A Decision support tool for capacity designing of BRT stations using discrete-event simulation

by
Louise Engelbrecht

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Supervisor: Mr. James Bekker
Faculty of Engineering
Department of Industrial Engineering

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Declaration

By submitting this thesis/dissertation electronically, I declare that the entirety of the work contained therein is my own, original work, and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

December 2010

ABSTRACT

The purpose of this study is to investigate the capacity of a proposed bus rapid transit (BRT) station in Cape Town. A bus rapid transit system is a high-capacity public transportation system that carries passengers from one point to another, providing a service that is faster and more efficient than an ordinary bus line. The implementation of these systems is increasing rapidly worldwide, serving as a solution to decrease traffic congestion.

The *capacity* of the proposed bus station, known as the Thibault Station, is investigated in the study by developing a simulation model. The aim is to develop a *stochastic* simulation model, which represents the flow of passengers throughout the station so that the station capacity can be investigated. By developing a stochastic model as opposed to a deterministic model, elements of uncertainty can be included into the model, thereby representing a system that is closer to the real-life situation under investigation. The majority of BRT systems, as well as past studies undertaken on the Thibault Station, are designed using deterministic calculations.

The study commences by researching literature on BRT systems and focuses on the current methods used to calculate station capacity requirements. Thereafter, the concept of *simulation* is introduced. Simulation is the method chosen to model and evaluate the passenger and bus operations at the Thibault Station.

The study presents the methods used to build and verify the simulation model. This is done to familiarise the user with a number of aspects of the model. The model can then be used as a *tool* to investigate capacity parameters and alternative designs or scenarios. Using the results of these investigations, *decisions* can ultimately be made regarding the planning and design components of *any* bus rapid transit station given that the model is adapted.

Scenario results, as well as interpretations of performance measurements, are presented at the end of the study. The results can be used for more realistic design of BRT stations using stochastic modelling.

OPSOMMING

Die doel van die studie is om ondersoek in te stel na die kapasiteit van ‘n hoëspoed bus vervoer stelsel (BRT). Die ondersoek is gebaseer op ‘n voorgestelde bus stelsel vir Kaapstad. ‘n BRT-stelsel is ‘n hoë-kapasiteit publieke vervoerstelsel wat passasiers van een punt na ‘n ander vervoer, deur ‘n diens te verskaf wat vinniger en meer doeltreffend is as ‘n gewone bus stelsel. Die implementering van hierdie tipe stelsels neem wêreldwyd toe en dien as ‘n oplossing om verkeersopeenhopings te verminder.

Die spesifieke busstasie wat ondersoek word staan bekend as die Thibault Stasie van Kaapstad se BRT-stelsel. Die kapasiteit van die stasie word ondersoek deur middel van simulasiemodellering. Die doel is om ‘n stogastiese simulasiemodel wat die vloei van passasiers modelleer te ontwikkel ten einde die kapasiteit van die stasie te ondersoek. Deur ‘n stogastiese model in plaas van ‘n deterministiese model te gebruik, kan elemente van onsekerheid ingesluit word. Dit verteenwoordig dus ‘n stelsel wat nader aan die werklikheid is. Tans word meeste BRT-stelsels ontwerpe gebaseer op deterministiese berekeninge, asook historiese studies wat onderneem is oor die Thibault Stasie.

Die studie begin deur literatuur oor BRT-stelsels te bestudeer en fokus daarna op die huidige metodes wat gebruik word om die vereiste kapasiteit van ‘n busstasie te bepaal. Die konsep van *simulasie* word daarna voorgestel. Simulasie is die metode wat in die studie gebruik word om die passasier- en busaktiwiteite van die Thibault Stasie te modelleer en te evalueer.

Die studie verskaf die metodes wat gebruik word vir die ontwikkeling en geldigmaak van die simulasiemodel. Gebruikers word op dié manier blootgestel aan die verskillende aspekte van die model. Nadat die gebruikers vertroud is met sekere aspekte van die model, word die model verder uiteengesit en word daar verduidelik hoe dit as ‘n instrument om kapasiteit parameters en alternatiewe ontwerpe van busstasies te ondersoek kan dien. Die resultate van die model kan gebruik word om beplannings- en ontwerpbesluite van enige busstasie te neem.

Aan die einde van die studie word scenarioresultate bekendgestel, asook die interpretasie daarvan. Die resultate kan gebruik word vir meer realistiese ontwerp van BRT-stasies met behulp van stogastiese simulasie modellering.

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1) INTRODUCTION

Traffic congestion has increased dramatically over the past two decades, and has become a threat to many developing countries' economy as well as the quality of life of its citizens. Traffic congestion is defined as a condition on networks that occurs as *use* increases, and is characterised by slower travelling speeds, longer trip times, and increased queuing. It occurs on roads when *traffic demand* is greater than the *capacity* of a road (AHD, 2003, u.w. 'traffic congestion'). In 2003, the Texas Transportation Institute recorded that congestion in the top 85 US urban areas caused $3.7 billion worth of travel delay and 2.3 billion gallons worth of wasted fuel. Internationally, countries are searching for ways to decrease congestion on roads.

This has led to the constant development of new technology, and different congestion-management strategies are developed and tested worldwide. Some include high- occupancy vehicle (HOV) lanes, congestion pricing, carpooling, vanpooling, ridesharing, bikeways, transit lanes and modes of public transport, a prevalent congestion-relieving alternative. Public transport in which cities could invest include metro rail, light rapid transit (LRT), monorail, suburban rail, standard bus systems and BRT systems.

Internationally, cities have realised that additional freeway and road capacity is quickly consumed by latent demand for travel, resulting in the reoccurrence of congestion shortly after the capacity upgrade (Vanderschuren *et al.*, 2008). This leads to the promotion of alternative high-occupancy modes of transport. As mentioned above, the dominant alternative is public transport, which is aimed at providing transport to people while reducing the number of vehicles on the road. Figure 1.1 shows the equivalent space requirements to transport the same number of people using public transport instead of privately owned vehicles.

A way of reducing congestion on roads in the future, while maintaining a focus on high-occupancy modes and curbing car use, is by introducing a relatively new transportation alternative, namely the bus rapid transit (BRT) system. BRT is a term applied to a variety of public transportation systems that use buses to provide a service that is of a higher speed than an ordinary bus line. The benefits of this system are numerous, one of which is the reduction of carbon emissions into the air (Frieslaar & Jones, 2006). Currently, there is a global drive towards finding greener, smarter and traffic-free transportation solutions.

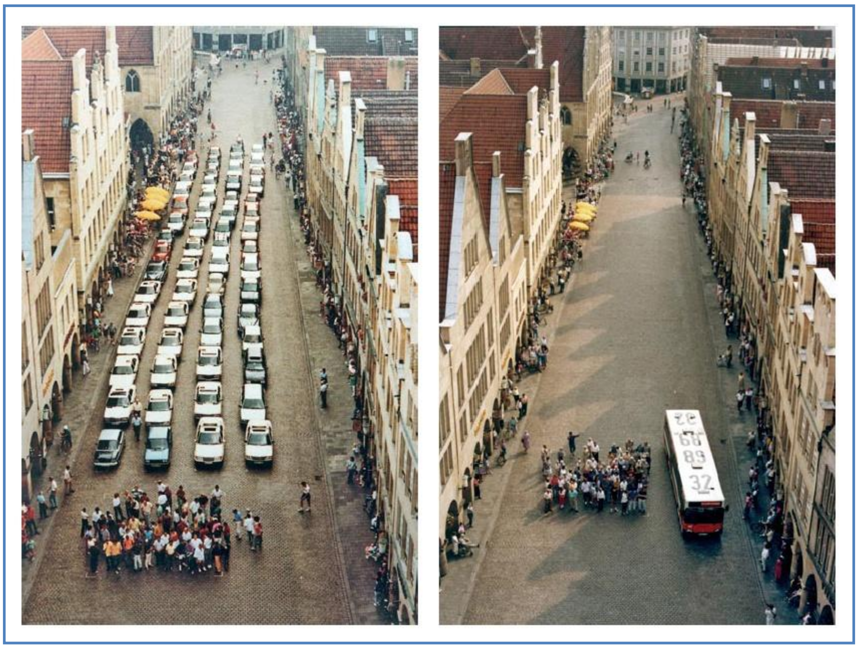

Figure 1.1 The space required to move an equivalent number of people by private vehicles compared to public transport (bus) (Litman *et al.*, 2007)

1.1) BACKGROUND

Cape Town is an area of high economic activity and growth. Considering the case of developing and expanding the Port of Cape Town to international levels, with the aim of serving as a possible oil and gas industry off the West Coast of Africa, international freight rail and road-based routes standards are necessary. For the port to be internationally viable, road access from the N1 Corridor is extremely important. The N1 Corridor leading to and from Cape Town is currently experiencing high levels of congestion during peak-hour travel periods and an underutilised road capacity, as 70% of the vehicles have single occupants (Frieslaar & Jones, 2006).

Recent studies performed by HHO Africa show that the N1 carries very high levels of traffic, which range from 95 000 to 120 000 vehicles per day. Further studies show that peak-period traffic flows are increasing at a rate of approximately 2.5% per annum. Moreover, inbound daily flows are increasing at a rate of 3.5%, whereas outbound flows are increasing at 5% per annum. These figures will continue to rise. Another major impact on traffic conditions could also include the potential developments along the N1 Corridor, which are estimated to have a capacity of an additional 30 000 people and provide 50 000 jobs (Frieslaar & Jones, 2006). Currently, the N1 Corridor is poorly served by public transportation. This need led to the development of a BRT system, which will be implemented in the future, to serve as a rapid mode of transportation in, from, and to Cape Town, thereby relieving congestion in the N1 Corridor.

