernández et al (2010), the stop model is integrated with an existing traffic simulation software program. The model is applied to several cases, including a ten stop interchange station partly integrated with the road traffic. A smaller terminal, completely separated from road traffic, is studied by Adhvaryu

(2006). Three alternatives of a three stop terminal are simulated and compared. Liang and Wang (2009), finally, develop their own model of a five stop terminal as the bus dispatch scheme of the terminal is optimized.

A number of components used in terminal simulation can be identified from these studies. All calculate a dwell time based on the number of alighting and boarding passengers and some include simulation of the passengers and of the surrounding road traffic. While none of the articles go into details of the modelling of bus arrivals, this is another component needed for terminal simulation. One last component, included to varying degrees, is the interactions between the buses. Since congestion and queues can cause delays, queues need to be properly captured so that terminal simulation is not simply a sum of individual stop simulations. When using traffic simulation software, these interactions primarily follow the rules of road traffic (possibly with some additional public transport related rules added). The traffic on terminals can be expected, to some degree, to follow different rules than road traffic. Other situations may arise and the rules may be different even for similar situations, such as priority rules around bus stops. The terminal simulation studies show some examples of such situations included in the models, for instance a case where different paths are taken depending on whether or not a stop is occupied.

The related area of stop simulation models includes studies focusing on improving stop modelling in road traffic simulation models (e.g. Silva, 2000), studies simulating larger public transport systems (e.g. Ancora et al, 2012, and Gunawan, 2013) and studies focusing on modelling the stop itself (e.g. Fernández, 2010, and Tan et al, 2013). Some components easily transfer from stop to terminal simulation, such as dwell time modelling. Interactions between buses may in some cases be similar between stops and terminals (e.g. a stop being occupied when a bus wants to enter), but there are also situations that differ. When a bus wants to exit a stop, for instance, priority rules are may not the same when the bus exits into road traffic and when it exits into a lane within the terminal area.

Dwell time modelling has been an ongoing research area for decades. The dwell time depends on a number of factors, the most important being the number of passengers boarding and alighting. Various functions can be formulated depending on the functional form and the number of factors included. Common varieties are linear in form and includes the number of boarding and alighting passengers together with a number of constants specifying the time per boarding or alighting and the dead time, which is the time needed for opening and closing of doors and other activities not dependent on the number of passengers (see e.g. Luo and Guo, 2010, and Seriani and Fernandez, 2014). Some studies include more factors or use other functional forms (see e.g. Fernández, 2010, and Tirachini, 2013).

Modelling of passengers in terminal and stop simulation can be done to various degree of detail. From pedestrian simulation, as in Seriani and Fernandez (2014), to versions where passengers are simply represented as numbers that are to board/alight. The latter can be found from probability distributions describing either the number of passengers for each departure or the arrival of passengers (Fernández, 2010). Traffic modelling can also be done to various degree of detail, from the detailed descriptions in traffic simulation software programs to simple probability distributions at entries and exits. If the simulation is delimited to the terminal itself, vehicle arrivals need to

be modelled. This can be done by modelling the headway between arrivals (see e.g. Bookbinder and Ahlin, 1990) or by using timetables (see e.g. Rietveld et al, 2001).

As has been described in this section, many of the components needed for terminal simulation has been studied previously. Modelling of the interactions between vehicles should still be improved, however. A dedicated terminal simulation model can include such interactions, while at the same time reduce the complexity in relation to a traffic simulation model by focusing on the aspects important for terminals. In addition, a model characteristic that to our knowledge has not been discussed in previous studies is the concept of modules representing different parts of a terminal.

## 3 The model

The simulation model developed in this study is based on discrete event simulation. In this simulation approach, the state of a system is updated at discrete points in time as an *event* occurs (Ross, 2006). This can be contrasted to the time-based approach common in road traffic simulation where the system is updated with fixed time intervals Barceló (2010). A bus terminal can readily be described by a set of events and their interdependencies, such as arrival to the terminal and initiating a driving process to a stop, and is thus well-suited to be represented by discrete event simulation. This approach has previously been tested on a smaller system consisting of a bus and tram stop, see Lindberg et al (2017). This study extends the previous model to larger, more general bus terminals and improves upon the modelling of vehicle interactions in order to properly capture blockages of various kinds between vehicles. The model is continuous in time and discrete in space and thus divides a terminal into cells. These are small enough for a vehicle to occupy a number of cells simultaneously. By keeping track of the occupation of these cells, interactions in the form of vehicles blocking each other throughout the terminal can be modelled and included. In the following subsections, a network description of a terminal will first be presented together with the events associated with a terminal. This is followed by a presentation of the modular approach of the model and description of each function and module. The section concludes with some details of the model implementation.

### 3.1 Events and network representation

A bus passing through a terminal will experience a number of events and processes. First there is the event of arriving to the terminal, then the one of starting to drive to some initial target point, followed by the arrival to this target point. Each of these are instant events that changes the state of the system. In-between events there may be processes associated with a time duration, such as driving to the target point in the previous example. In an event-based description, these processes do not change the state of the system (the state is fixed while the bus is in the process of driving and not changed until it arrives to the target point). Using this description of events and processes, a terminal can be represented by a network. A small example of such a network describing the events and processes of a part of a terminal can be seen in

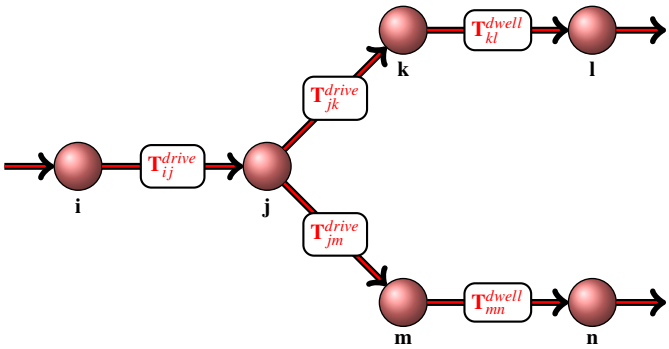


Fig. 1: A small example network representing part of a terminal. The arcs represent processes and the nodes events corresponding to the start and end of processes.

figure 1. The nodes of the network represent events changing the state of the system, while the arcs represent the processes and thus have a time duration. One node may be associated with several events, $j$ in figure 1 is associated with the end of one driving process and the start of two other driving processes, for instance. All events are related to a particular position at the terminal (e.g. where a vehicle starts to drive in to a stop) and events belonging to the same node are related to the same position. The processes are related to the distances between the locations of two directly connected events (e.g. the road section from where a vehicle starts to drive in to a stop to the front of the stop). The time of an event $i$ is denoted $t_i$ and the duration of a process occurring between $i$ and $j$ is $T_{ij} = t_j - t_i$.

In order to formulate a terminal model using the presented network description, the various events (combined into nodes) and processes (arcs) of a terminal need to be defined. The number of events and processes to include in the network are to some degree arbitrary, however. Driving through a particular section of a terminal could be considered as one process (driving through the whole section at once) or several processes corresponding to separated stretches of the section. Different kinds of events can in some circumstances also be combined into one if there are no decision points between them. Here, processes are combined into one if they occur directly after one another without any decisions in-between and if all information needed for the later events are known at the start of the first event. There is one exception to this, where the time of a set of processes are calculated even though they rely on a future state of the system. This is related to driving sections, which are divided into cells small enough for a vehicle to occupy several cells at once. The processes of driving through the cells in a section are combined into one process where the driving time through all cells are calculated immediately. In figure 1, this means that all of the depicted driving processes would most likely span over several cells. Only the state of the first cell can be known to stay fixed during the combined process (all information needed for calculating driving time through later cells are not yet known). When reaching cells further ahead, the situation may have changed (a vehicle in front may have stopped). If the initially calculated time of the process is incorrect, this is updated and adjusted

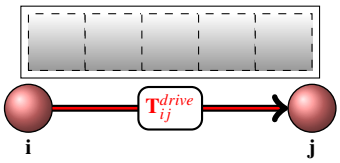


Fig. 2: One module representing a driving section with five cells. At arrival to the module, node i, the process of driving is initiated.

after the process has finished. This is possible since the model continuously keeps track of a vehicle's effect on neighbouring vehicles and the extra driving time associated with a vehicle stopping in front is thus known. This will be discussed in more detail in sections 3.4 and 3.7.

With the focus of the model being on queues and blockages between vehicles, several simplifications are made in regard to acceleration behaviour and differences between vehicles. All vehicles are assumed to be driving at the same, constant speed and having the same minimum time distance to any vehicle driving in front. In a stationary queue of vehicles, the distance between vehicles will be one cell. The cell length also dictates all lengths of a terminal, as well as the length of vehicles, which all need to be an integer number of cells.