This study focuses on the BRT public transportation alternative. The future Cape Town BRT system will be used as a case study on which investigations will be based.

1.2) Research problem

For a BRT system to operate efficiently, optimal throughput of passengers needs to be reached. Factors that affect the speed and ease at which passengers travel throughout the system includes rapid and efficient bus operations, facilities, the physical layout of stations as well as bus designs.

Capacity and system sizing requirements for estimated demand are currently calculated using simple deterministic equations. These are used and accepted worldwide. Figures (fixed parameter values) derived from these equations are then used to model the entire BRT system to investigate the *flow* of buses throughout the system. Bottlenecks are identified at stations as well as other areas of improvements.

Since models are mainly used to investigate the *flow* of buses throughout the *entire system*, a need exists to investigate the effects of these fixed parameters on the *capacity* of a *single bus station*. Because these parameters are predetermined, fixed figures, they ignore any randomness in modelling the operations of a bus station, which is unrealistic. It is, therefore, necessary to investigate what effect these parameters will have on the capacity of a single bus station when bringing in elements of randomness, uncertainty or change. This could be done through stochastic modelling. Stochastic modelling includes the use of random inputs into the model, which results in a random output. An example of a random input would include the number of passengers entering the station at any time of the day. This time-dependant event can be studied using a specific probability distribution to determine the number of passengers in the station at any time of the day.

1.3) RESEARCH OBJECTIVES

The following objectives are set for this study:

- **Model** the passenger flow processes of the Thibault Station using deterministic values provided by Pendulum Consulting, a consulting dealing with the development of the BRT system for Cape Town
- **Predict** performance of the Thibault Station using stochastic elements and identify opportunities for improvement
- **Analyse** capacity parameters by evaluating different scenarios. This includes variations of capacity parameters, as well as testing the stations' capacity by altering physical design parameters, station configurations etc.
- **Report findings and conclusions** on the capacity of the Thibault Station.

1.4) OVERVIEW OF CHAPTERS

Information on public transportation is addressed in Chapter 2 to provide the reader with the appropriate background of transportation. In Chapter 3, BRT systems are described and the characteristics of BRT stations – such as station design elements, configurations and operation – are explained. Chapter 4 follows with a discussion of BRT capacity issues and the calculations used for determining the capacity of a BRT station. Chapter 5 concludes the literature study by presenting information on *simulation*, which is the method used to model the BRT station. After the literature review, the objectives of the problem to be investigated in this study are presented in Chapter 6. This is followed with the concept model, which is described and illustrated in Chapter 7. In Chapter 8, the development of the simulation model is explained, after which the base simulation model is presented. Important issues regarding the understanding and use of the model are explained. The simulation model is verified and validated in Chapter 9 and Chapter 10 introduces the stochastic models, which are adaptions of the model presented in Chapter 8. Scenarios are then constructed from these models and are explained in the chapter. Results and analysis of the various models are presented in Chapter 11 and the study concludes by addressing aspects of management related to the study.

2) Aspects of Public Transport

This chapter provides general information on public transport, with the aim of placing BRT systems within the framework of modes of public transport. It concludes with a brief section on the history of BRT systems.

2.1) Background on public transport

Public transport is essential to providing citizens with effective access to goods and services across, for example, cities. Modes of public transport include metro rail, light rapid transit (LRT), monorail, suburban rail, standard bus systems and taxis. The basic requirement and primary objective of any mass rapid-transit system is to move large numbers of passengers. Passenger capacity is therefore a key area of concern and is affected by several factors, which differ from other modes of public transport.

Some of the factors that affect passenger capacity include:

- Size of the vehicle
- Number of vehicles that can be grouped together
- Headway between vehicles (amount of time that elapses between vehicles to allow safe operation)
- Availability of limited stop or express services
- Boarding and alighting techniques.

The most prevalent determinants in public transport decision-making have always been passenger capacity and infrastructure costs. In the past, there were fairly strict technology capacity limitations and this meant that buses, LRT and metro could only operate in narrowly defined circumstances. It was previously thought that bus services could only operate in a range up to 5 000 – 6 000 passengers per hour per day (pphpd), where LRT could cover approximately 12 000 pphpd. Any figures above these numbers would require metro or elevated rail systems (Litman, Hook & Wright, 2007).

However, this traditional view has shifted. With the first BRT system implemented in Bogota, which can now reach a peak-hour capacity of 45 000 pphpd, a new opinion has been created. A BRT system is defined as a high-quality bus-based, transit system that delivers fast, comfortable and cost-effective mobility through the provision of segregated, right-of-way infrastructure, rapid and frequent operations, and excellence in marketing and customer service (Litman, Hook & Wright, 2007).

The effect that new technology has on the operating ranges of public transport is extremely large and the difference between the traditional views, compared with the new technologically driven views, can be seen in Figure 2.1.

The recently implemented BRT systems have the potential to serve as an effective mode of urban transport and have already proven to be one of the world's most cost-effective public transport systems. This is owing to the rapid development of such systems as well as the rapid and high-quality service.

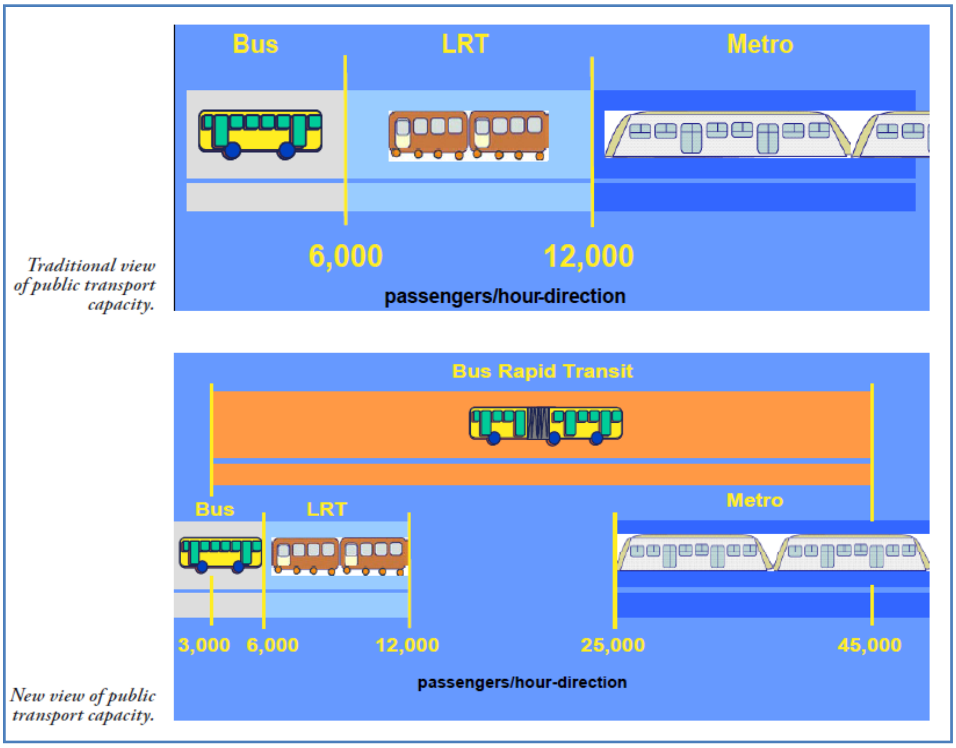

Figure 2.1 Views on transport capacity (Litman *et al., 2007)*

2.2) BRT HISTORY

One of the first and best implemented BRT systems in the world is in Curitiba, Brazil. It was implemented in 1974 and features the following characteristics (Hook, 2009):

- Physically segregated, exclusive bus lanes
- Large, comfortable articulated or bi-articulated buses

- Fully enclosed bus stops that feel like a metro station, where passengers pay to enter the BRT station through a turnstile rather than paying the bus driver
- A bus station platform level with the bus floor
- Free and convenient transfer between lines at enclosed transfer stations
- Bus priority at intersections, largely by restricting left-hand turns by mixed-traffic vehicles
- Private bus operators paid by the bus kilometre.

There are different kinds of BRT systems. A fully featured BRT system, as in Curitiba, is known as a 'trunk-and-feeder' system. A trunk-and-feeder system requires passengers to take a feeder bus (which operates in mixed traffic) to a transfer terminal where they switch to a special, higher-capacity, articulated trunk-line bus that interfaces with the elevated BRT platforms (Hook, 2009). A potential problem with this system is the bottleneck that forms at the bus station. During rush hour, buses line up back to back, waiting to discharge passengers.

In 2000, this system was improved and a second phase of BRT systems was implemented in Bogota. The bottlenecks were addressed and improved by introducing a passing lane and multiple stopping bays at each station. A passing lane is only required at a bus station. This allowed up to five buses to stop at the station at the same time, while being able to alight and pickup new passengers regardless of whether or not a bus is in front of it.

Between 2001 and 2009, more than 15 fully featured BRT systems were built across the world. Other systems, for example in Sao Paulo and Porto Alegre, use normal buses and operate in mixed traffic. The disadvantage is that the interface with the bus station platform lacks special BRT characteristics, which allow fast boarding and alighting of passengers. This results in frequent bottlenecks and lower capacity of stations.