### 3.2 A modular approach

As described in the previous section, the model divides a terminal into cells. As a vehicle passes through a terminal and drives through these cells, it goes through a series of events and processes, such as driving (generally through several cells at once) and dwelling at a stop. In this section an additional concept is introduced; the one of modules. This idea is based on the terminal property of repeating sections. In general, a terminal will consist of a limited number of sections repeated throughout the terminal, such as a particular type of stop or a driving section. These may be limited to a singular point on the terminal or have an extension with many cells. Each type is also associated with a set of events and processes. A terminal entry, for example, has a set of vehicle generation related events and is considered as a single point where the vehicles arrive to the terminal. A stop, on the other hand, will have several cells and events related to dwell time and entering and leaving the stop. The model incorporates this property of repeating sections by constructing modules based on common sections; entry, exit, driving section and stop. These modules can be combined in various ways in order to construct a range of different terminals. Figure 2 shows how one module, in this case a driving module, relates to the cells of a terminal and to the network description. By using the modules that have been presented, different terminal layouts can easily be constructed, extended and modified. An example flow chart of a terminal constructed from these modules can be seen in figure 3.

The four modules that have been presented initiates all events of the model as vehicles are routed through the terminal (possibly with the help of logical components such as switches). The vehicles are in this routing treated as point particles being

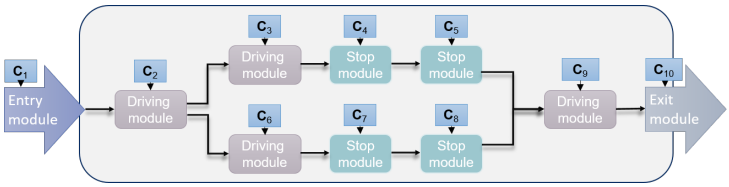


Fig. 3: Flow chart of an example terminal constructed from the entry, exit, driving section, stop and switch modules, where $\mathbf{C}_x$ represents parameter input.

Table 1: The functions used by each module

| | Vehicle generation | Driving time | Dwell time | Waiting time at pedestrian crossing | Waiting time at exit |
|---|---|---|---|---|---|
| Entry module | X | | | | |
| Driving module | | X | | X | |
| Stop module | | X | X | X | |
| Exit module | | X | | | X |

moved to the various parts of a terminal. Each vehicle is associated with a set of parameters set at generation and variables initialized at generation and updated during its way through the terminal. These parameters and variables are used for routing, statistics and to calculate the time of processes. For these time calculations, a number of functions shared between the modules are used. There is one function for each type of process: driving time, dwell time, waiting time at pedestrian crossing and waiting time at exit. There is also a function calculating the intergeneration time of vehicle arrivals. A particular module can call upon the various functions several times. How often the various functions are called in a module is related to the number of events. Each time a process is initiated, a time duration from one of the functions is needed. Table 1 shows the connections between the various modules and the functions. Most of the functions in the model calculates the time needed based on common probability distributions. The driving time function is more complex as it keeps track of occupation of cells. When driving times are calculated, the states of these cells are checked in order to take account of other vehicles and blockages and then updated to include the occupation of the considered vehicle. This will be discussed in more detail in section 3.4. In the following subsections, the functions and the modules of the model will be described in more detail.

### 3.3 Vehicle generation function

The vehicle generation function accepts an arrival line number together with a number of line specific parameters as input. The purpose of the function is to calculate the

intergeneration time between vehicle arrivals. This can be done in various ways depending on the system that is to be modelled. For high frequency bus lines, a headway probability distribution might be appropriate (such as the Poisson distribution). For lines with lower frequencies, the arrival time should instead be based on the timetable. Here, the intergeneration time is calculated based on a timetable with an added log-normal probability distribution controlling the punctuality. The module could easily be extended with different distribution alternatives.

### 3.4 Driving time function

The driving time function is called upon whenever a driving time is needed. It is here that interactions between vehicles takes place, such as having to wait on a stationary vehicle in front or on a passing vehicle when leaving a stop. While the modules treat the vehicles as point particles, their lengths are here taken into account. The function accepts a number of input parameters from the vehicle in question, together with module specific parameters and parameters that are in common for all modules. The two main tasks of the function are to calculate the driving time and to keep track of the occupation of cells. The road space of the modules is divided into a number of cells and by storing occupation time windows together with vehicle ID and length for each of these cells, various vehicle interactions can be modelled by checking which cells are occupied by other vehicles. In a similar manner, occupation time windows are also stored for the stops of the model. When a vehicle is to drive through a section, the occupation time windows of the cells of that section are checked to determine if the vehicle can drive directly or need to wait. From this the total driving time through all cells of the section is calculated and new occupation time windows for the considered vehicle are stored for each affected cell. The occupation time window of a cell correspond to the time from the arrival of the front of a vehicle to the departure of its rear end. If a vehicle needs to wait before entering one of the cells in a section, all cells it presently occupies needs to be updated with new departure times (the original departure times were calculated under the assumption that the vehicle would not need to stop). This can also affect followers of the considered vehicle. Their occupation time windows are thus also updated. An important aspect of the modelling approach is the fact that a driving time of a particular process of a module cannot be changed after having been returned from the driving time function and initiated. In order to update affected followers, the additional waiting time is for this reason stored. After a vehicle has completed the driving time in a section, this additional waiting time is retrieved and the vehicle spends extra time in the section (see e.g. figure 4).