Future BRT systems will be a mixture of trunk-and-feeder systems combined with traditional direct service busways. Examples of such systems, which are currently under construction, are in China, as well as the Rea Vaya BRT system being built in Johannesburg. When comparing these two BRT systems, there are many differences in the designs of buses, roads, platforms or stations, as well as the methods of purchasing tickets and the way passengers board and disembark from the buses.

Systems in the United States most closely resemble the BRT systems in Latin America. These systems have prepaid boarding tickets, which decrease the boarding and disembarkation times and thus result in a significant decrease in overall travel time. Travel time refers to the time it takes a passenger to board a bus and travel to the destination - including the time it takes the passenger to disembark the bus.

It is apparent that there is a need to increase the efficiency of architectural platform designs or stations, as well as passenger access facilities (i.e. turnstiles). System designs change each year to increase the speed of the systems. As this is a continuous process, a need exists to look into the factors that could affect the travel time in BRT systems. Factors to consider include, for example, different station designs, bus designs, methods of purchasing tickets, entering and disembarkation of the buses and services offered.

Although there are other public transport options available – such as metro rail, light rapid transit (LRT), monorail, suburban rail and standard bus systems – the rise in bus rapid-transit systems is mostly related to the cost-effectiveness of this mode of transport and the fact that a BRT system infrastructure is flexible and scalable. BRT systems can therefore be built and expanded cost-effectively according to the city's conditions.

To conclude this chapter, a picture of the evolution of bus services is shown in Figure 2.2. This picture clearly shows how BRT systems developed, as well as some unique features of BRT systems.

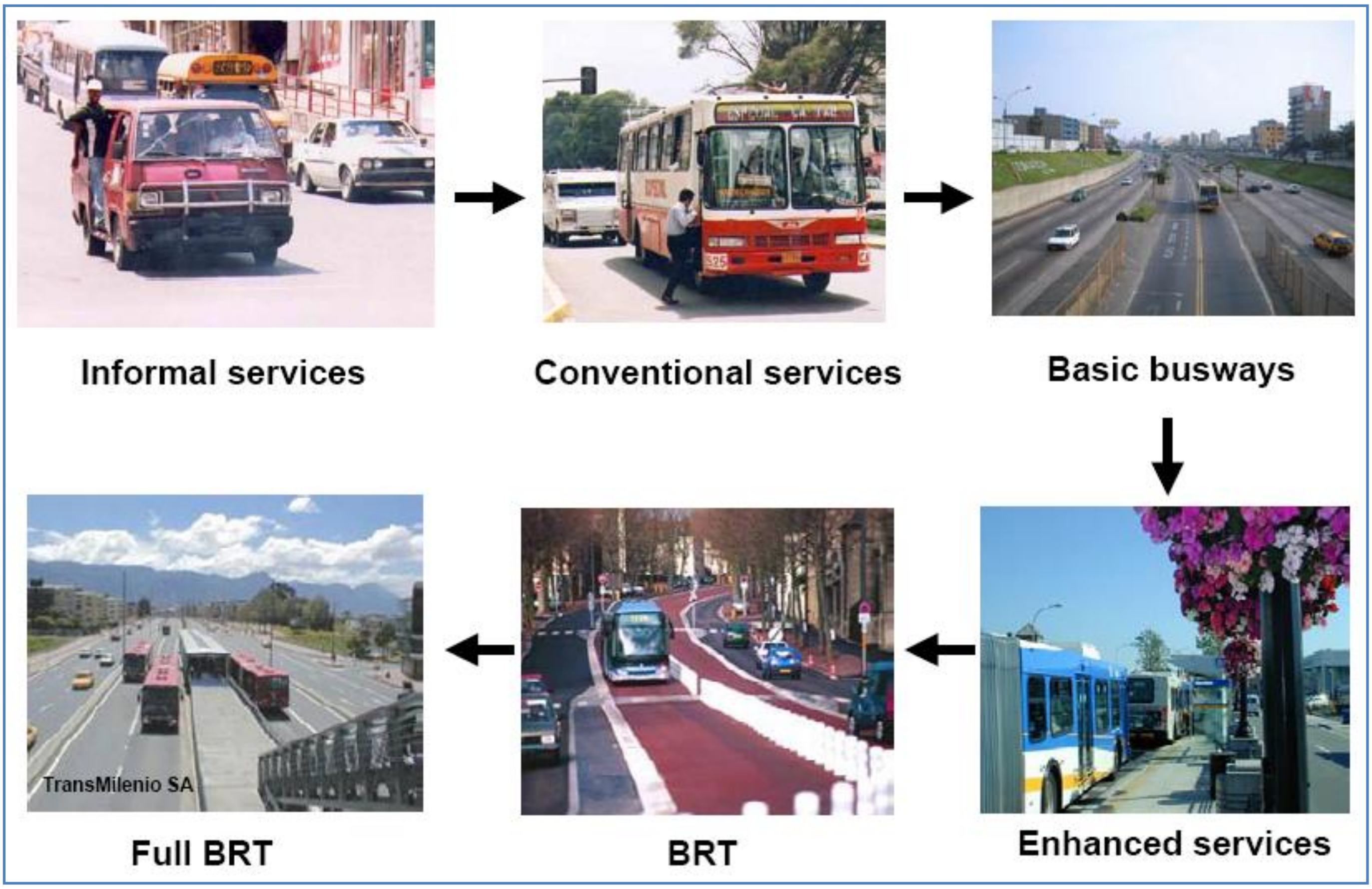

Figure 2.2 Bus system evolution (Litman *et al.,* 2007)

2.3) SUMMARY: CHAPTER 2

This chapter dealt with public transportation and puts BRT systems into context within public transportation modes. The main objective of any public transportation mode is to move large numbers of passengers quickly and affordably. This is the most effective way of providing citizens with access to goods and services across cities and towns. The key determinant regarding any choice of public transportation mode includes the infrastructure cost, operating cost as well as the passenger capacity. In the evolution of public transportation modes, passenger capacity has been increased, as well as the speed of services. This is due to the new technologically driven society who enabled the development of these new rapid and efficient ways of transportation, such as BRT systems. The chapter ends with history of BRT systems and shows how BRT systems have developed since the first implemented system in Curitiba during 1974. More detailed information regarding concepts and the operation of BRT systems are explained in Chapter 3.

3) THE BRT SYSTEM

This chapter addresses important literature on BRT systems; not only for the purpose of understanding the system better, but also to indicate the areas in a BRT system that affects system capacity. Because the *capacity* of a BRT station is the main area of investigation in this study, BRT stations, facilities and BRT vehicles will be concentrated on.

3.1) BRT STATIONS AND FACILITIES

Stations are a key element to providing efficient capacity along a BRT line and are therefore discussed in this section. BRT stations form an important link between the customers and the BRT system. Stations also form the identity of BRT systems, which is communicated through visual features and physical facilities that the system provides. These distinguish BRT systems from other public transportation services and make BRT a premium service.

BRT stations generally serve more high-demand corridors where more customers per station can be expected. Stations must provide comfort, amenities, safety and reliability. Important primary characteristics of BRT stations regarding the study area include the following points:

3.1.1) PLATFORM LAYOUT

The size and layout of BRT stations have a great impact on the capacity and efficiency of the system. In many cases, station platforms are the biggest constraint because of the size and design requirements. This can ultimately result in the platform size (being able only to hold a certain number of passengers) dictating the passenger volumes of the system. Station-sizing aspects are mostly dependant on the peak-hour passenger volumes estimated for that station, as well as the frequency of buses that need to be accommodated for at the station.

Station designs are taken from Litman *et al.* (2007). In the past, station configuration has taken one of two different designs. The first is a *median station*, which serves both directions of BRT lanes. The schematic layout can be seen in Figure 3.1. The second station design is called a *staggered station* and the layout can be seen in Figure 3.2. The figures show the relative space requirements for each of these station designs. The staggered station saves a marginal amount of space (in terms of width) since each station only has to accommodate approximately half the amount of passengers travelling in a single direction.

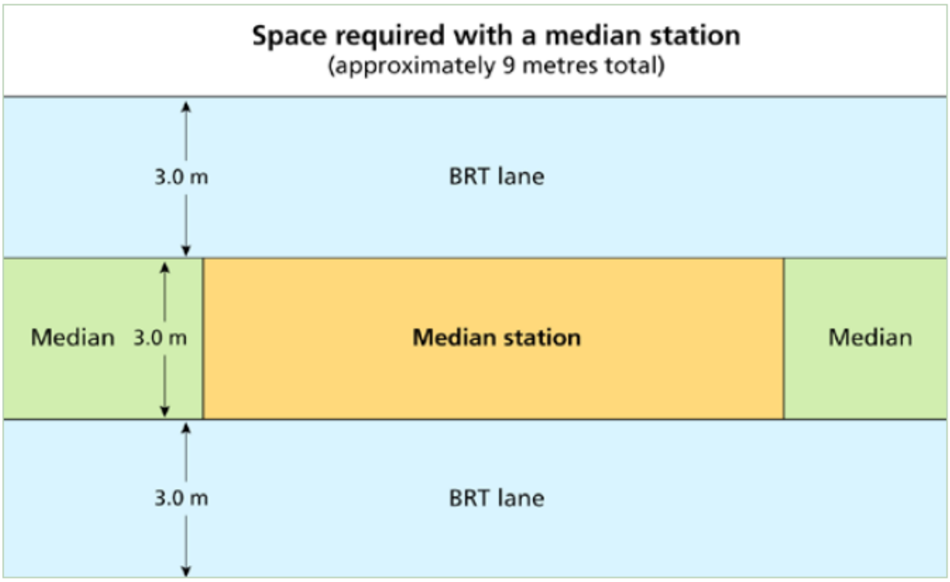

Figure 3.1 Width requirement of a median station (Litman *et al.*, 2007)

A single station in the median is more customer friendly and convenient, as passengers only need to walk over the platform to change direction, while staggered stations require complicated infrastructure to link the two stations. This often leads to increased costs and therefore the gain in decreased width is mostly not seen as a significant benefit in comparison to the operational disadvantages associated with staggered stations.

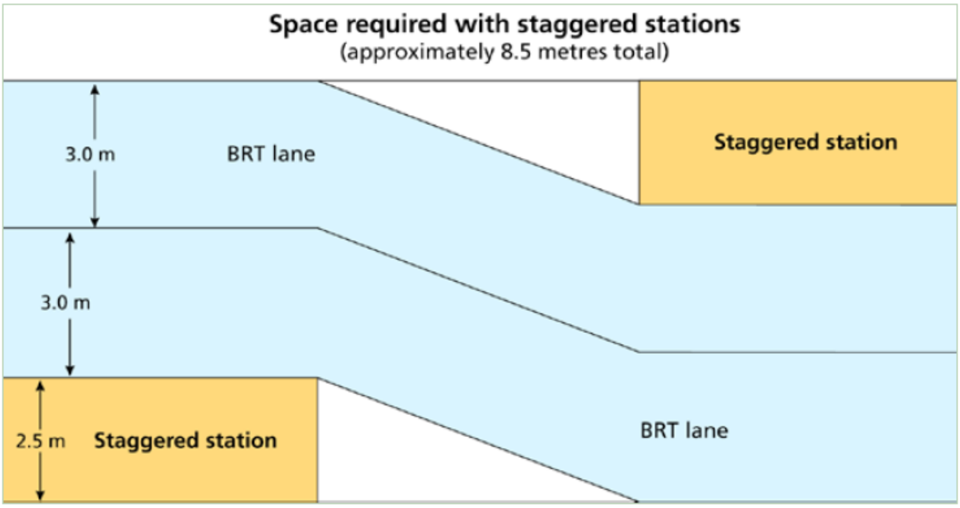

Figure 3.2 Width requirement of a staggered station (Litman *et al.*, 2007)

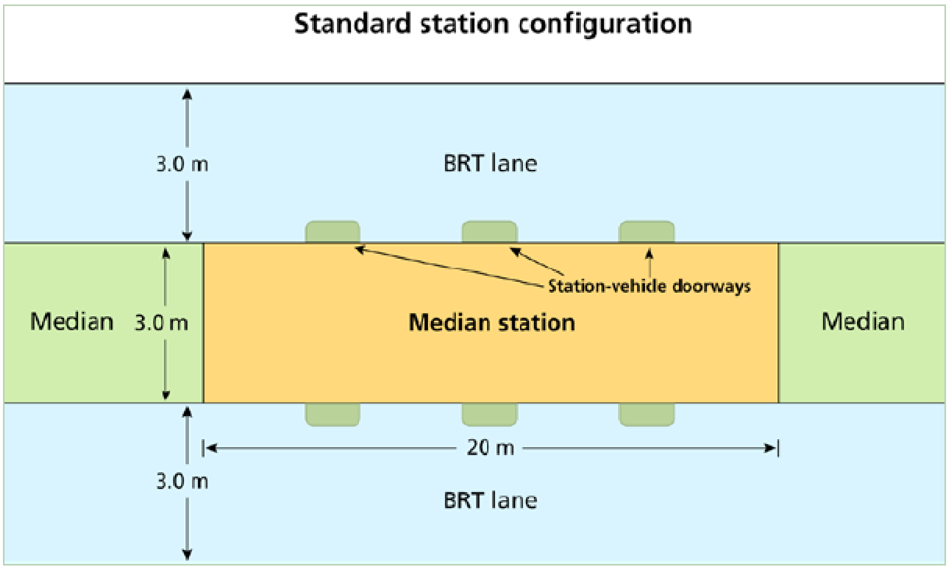

Figure 3.3 Standard station configuration (Litman *et al.*, 2007)

The standard station configuration is a median station, which can be seen in Figure 3.3. If two buses stop simultaneously at a median station at peak hour with their doors opposite each other, the station load will be worsened. In this case, the station width must be increased to meet capacity demand. An alternative elongated station configuration exists, which offsets the placement of the buses' doors in each direction and therefore this configuration requires less station width. The elongated station configuration is shown in Figure 3.4. Specific calculation of platform width and length is addressed in Chapter 4.

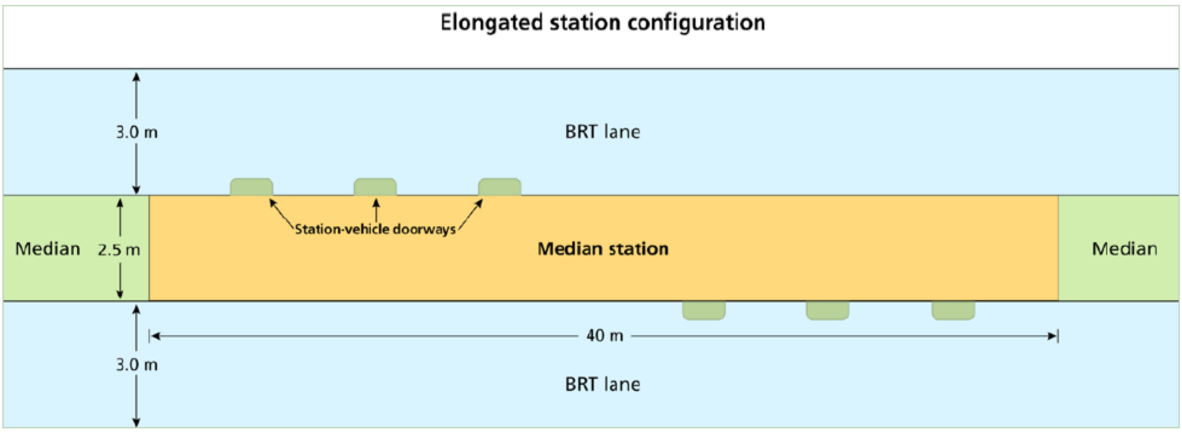

Figure 3.4 Elongated station configuration (Litman *et al.*, 2007)

3.1.2) PASSING CAPABILITY

Passing capability refers to lane configuration changes from a single lane to two lanes. The additional passing lane and extra space at a station allows express services (buses that do not stop at the station) to pass through, as well as for additional parking bays (buses can move in and out of a parking bay while there is another bus parked in front or behind it).

The passing capability and manoeuvrability of buses in a station has a great impact on the efficiency of a station. More information on this matter is provided in Section 4.6 and 4.7 of Chapter 4.

3.1.3) FARE-COLLECTION METHODS

'Fare collection' is the process of customer payment for the trip while 'fare verification' is the process of checking if the customer has actually paid for their intended (or completed) trip (Litman *et al.*, 2007).

The method of fare collection and fare verification has a great impact on the operational efficiency of BRT systems and is normally based on specific demand elements of BRT systems. There are two types of fare collection methods, namely 'on-board fare collection' and 'off-board (pre-payment) fare collection' (Litman *et al.*, 2007).

On-board fare collection could be an option when operating costs need to be minimised, especially at certain times of the day or at stations where there are low passenger volumes. Off-board collection may be used at large boarding points especially at peak hours where the system will then reduce the passenger service times, station times, station dwell times as well as bus travel times.

Europe often has 'proof-of-payment' techniques for fare verification, which is also known as the 'honour' system. Occasional checks are done by public transport staff, and if a passenger cannot show a proof of payment, the passenger is charged with a fine. Turnstile techniques are a more common method of fare verification. A turnstile is a mechanical device used to control the entry of passengers from one public area to another, usually permitting the passage of an individual once a fee has been paid (AHD, 2009, u.w. 'turnstile').

Off-board fare collection and fare verification reduces the station dwell times, which in turn increases the overall efficiency of the system. This does, however, require a segregated environment between the paid (inside the station) and unpaid (outside the station) customers.

3.2) BRT VEHICLES

The vehicles form the second factor that affects capacity. BRT vehicles have a direct impact on speed, capacity, environmental friendliness, and comfort, both actual and perceived (Hinebaugh & Diaz, 2009). These are an element of the system in which customers spend most of their time and consequently, most of the public impression of BRT systems comes from the vehicles. Important primary characteristics of BRT vehicles concerning this study area are discussed below:

3.2.1) BRT VEHICLE CONFIGURATION

The physical configuration of BRT vehicles primarily concerns the size, floor height and body type. The sizes of the BRT vehicles are discussed in the next chapter. Floor heights of the vehicles could either be low or high from the ground. High-floor vehicles, in conjunction with platform-level boarding, has proven to reduce dwell times and offer easier boarding and alighting access for physically disabled passengers. Lastly, the body types of the vehicles depend mainly on the capacity requirements of the system and are therefore discussed in the next chapter.

3.2.2) PASSENGER-CIRCULATION ENHANCEMENT

A considerable amount of enhancement could be done to vehicles in order to accelerate the movement of passengers from boarding and disembarking the vehicles as well as the movement inside the vehicles. This could include the use of wider doors, different seating and standing arrangements, design alterations, etc.