While the general modelling approach presented is used for all driving time calculations, different types of events will result in different calculations. These types of events are driving through the section (calculate time windows for each cell), driving in to a stop (calculate time windows for the cells before the stop and enter the stop if it is unoccupied), dwelling (calculate time window for stop occupation), driving out from a stop (calculate time windows for the cells adjacent to the stop with any need to wait on passing vehicles taken into account) and driving through a junction (calculate time window if both cross section and the road on the other side are unoccupied).

### 3.5 Dwell time function

Dwell time is here modelled with a number of simple linear functions. There are three variants depending on whether the bus is to let passengers alight, board or both. The number of passengers are found from a normal probability distribution (rounded to an integer). Boarding passengers are assumed to only use the door in the front, while alighting passengers are assumed to spread evenly on the rest. If the bus is only letting passengers alight, the dwell time can be calculated from

$$t_{DT}^{alight} = t_0 + t_{alight} \left\lceil \frac{n_{alight}}{n_{doors} - 1} \right\rceil,$$

where $t_0$ is the dead time, a constant that captures the time a vehicle is dwelling at a stop without letting passengers board or alight (including opening and closing of the doors), $t_{alight}$ is the time per alighting passenger, $n_{alight}$ is the number of alighting passengers and $n_{doors}$ is the number of doors. The dwell time for a bus only letting passengers board is

$$t_{DT}^{board} = \max(t_{to\_dep},\ t_0 + t_{board} n_{board}), \tag{1}$$

where $t_{to\_dep}$ is the time until the planned departure time, $t_{board}$ is the time per boarding passenger and $n_{board}$ is the number of boarding passengers. If both boarding and alighting are to take place, the dwell time is

$$t_{DT}^{both} = \max\left(t_{to\_dep},\ t_0 + \max\left(t_{board} n_{board}, \left\lceil \frac{n_{alight}}{n_{doors} - 1} \right\rceil\right)\right). \tag{2}$$

### 3.6 Waiting time functions

The two waiting time functions, at an exit and at a pedestrian crossing, uses probability functions to model the delay. For a pedestrian crossing and an unsignalized exit, a binomial distribution is used to first determine if there is a need to wait. If it is needed, this is followed by a calculation of the waiting time using a lognormal distribution. If the exit instead has a vehicle actuated traffic signal where the signal is red until a vehicle is detected, there will always be a waiting time which is also modelled with a lognormal distribution.

### 3.7 Driving section module

A driving section module represents a stretch of the terminal roadway without any branching and merging within the section (this is instead modelled by combining driving sections). The section can include a pedestrian crossing in the beginning of the road stretch. In this module, a vehicle waits on pedestrians (if needed) before driving through the section. Required parameter input into the module includes vehicle parameters and length parameters. There are three versions of this module for slightly varying situations; a general driving module, first module after entry (includes a queue for vehicles blocked from entry into terminal) and a junction module

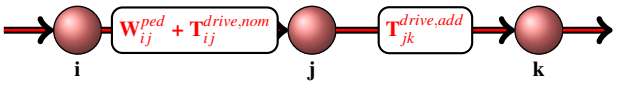


Fig. 4: Network representations of the driving module. At node *i*, a combined waiting and nominal driving process is initiated. At *j* an additional (iterative) driving process is initiated to account for any error in the initial calculation.

(one module needed for each combination of origin and destination in the junction). Vehicles are assumed to not enter a junction if another vehicle is already driving through it or if the vehicle will need to stop in the middle of the crossing. In other words, a vehicle will not drive through the section if there is a vehicle standing still on the other side. An important behavioural aspect for driving sections, both for junctions and for merging of two driving section modules, is the question of priority. Here, vehicles are assumed to follow a simple first arrival drives first principle.

Figure 4 shows a network representation of the first, general version of the driving module. The processes of waiting on pedestrians and driving though the section is merged into one process. At the first node, *i*, the vehicle thus starts the process of waiting on pedestrians and driving through the section (the waiting time can be equal to zero if no pedestrian crossing or no waiting pedestrians). The time of the processes are given by the functions controlling the waiting time at pedestrian crossings and the driving time. At the end of the process, node *j*, there may be a need to adjust the initially calculated nominal driving time. This is needed if the time from the original driving time calculation was too short due to a vehicle in front having stopped. This additional driving time is again given by the driving time function. This is done iteratively until the time returned is equal to zero.