3.3) THE THIBAULT STATION FACILITY DESIGNS

Having discussed the BRT station capacity factors in general, the specifics of the Thibault Station will now be presented.

The characteristics of the proposed service at the trunk stations, of which the Thibault Station is one, are:

- High floor (940 mm)
- High-capacity 18 m articulated buses
- Level access between station platform and bus
- Ramped access to the station.

Figure 3.5 illustrates the proposed design of the trunk stations for the Cape Town BRT system. It shows that the station will be closed and located in the median. The platforms are raised to facilitate the ease and access of level boarding onto the high floor articulated buses. A ticket booth and fare verification facilities are provided at the entrance of the station to ensure easy access to ticket sales and pre-board fare collection.

Figure 3.5 The proposed station design for trunk stations (Tofie, 2010)

The renderings of the trunk station designs are shown in Figure 3.6.

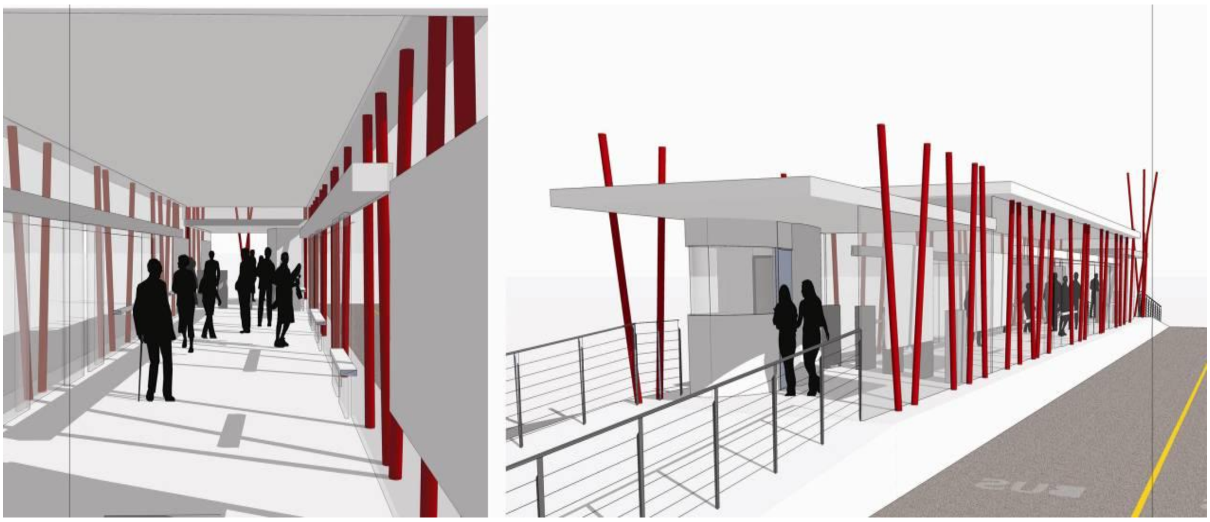

Figure 3.6 Renderings of the trunk station designs (Tofie, 2010)

Figure 3.7 shows the off board method of fare verification with contact-less smartcards.

Figure 3.7 Offboard fare collection method (Tofie, 2010)

There are two types of trunk vehicles operating from the Thibault station. The 18 m articulated bus has a typical interior layout as shown is Figure 3.8, whereas the 12 m airport bus has a typical layout as shown in Figure 3.9.

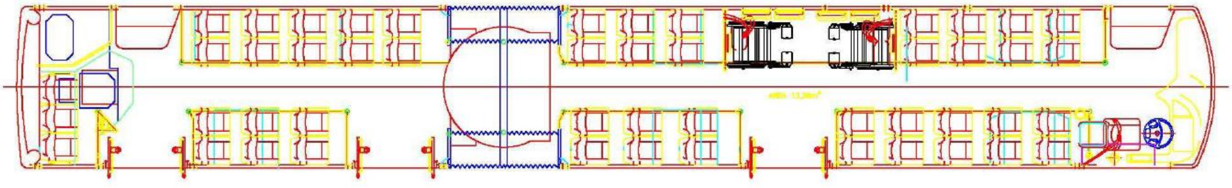

Figure 3.8 Interior layout of the 18 m trunk vehicle (Tofie, 2010)

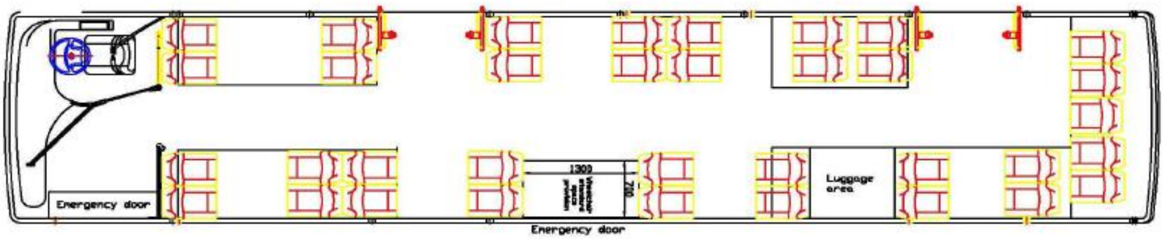

Figure 3.9 Interior layout of the 12 m airport vehicle (Tofie, 2010)

An overview of the trunk vehicle specification is shown Table 3.1.

Vehicle Type	18 m articulated	12 m airport trunk
Dimensions	Length: 17.5 - 18.7 m	11.5 - 12.7 m
	Width: 2.5 - 2.6 m	2.5 - 2.6 m
Floor height	940 mm (+/- 25 mm)	940 mm (+/- 25 mm)
Number of doors	3 right sided doors	2 right sided doors
Wheelchair positions	2	1
Capacity	120	40

Table 3.1 Vehicle specifications (Tofie, 2010)

3.3) SUMMARY: CHAPTER 3

Chapter 3 provides the reader with essential information on how BRT systems work as well as the important aspects which define the capacity of a system. It covers information on the main characteristics of BRT systems – such as BRT stations, facilities and vehicles. These characteristics are also key determinants of the capacity of BRT systems. Station platform layouts, passing capability of vehicles, and fare collection methods are all elements of a BRT system which affect the capacity at which a system runs. Different station platform designs were discussed and illustrated to give a better understanding of the flow of vehicles at a BRT station. Another characteristic of BRT systems is the types of vehicles used, and factors such as vehicle configuration and passenger circulation were discussed. The specific system designs of the Thibault station were presented at the end of the chapter.

All the above characteristics have great effects on the overall capacity, speed and frequency of BRT systems. The components and factors which determine the capacity of a system, are discussed in Chapter 4.

4) VEHICLE AND PASSENGER CAPACITIES

The purpose of this chapter is to address the elements of a station which affects the capacity of a bus station, and to show the equations used to determine and evaluate the capacity of a BRT system. This chapter commences by providing the reader with an overview of the procedures used to estimate the capacity of pedestrian circulation. This is based on a relative scale of pedestrian comfort and convenience. The chapter continuous by presenting the calculations used to determine and evaluate the capacity of BRT systems.

4.1) OVERVIEW OF PASSENGER CIRCULATION

The *Transit Capacity and Quality Manual* (Kittelson, 2003) presents procedures used for estimating the capacity of various elements of transit terminals. These are principles of transportation which are used as a basis for planning and analysing most transit systems. An overview on the manual's procedures for estimating the capacity of passenger circulation on walkways and queuing areas at platforms are subsequently provided.

Research has shown that a breakdown in pedestrian flow occurs when dense crowds of pedestrians form, causing limited and uncomfortable movement. Therefore, procedures were introduced which are based on maintaining desirable pedestrian levels of service (LOS), and are addressed in this section. Procedures for evaluating pedestrian capacity and level of services (LOS) are provided in Fruin's *Pedestrian Planning and Design* (1971).

An important objective when designing a pedestrian facility, is to provide adequate space to accommodate peak-hour demand estimates, while ensuring pedestrian safety. The method used to achieve this, is to design a station according to a certain LOS. The levels of service for walkways and queuing areas are discussed, since these are relevant to the study area. Pedestrian traffic can also be evaluated qualitatively, by using LOS concepts similar to vehicular traffic analysis. Relationships between pedestrian flow measures, such as speed, space and delay are contained in the *Highway Capacity Manual* (Transportation Research Board, 2000).

The capacity of walkways is controlled by the following factors (Kittelson, 2003):

- Pedestrian walking speed

- Pedestrian traffic density
- Pedestrian characteristics
- Effective width of the walkway at its narrowest point.

Figure 4.1 shows the relationship between the pedestrian flow rate and the average pedestrian space on an effective walkway (Kittelson, 2003). Three curves are shown, each representing a different type of pedestrian flow. It shows that the maximum flow rate of pedestrians allow an average space of 0.5 m^2 for each person. The figure represents the maximum throughput, which is under extreme conditions during peak-hours. It is necessary to use the LOS analysis approach to design a facility, to include the needs of impaired persons and safety conditions to ensure comfort and convenience to all pedestrians. The Kittelson (2003) provides LOS criterion for pedestrian flow, which is based on subjective measures, which can be imprecise and differ between populations. However, the ranges of walking speed, space and flow rates can be re-defined by using the qualitative relationships in the *Highway Capacity Manual* (Transportation Research Board, 2000), which can be used to develop new criteria.