### 3.8 Entry and exit modules

The entry and exit modules handle arrival and departure of vehicles from the terminal. In the entry module, buses are generated iteratively with arrival times found from the vehicle generation function. Outside traffic is not included in the simulation, but can still be represented indirectly through the use of probability distributions affecting the arrival time in the vehicle generation function. A network representation of the entry module can be seen in the left part of figure 5. It has one single node where vehicles are generated before being forwarded to the next module. At generation, vehicle specific parameters and variables are associated with the vehicle, such as line numbers (arrival and departure line), planned arrival and departure time, vehicle length, number of doors and a number of variables used for routing and vehicle statistics.

In the exit module, vehicles either leave directly or they first need to wait on a traffic light or outside traffic. This module includes a short stretch of driving as the vehicle leaves the terminal. The right part of figure 5 shows a network representation of the exit module. There are two nodes, one that either initiates driving (if there is no need to wait) or the combined process of waiting at the exit followed by driving. The second node terminates the vehicle (it leaves the terminal). Module parameters

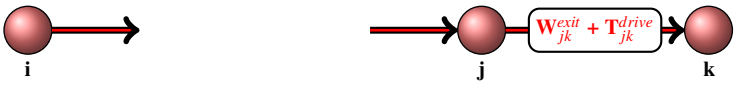


Fig. 5: Network representations of the entry module (left) and the exit module (right). At node $i$ in the entry module, vehicles are generated. At node $j$ in the exit module, a vehicle will initiate a combined waiting and driving process.

include the length of the stretch of driving and vehicle specific parameters. The module get the time of processes from two functions, the driving time function and the waiting time at exit function.

### 3.9 Stop module

A stop module represents one stop at the terminal together with adjacent roadways. Different stop layouts need to be modelled differently and here two similar types of stops have been modelled. The model could easily be extended with modules representing more types of stops. The types included consist of one berth, have an adjacent driving lane and either a linear or a sawtooth design. The stop operates independently, meaning that a vehicle wanting to enter or leave the stop can do so even if there is an occupied stop in the front or in the back. The module based on this stop includes the stop itself, the adjacent driving lane and the driving section before the stop (for a row of stops this will be the driving section between stops). It also has the possibility to add a pedestrian crossing before the stop.

The behaviour of the buses and their drivers will have an effect on the events of the module and this can differ between different drivers, terminals and cultural contexts. Here, a number of assumptions are made related to driver behaviour. First, if a vehicle is to enter a stop that is already occupied, it will wait behind the bus in the stop and block the way for any bus wanting to drive past the stop. Second, a bus entering a stop will be completely out of the driving lane first when the back of the vehicle enters the stop. Third, a vehicle will not let passengers board and alight while waiting to enter an already occupied stop. Fourth, when there is a conflict between a bus wanting to leave a stop and another bus wanting to drive past, the passing bus will drive first if its front is parallel with the stop, otherwise the bus in the stop will drive first. All of these vehicle interactions are handled when calculating the driving times in the driving time function.

A network representation of the stop module can be seen in figure 6. At node $i$, two processes can be initiated corresponding to two different paths of driving. In both cases the vehicle may need to wait on a pedestrian crossing. After this, the vehicle either drives past the stop or to the stop. At node $j$ there is a possibility to (iteratively) adjust the time of the initial driving time calculation if this was too short (as previously described in section 3.7). After this process, the vehicle is in the stop and a dwell time process initiates at $k$. This is followed by a new driving process $l$ as the vehicle drives out from the stop. At $m$, the two paths of driving are combined and there is, again, a possibility to adjust the driving time calculation. The

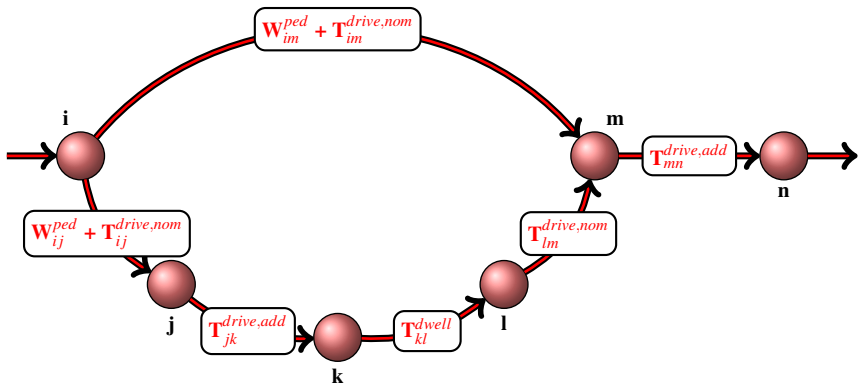


Fig. 6: Network representations of the stop module. At node $j$ and $m$, additional driving time processes are iterated until the additional time is equal to 0.

time of processes are found from the functions controlling dwell time, driving time and waiting time at pedestrian crossing.

### 3.10 Model output and performance measures

Capacity is not as clearly defined for terminals as for individual bus stops and is for this reason not considered directly in the model. Instead, a number of performance measures related to capacity are defined. Near or over capacity, one can expect more time spent waiting for each individual vehicle as well. Based on this idea, the performance measures include vehicle averages of driving delays (the time spent waiting in queues and at blocking vehicles) and the fraction of vehicles experiencing no driving delay at all. Also included are the average deviation from the planned departure in the timetable, the lateness, and the average time from the terminal entry to the exit, the terminal time. The model could be extended to include more performance measures.

### 3.11 Model implementation

The model has been implemented in SimEvents, a discrete-event simulation engine and component library developed by MathWorks (2016). In the implementation, the modules are constructed from components in the SimEvents component library and the functions consist of MATLAB functions accessible from the SimEvents model. A general ambition of the implementation is to keep modules general and minimize the adjustments needed in order to adapt the modules to a specific terminal and situation. To this regard, only a limited set of parameters are set in direct relation to a module, such as identification number and module variant (if there are different versions of the module). Other parameters accepted by modules are either global ones, specified in relation to the module identification number and accessible from all parts of the

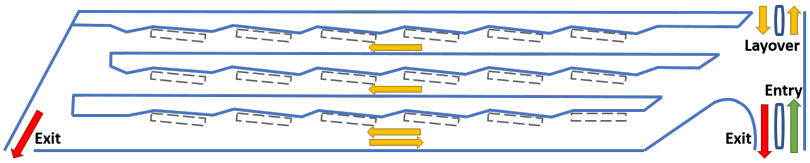


Fig. 7: The bus terminal at Norrköping interchange station

model, or vehicle specific ones (set at vehicle generation). Many of the global module parameters are specified in vectors where the right element can be accessed by using the module identification number.

## 4 Numerical experiment

The model is tested and evaluated in a case study of the bus terminal at Norrköping interchange station in Sweden. A number of scenarios is simulated and evaluated for the afternoon peak period between 3 and 5 pm. In this section the terminal in question will be presented, followed by the data used and the results of the case study.

### 4.1 Norrköping bus terminal

Norrköping interchange station is a multi-modal station with over 6000 boarding passengers each day and expected increases in demand over the coming years. The bus terminal of the station consists of 18 bus stops and is used by several different types of bus lines, both regional and long-distance. The stops are arranged in three rows with six saw-tooth bus stops each, see figure 7. At the south-east side there is a combined entry and exit connected to a roundabout and at the south-west side there is an exit regulated by a vehicle actuated traffic light. To the north-east, there is a layover area used when buses need to wait between arrival and departure from the terminal. The various lengths of the terminal are determined by taking measurements of a drawing of the terminal.

The terminal is modelled with 47 modules; 1 entry module, 2 exit modules, 18 stop modules and a large number of driving section modules, including two sets of junction modules used on the east side of the terminal were many routes intersect. Since observations of the terminal have made it obvious that there are very few interactions between pedestrians and vehicles, no pedestrian crossings are included (pedestrians are assumed to cross when no vehicle will be affected). The layover area is considered to be outside of the terminal and is modelled as a simple waiting time process. The cell size is set to 1 meter.

Table 2: The probability distributions used in the case study

| | Distribution | Parameter 1 | Parameter 2 | Parameter 3 |
|---|---|---|---|---|
| Vehicle lateness at arrival (min) | Lognormal | $\mu = 2.97$ | $\sigma = 0.258$ | shift $= -20.8$ |
| No of passengers | Normal | $\mu = 10.7$ | $\sigma = 0.820$ | |
| West exit delay - uncongested (s) | Lognormal | $\mu = 1.43$ | $\sigma = 0.647$ | shift $= 1$ |
| West exit delay - congested (s) | Lognormal | $\mu = 4.07$ | $\sigma = 0.216$ | shift $= 0$ |
| East exit delay (s) | Lognormal | $\mu = 1.10$ | $\sigma = 0.605$ | shift $= 0$ |

## 4.2 Data

Timetables for spring 2018 are used in the case study. These include 21 regional lines with up to six arrivals and departures to the terminal during the time period. Each line always uses the same stop, both for alighting and boarding, as well as the same exit. Most of the lines have the terminal as their end/start stop and a vehicle arriving as one line may depart as another. The time between arrival and departure varies and vehicles with longer waiting times drive to the layover area to not occupy a stop. The layover area is assumed to be used when there is more than six minutes to departure and there is a requirement to drive back to the departure stop five minutes before departure. Four different bus types are used, one of these being a double-decker bus. The buses are of low-floor type, have lengths between 12 and 15 meters and have two doors. Boarding is only allowed at the front door and alighting at the back door, except for the double-decker bus where both processes are allowed at both doors. Aside from the regional bus lines, there are also a total of 13 long-distance departures. These do not use the layover area. No empirical data has been available for the long-distance lines and these are for this reason assumed to behave as the regional ones. Their lengths are assumed to be 15 meters.