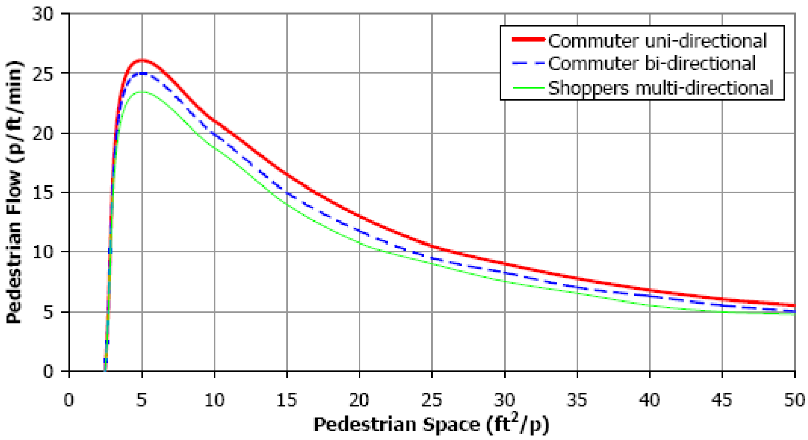

Figure 4.1 Pedestrian flow rates vs. pedestrian space (Kittelson, 2003)

Figure 4.2 lists the criteria for pedestrian level of service for walkways in transit facilities. The levels of service are based on the average pedestrian space and the flow rates. An additional criterion has been provided, which shows the average speed and volume-to-capacity ratios. The maximum flow rate presented in Figure 4.1 corresponds to LOS ‘E’ in Figure 4.2. Illustrations and descriptions for the different LOS for walkways are displayed in Figure 4.3 (Kittelson, 2003*)*.

LOS	Pedestrian Space (ft²/p)	Expected Flows and Speeds: Avg. Speed, *S* (ft/min)	Flow per Unit Width, *v* (p/ft/min)	*v/c*
A	≥ 35	260	0-7	0.0-0.3
B	25-35	250	7-10	0.3-0.4
C	15-25	240	10-15	0.4-0.6
D	10-15	225	15-20	0.6-0.8
E	5-10	150	20-25	0.8-1.0
F	< 5	< 150	*Variable*	*Variable*

LOS	Pedestrian Space (m²/p)	Expected Flows and Speeds: Avg. Speed, *S* (m/min)	Flow per Unit Width, *v* (p/m/min)	*v/c*
A	≥ 3.3	79	0-23	0.0-0.3
B	2.3-3.3	76	23-33	0.3-0.4
C	1.4-2.3	73	33-49	0.4-0.6
D	0.9-1.4	69	49-66	0.6-0.8
E	0.5-0.9	46	66-82	0.8-1.0
F	< 0.5	< 46	*Variable*	*Variable*

v/c = volume-to-capacity ratio

Figure 4.2 Pedestrian level of service on walkways (Kittelson, 2003)

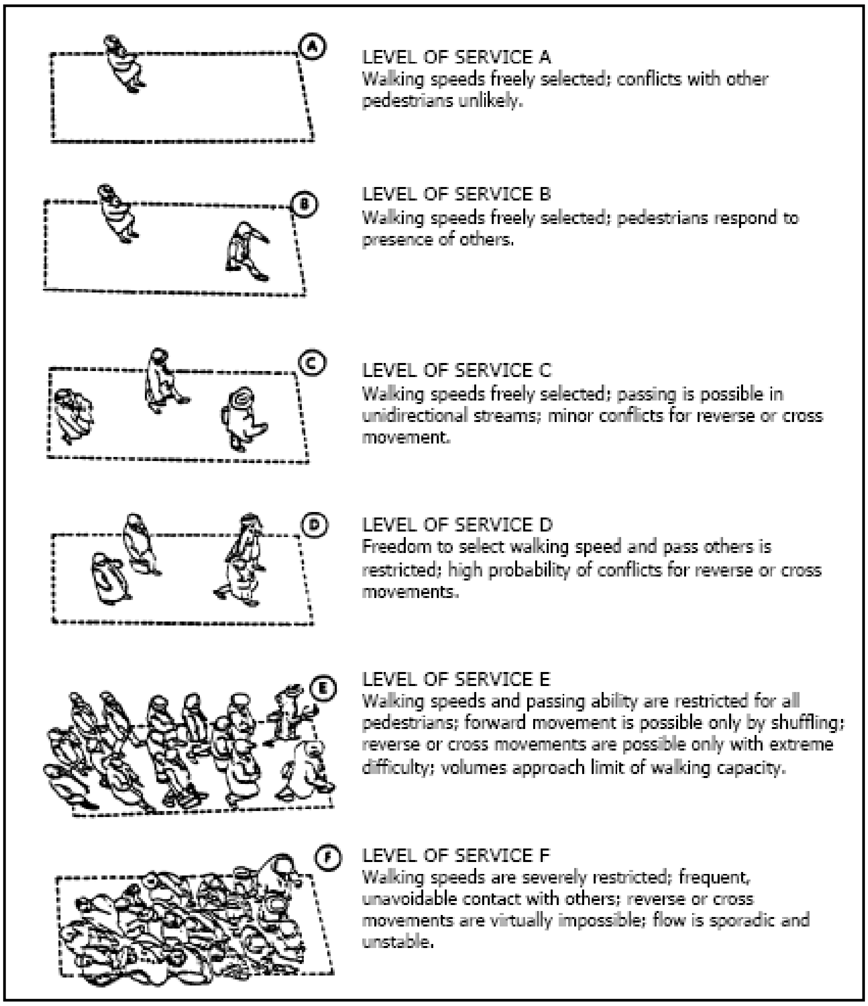

Figure 4.3 Illustration of walkway levels of service (Kittelson, 2003)

For queuing areas, the primary measure for defining LOS is the average space available to each pedestrian. The LOS thresholds for queuing areas are listed in Figure 4.4 (Kittelson, 2003). These areas are based on the average standing space per person and the perceived levels of comfort, which is presented by the inter-person spacing (distance between people). The LOS is a function of the amount of time a pedestrian waits in the queue, the number of people waiting as well as the conditions of comfort. In general, the longer pedestrians wait the greater space they will require.

	Average Pedestrian Area		Average Inter-Person Spacing	
LOS	(ft^2/p)	(m^2/p)	(ft)	(m)
A	≥ 13	≥ 1.2	≥ 4.0	≥ 1.2
B	10-13	0.9-1.2	3.5-4.0	1.1-1.2
C	7-10	0.7-0.9	3.0-3.5	0.9-1.1
D	3-7	0.3-0.7	2.0-3.0	0.6-0.9
E	2-3	0.2-0.3	<2.0	<0.6
F	< 2	< 0.2	*Variable*	*Variable*

Figure 4.4 Pedestrian level of service for queuing areas (Kittelson, 2003)

Subsequently, the LOS illustrations and explanations for queuing areas (with standing passengers) are provided in Figure 4.5 (Kittelson, 2003). LOS E category queuing areas are encountered in most crowded spaces, where as category A allows passengers to move around freely without disturbing others.

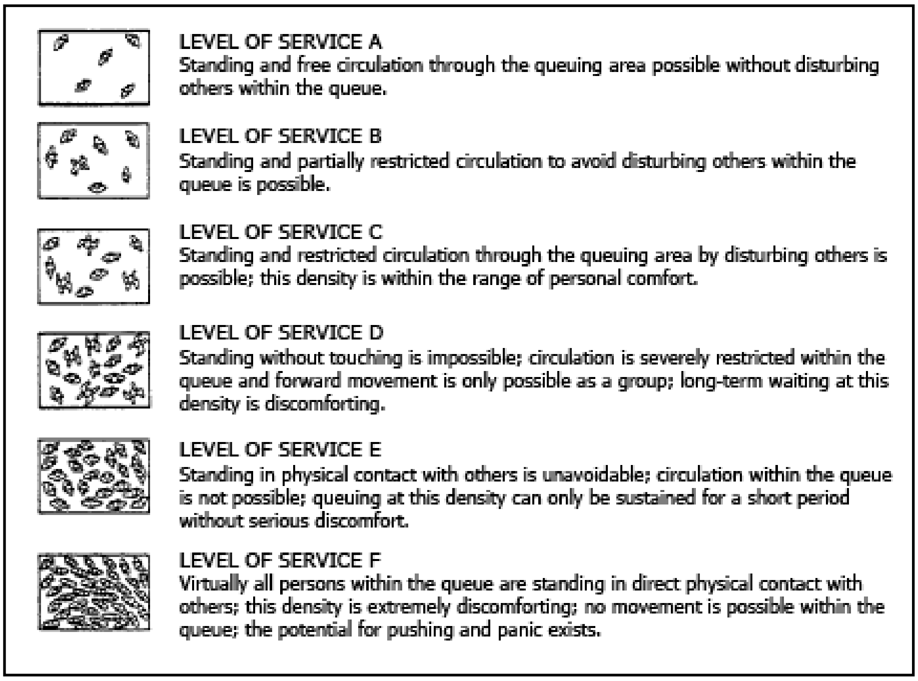

Figure 4.5 Illustration of queuing area level of service (Kittelson, 2003)

The calculations used to determine and evaluate the capacity of a BRT system, are presented from Section 4.2 onwards. These are obtained from the *Bus rapid transit planning guide* (Litman *et al.*, 2007) and are used to plan and evaluate the majority of BRT systems currently implemented.