For the regional lines, data of vehicle arrivals for a period of close to five weeks during January and February 2018 has been used. This data gives the arrival time to the stop and have been adjusted to the terminal entry by using the distances between stops and entry and the same speed as the one used in the simulations. Incomplete data points were removed, together with arrivals registered incorrectly (not registered until the time of their new departure). A lognormal probability distribution was then estimated based on lateness data (arrivals compared to the timetable) and used for all of the lines. The lognormal parameter values are given in table 2. The estimation used a shift in the data to allow for the negative data points (arrival before the planned arrival time).

The parameters needed for dwell time calculations include probability distribution parameters for calculation of number of boarding and alighting passengers, time per boarding and time per alighting passenger and deadtime, the fix constant that captures both the time after the vehicle has stopped until first boarding or alighting activity and the time after the last activity until the vehicle leaves (opening and closing of doors etc.). Here, dwell time function parameters from Tirachini (2013) are used. Boarding time per passenger is set to 4.6 s, alighting time to 1.3 s and dead

time to 5.2 s. This corresponds to a low-floor bus, payment using a magnetic strip prepaid card at the front door and alighting at the back door. The same values are used for all bus types, including the double-decker.

For the estimation of number of boarding passengers distribution parameters, registered smart card passenger boardings has been available. Average number of boardings per departure was calculated for each line and a normal probability distribution was estimated, see table 2. The number of boardings are thus simulated using the same distribution for all lines. This distribution is expected to slightly underestimate real values, since boarding passengers can pay not only by smart card, but also with credit card as well as a mobile app. The boarding data is thus incomplete, but since boardings during the time period in question largely consist of commuters, smart card is expected to be the most common means of payment. As for alighting passengers, no data was available and the same estimated distribution as for boarding passengers was used as a simple approximation.

Delays at the two exits of the terminal are controlled by probability distributions. At the west exit, with a vehicle actuated signal, vehicles always need to wait until the signal changes. This is usually only a short delay, but sometimes vehicles experience longer delays due to congestion on the road outside of the terminal. The congested situation is not included in the base scenario, but in a separate one (see section 4.3.2). Both these situations are modelled with lognormal distributions with parameters estimated from empirical measurements at the west exit during two time periods (two days). At the east exit, with a roundabout, vehicles will not always need to wait. Both the likelihood of having to wait and the parameters of a lognormal distribution for the waiting time need to be estimated. Empirical measurements of one time period have been carried out for this purpose. The likelihood for having to wait is 37.5% and all exit delay distribution parameters can be found in table 2.

The driving parameters are the speed of the vehicles and the minimum time gap between vehicles. The former is set to a value suggested by a practitioner, 5.6 m/s, and the latter is taken from measurements of stop-and-go road traffic in Neubert et al (1999) and set to 1.8 s.

## 4.3 Results

A number of scenarios have been simulated, including a base case corresponding to the current situation at the terminal. Two other scenarios investigate the effect of an increase in the number of passengers and the effect of longer delay at the south-west exit. In the last scenario, the bus lines have been reallocated in order to use fewer stops. All scenarios have been simulated with 100 iterations, where each of these have between 46 and 55 observations.

### *4.3.1 Increased number of passengers*

In this scenario the effect of an increase in the number of passengers is simulated. The expected values of the normal distributions determining the number of boarding and alighting passengers are increased to four and ten times the current number of

Table 3: Results for the increased number of passengers scenario in the form of average values related to the base case with 95% confidence intervals

| | Relative driving delay | Relative terminal time | Relative lateness |
|---|---|---|---|
| 4x passengers | $1.01 \pm 0.13$ | $1.03 \pm 0.01$ | $1.64 \pm 0.11$ |
| 10x passengers | $2.26 \pm 0.30$ | $1.36 \pm 0.01$ | $7.26 \pm 0.16$ |

passengers (from 10.7 to 42.8 and 107). The terminal in question has few departures in relation to its size and large increases in demand are expected to have little effect on its operation. The fraction of vehicles that experience no driving delay at the terminal goes from 40% at the base case to 44% at four times the number of passengers and 47% at ten times the number. Since longer dwell times give rise to an increased risk of vehicles needing to wait on a blocked stop, this improvement means that the timetable is sparse enough for few such situations arising. This is not unexpected for the terminal in question. The improvement also implies that longer dwell times may reduce some specific conflicts between vehicles present at the terminal due to the dwelling vehicle arriving later. The results for driving delay, lateness and terminal time are shown in table 3. Averages of the results from individual iterations of the simulation with 95% confidence intervals are related to the base case. The driving delay is almost identical to the base case at four times the number of passengers and higher at ten times the number. Increased dwell times thus results in more and longer driving delay, even if the fraction experiencing delay actually decreases.