4.2) CAPACITY ELEMENTS OF BRT SYSTEMS

Capacity, speed and high-frequency buses are the principal features of BRT systems. Stations need to be designed to handle high volumes of passengers comfortably as well as provide for the correct frequency of services. This chapter, therefore, addresses *decisions* affecting the following basic parameters (Litman *et al.*, 2007):

1) Sufficient system *capacity* to handle expected passenger demand
2) Service *speeds* that minimise travel times
3) *Frequency* of service to minimise waiting times.

A system, which is designed to achieve a certain level of capacity and speed, is built on many interdependent design components. Components of *customer* and *vehicle* flows ultimately determine the capacity and speed performance of a BRT system. The building blocks of these components are defined by the terms presented subsequently. Thereafter the formulas are shown of how a corridor's capacity requirements are calculated and the impact certain factors have on the outcome of a corridor's capacity. A corridor is broadly defined as geographical area that accommodates travel or potential travel. It is normally considered to be a 'travel shed', where trips tend to come together in a linear pattern (*Guidebook for transportation corridor studies*, 1999).

4.3) DEFINING BRT COMPONENT BUILDING BLOCKS

Once the expected passenger demand has been estimated in the demand analysis and modelling process (which is not included in this study), system designers should aim to satisfy three objectives when designing for the objectives to handle the expected passenger demand at a corridor. According to Litman *et al.* (2007), the objectives are the following:

1) Meet current and projected passenger demand
2) Achieve average vehicle speeds of 25 km/h or higher
3) Minimise door-to-door travel times for customers.

These objectives are made up out of many interdependent design components.

4.3.1) Saturation level

Considering the saturation level is a good starting point in achieving high capacity and speed, and can be defined as the percentage of time that a vehicle stopping bay is occupied. The term is also used to characterise a roadway, and in particular, the degree to which traffic has reached the design capacity of the road (Litman *et al.*, 2007).

When capacity is referred to, it is normally given with an acceptable *level of service* rather than the maximum number of vehicles or passengers that could pass through a road or a system (Litman *et al.,* 2007). When after a certain point the road or system gets congested and vehicles are still increasing, they move slower and slower, and so the *level of service* decreases (saturation level increases).

For BRT systems the saturation level is not clear, since stations and bus activities could be irregular. Stations could become congested at even low levels such as 10 to 30%, but generally an acceptable level would be when stations have less than 40% saturation. Any level above 40% allows for an increase in the risk of congestion. The graph in Figure 4.6 indicates the impact of stopping bay saturation on speed (Litman *et al.,* 2007). It is clear from the graph that as the average vehicle speed decreases at a stopping bay, the saturation level increases. Therefore, a precise level of saturation is not clear. When the saturation level is greater than one, the level is known as unstable and queues will start to form at the stopping bays.

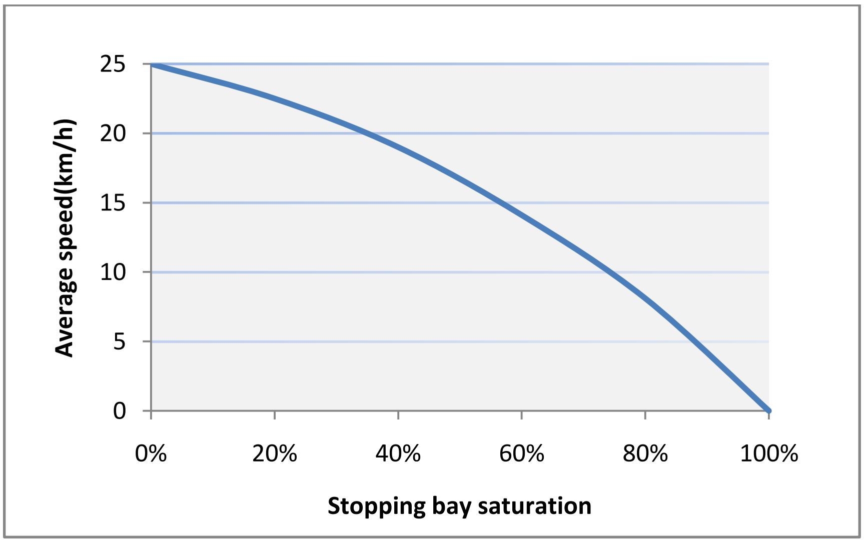

Figure 4.6 Stopping bay saturation level vs. average vehicle speed (Litman *et al.*, 2007)

4.3.2) *STOPPING BAY*

A stopping bay is defined as a designated area in a BRT station where a bus will stop and align itself to the boarding platform (Litman *et al.*, 2007). At a Bogotá's TransMilenio Station, one of the first BRT stations in the world, each station initially only had one stopping bay. A new innovation of multiple stopping bays at each station showed a drastic increase in capacity and speed. This allowed a saturation level of 40% at each stopping bay. Figure 4.7 is an illustration of a TransMilenio station (*TransMilenio - BRT network*, [s.a.]).

Figure 4.7 An illustration of a TransMilenio Station

4.3.3) *SERVICE FREQUENCIES AND HEADWAYS*

The service frequency refers to the number of buses stopping at a station per hour. The waiting time between vehicles, is known as the headway (Litman *et al.*, 2007). The higher the service frequency, the lower the headway, which in turn increases the possibility of congestion at stopping bays. The relationship between service frequency and congestion can be seen in Figure 4.8.

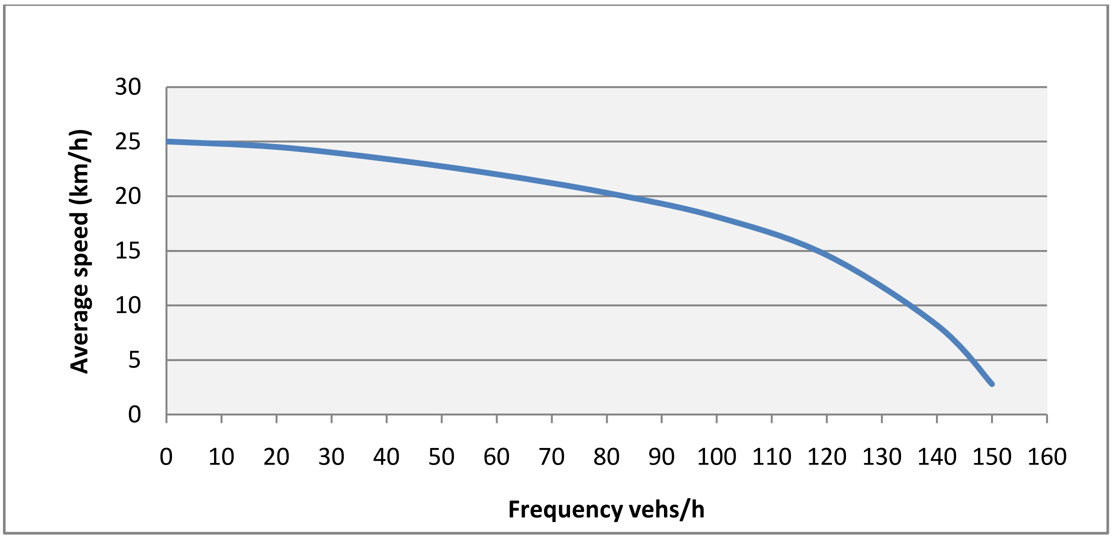

Figure 4.8 The service frequency and the potential impact on vehicle speed (Litman *et al.*, 2007)

A key objective is therefore to minimise customer waiting time by balancing the impact of headways on stopping-bay saturation (Litman *et al.*, 2007).

4.3.4) Load factor

The load factor is the percentage of a vehicle's total capacity that is actually occupied (Litman *et al.*, 2007). An example could be a bus with a maximum capacity of 160 passengers but with an average use of 128 passengers, which gives a load factor of 80%.

4.3.5) Dwell time

The amount of *total stop time per vehicle* will affect the system's overall efficiency. The amount of time that any given vehicle is occupying a given stopping bay is known as the *dwell time. Total stop time per vehicle* is the contribution to stopping bay saturation that each vehicle adds (Litman *et al.*, 2007). The dwell time is made up of three components, namely boarding time, disembarkation time and dead time. Factors that affect the dwell time include:

- Passenger volumes
- Number of doorways on a vehicle
- Width of the doorways
- High platform or low platform characteristics
- Open spaces
- Doorway control systems.

A common feature of BRT systems is the low dwell times. These times could be 20 seconds or even less. Dwell times are generally higher at peak-hour times because of the increased number of passengers that need to board and alight the buses.

4.3.6) Renovation factor

The renovation factor is defined as the average number of passengers that are on a vehicle divided by the total boardings along a given route.

4.4) Calculating corridor capacity

Calculation of the corridor capacity starts with Equation 4.1. This equation shows the main factors, which determine the capacity of a system. The equations and graphs presented in the following sections are taken from the *Bus Rapid Transit Planning Guide* by Litman *et al.* (2007).

Equation 4.1 The basic formula to determine corridor capacity:

$$Co = Cb \times Lf \times F \times Nsp \qquad (4.1)$$

Where:

Co	*Corridor capacity (pphpd)*
Cb	*Vehicle capacity (passengers/vehicle)*
Lf	*Load factor*
F	*Frequency (vehicles/hour)*
Nsp	*Number of stopping bays*

Equation 4.1 shows the basic formula for corridor capacity measured in *passengers peak hour per direction* (pphpd) but does not show the detailed interrelationships among different design factors such as vehicle size, dwell times and renovation factors. Therefore, to calculate the capacity for a specific system, the following detailed capacity formula is used:

Equation 4.2 Detailed formula for corridor capacity

$$Co = \frac{Nsp \times X \times 3600}{[\frac{Td \times (1 - Dir)}{Cb} + (Ren \times T1)]} \qquad (4.2)$$

Where:

Co	*Corridor capacity (pphpd)*
Nsp	*Number of stopping bays*
X	*Saturation level*
3 600	*Number of seconds in an hour*
Td	*Dwell time*
Dir	*Percentage of vehicles that are limited-stop or express vehicles*
Cb	*Capacity of vehicle (passengers/vehicle)*
Ren	*Renovation rate*
T1	*Average boarding and alighting time per passenger*

This equation can be used to test different design components and changes to see what impact it has on the corridors' capacity.