The driving delay can be set in relation to the total time vehicles spend on the terminal, the terminal time. It is evident from table 3 that the effect on this metric is smaller when increasing the number of passengers. The terminal time includes planned layover time (the average time between arrival and departure is 12 minutes). Neither the driving delay nor the terminal time tells anything of a vehicle's lateness in relation to the timetable, which instead is given by the third metric. As expected, increased dwell times result in more lateness, almost twice as high for four times the number of passengers and over seven times as high for ten times as many. These values do not include any blockages occurring between the stop and the terminal exit. Based on the result presented, it can be concluded that the number of passengers can be greatly increased, at least four times the present number, with very little effect on the vehicles.

#### *4.3.2 Longer delay at the south-west exit*

The situation with outside congestion at the south-west exit is investigated in this scenario. The parameters of the probability distribution controlling delay at this exit are estimated from a congested situation instead of an uncongested one (see table 2). This will affect not only vehicles that are to use this exit, but may also affect other vehicles. If more than one vehicle is waiting on the exit, the return lane used to get to the other exit, the layover area and to return to another stop will be blocked. This should reduce the fraction of vehicles experiencing no driving delay. As expected,

Table 4: Results for the longer delay at the south-west exit scenario in the form of average values related to the base case with 95% confidence intervals

| Relative driving delay | Relative terminal time | Relative lateness |
|---|---|---|
| $5.35 \pm 0.19$ | $1.17 \pm 0.01$ | $1.01 \pm 0.09$ |

this metric is reduced from 40% to 28%. These numbers do not include delay at the exit since this depends on the situation outside of the terminal and is not included.

The results for driving delay, lateness and terminal time are shown in table 4. Again, averages of the results from individual iterations of the simulation with 95% confidence intervals are related to the base case. The average driving delay has increased substantially, even though it does not include the delay at the exit. While the terminal time includes the delay at the exit, it is still only slightly increased. The lateness is almost not affected by the situation at the exit at all.

#### *4.3.3 Reallocation of lines to stops*

In this last scenario, the lines have been allocated differently to the stops in order to reduce the number of stops needed. Out of the 18 stops, 14 are used in the base case. In the reallocation scenario, a number of these have been merged without introducing conflicts (if the vehicles would arrive and depart according to the planned times). This results in only 9 stops being used. The reduction in the number of stops is expected to worsen the situation, but this may not necessarily be the case since the departures per stop are still relatively few. The fraction of vehicles that experience no delay goes from 40% to 37%. The results for the other three metrics can be seen in table 5. As previously, averages of the results from individual iterations of the simulation with 95% confidence intervals are related to the base case. While there is a slight reduction in the fraction of vehicles experiencing no driving delay, the average driving delay is almost the same, and so is the average time spent at the terminal and the deviation from the timetable at departure. It can thus be concluded that this terminal is greatly over-dimensioned in relation to the amount of traffic at the terminal and could operate sufficiently with half the number of stops.

Table 5: Results for the reallocation of lines to stops scenario in the form of average values related to the base case with 95% confidence intervals

| Relative driving delay | Relative terminal time | Relative lateness |
|---|---|---|
| $1.17 \pm 0.13$ | $1.02 \pm 0.01$ | $1.04 \pm 0.09$ |

## 5 Conclusions

In this study, a terminal model has been developed. This model has a modular structure where modules of basic spatial sections of terminals can be combined into various terminal layouts. Detailed vehicle interactions are modelled, which allows the model to capture blockages and queues forming at a terminal. The model has been applied and tested in a numerical experiment. The results show that different scenarios can be tested and evaluated. One scenario could for instance conclude that a significant reduction in the number of stops had very little effect on the vehicles. This shows how the model could be utilized in planning processes of new terminals or redesign of existing ones.

Future work includes validation of the model using data for a more congested case terminal and more thorough case studies of both new terminals and exiting ones. The model can also be extended to include more types of stops, as well as other dwell time formulas and probability distributions for vehicle arrivals. There are several ways the model can be further developed, including introducing heterogeneous vehicle movements. Of interest is also to study how to plan the allocation of lines to stops at the terminal.

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