An acceptable level of service is typically defined as the ability to achieve an average commercial speed of 25 km/h. A general assumption for achieving this level of service is a saturation of approximately 40% (X = 0.4). This value will be used throughout the chapter as the desired saturation level. Equation 4.2 will be broken down into parts in order to better understand each component's effects on corridor capacity.

Factors that most likely affect vehicle and customer flows include:

- Vehicle sizes
- Stopping bay interfaces
- Number of stopping bays at each station
- Frequency of stations
- Load factor per vehicle
- Station design.

These factors will be addressed in following sections, and techniques will be shown to overcome potential bottlenecks at certain points.

4.5) BRT Vehicle sizes

System designers have many vehicle size options to choose from. The right vehicle size is not always the largest, affordable bus. The following table summarises the sizes available to system developers:

Vehicle type	**Vehicle length** (metres)	**Capacity** (passengers per vehicle)
Bi-articulated	24	240 - 270
Articulated	18.5	120 - 170
Standard	12	60 - 80

Table 4.1 BRT vehicle sizes (Litman *et al.*, 2007)

The 18.5 m articulated vehicles are becoming the standard bus for BRT systems. For each situation, however, there would be a best choice.

Corridor capacity can be increased by increasing vehicle length. However, a point of diminishing return is eventually reached, as can be seen in Figure 4.9. The graph displays the effect a given set of parameters has on the corridor capacity:

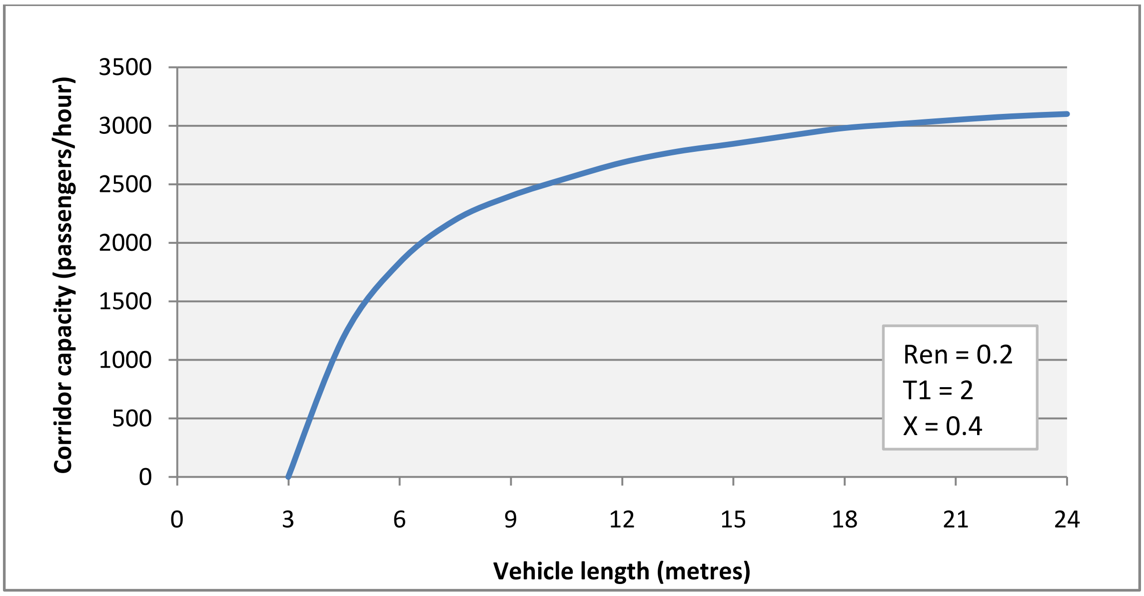

Figure 4.9 Example curve for BRT vehicle size vs. corridor capacity (Litman *et al.*, 2007)

Generally, it can be said that for every additional metre in bus length, an additional 10 passengers can be accommodated. This varies between different cultures, depending on the acceptable spatial arrangement (this is an average value across existing systems). The following equation determines the relationship between vehicle length and vehicle capacity (for conventional buses which exclude double-decker buses):

Equation 4.3 Calculating vehicle capacity from vehicle length

$$Cb = 10 \times (L - 3) \qquad (4.3)$$

Where:

Cb	*Vehicle capacity (passengers/vehicle)*
10	*10 Persons/metre*
L	*Length of the vehicle (metres)*
3	*3 Metres of space for the driver*

The BRT vehicle length also affects the dwell time. Generally, vehicles require 10 seconds to open and close their doors and pull in and out of the parking bay. For longer vehicles, an additional one-sixth of a second can be added to every 1 m increase in vehicle length. Therefore, the impact of vehicle length on the dwell time can be calculated as follows:

Equation 4.4 Impact of vehicle length on dwell time

$$Td = 10 + (L \div 6) \qquad (4.4)$$

Where:

Td	*Dwell time in seconds*
10	*The average time for pulling in and out a bay in seconds*
L	*Length of vehicle (metres)*

If Equation 4.3 and 4.4 are substituted into Equation 4.2 the formula becomes:

Equation 4.5 Corridor capacity calculation

$$Co = \frac{Nsp \times 1{,}440}{\dfrac{\left(10 + \frac{L}{6}\right) \times (1 - Dir)}{10 \times (L - 3)} + (Ren \times T1)} \qquad (4.5)$$

4.5.1) Optimising vehicle capacity

To optimise *vehicle capacity*, Equation 4.6 can be used. This equation is a re-arrangement of the basic corridor capacity in Equation 4.1. It is used when the saturation level, at a stopping bay, is low enough (< 40%). In this case the vehicle capacity should be based on the corridor capacity (obtained from the demand analysis) and on a link that yields a reasonable potential frequency and load factor.

Equation 4.6 Determining the required vehicle capacity

$$Cb = \frac{Co}{(Lf \times F \times Nsp)} \qquad (4.6)$$

Where:

Co	*Corridor capacity (pphpd)*
Cb	*Vehicle capacity (passengers/vehicle)*
Lf	*Load factor*
F	*Frequency (vehicles/hour)*
Nsp	*Number of stopping bays*

For example: When a corridor capacity is estimated to be 15000 pphpd with two stopping bays, a potential frequency of one minute and a reasonable load factor of 0.85 then:

$$Cb = \frac{15000}{(0.85 \times 60 \times 2)} = 147\ passengers/vehicle$$

Therefore a 18.5 m articulated vehicle would be sufficient, according to Table 4.1.

4.5.2) *Calculating Fleet Size*

If the vehicle size has been chosen and the demand on a certain link (station) is known, the fleet size can be calculated by using Equation 4.7.

Equation 4.7 Calculating operational fleet size for a corridor

$$Fo = \frac{(D \times Tc)}{Cb} \qquad (4.7)$$

Where:

Fo	*Operational fleet size for corridor*
D	*Demand on critical link (pphpd)*
Tc	*Travel time for a complete cycle (hours)*
Cb	*Vehicle capacity (passengers/vehicle)*

This equation gives the *number of vehicles* necessary to serve a particular passenger demand at a station of a certain vehicle capacity. The fleet size must also be adjusted in the case of mechanical problems, maintenance procedures, or any reason why a vehicle may not be in operation. Consequently, the total fleet size includes a contingency factor of 10% (Litman et al., 2007), which will ensure continued service in the case of such an event occurring. The total fleet size is calculated using Equation 4.8.

Equation 4.8 Calculating the total fleet size for a corridor

$$Ft = Fo + (Fo \times Cv) \qquad (4.8)$$

Where:

Ft	*Total fleet size*
Fo	*Operational fleet size for corridor*
Cv	*Contingency value of 10%*

4.6) STATION-VEHICLE INTERFACE

Techniques to reduce the average boarding and disembarkation times per passenger are discussed in this section. Referring back to Equation 4.2, which gives a detailed capacity formula, T1 indicates the average boarding and disembarkation time per passenger. The five topics, which are discussed relating to the station-vehicle interface, involve:

1) Fare collection
2) Platform-level boarding
3) Vehicle acceleration and deceleration
4) Doorways
5) Customer space on station platforms.

4.6.1) FARE COLLECTION

Onboard fare collection is the main determinant of boarding times because the driver is responsible for fare collection as the passenger enters the vehicle. This is common in most conventional bus services. When fare collection and verification is performed outside the vehicle, the delay at boarding and disembarkation is dramatically reduced. Offboard collection and verification is said to reduce boarding and alighting times from 3 to 0.3 s per passenger (Litman *et al.*, 2007). This reduces the station dwell time, which in turn reduces the congestion at stopping bays. Although offboard collection and verification indicates a clear reduction in boarding and disembarkation times, there is no clear indication in a system's capacity that shows whether on- or offboard collection is more favourable. This depends highly on the demand figures, physical configuration and cost of each system. The cost-benefit analysis of offboard collection is shown in Figure 4.10:

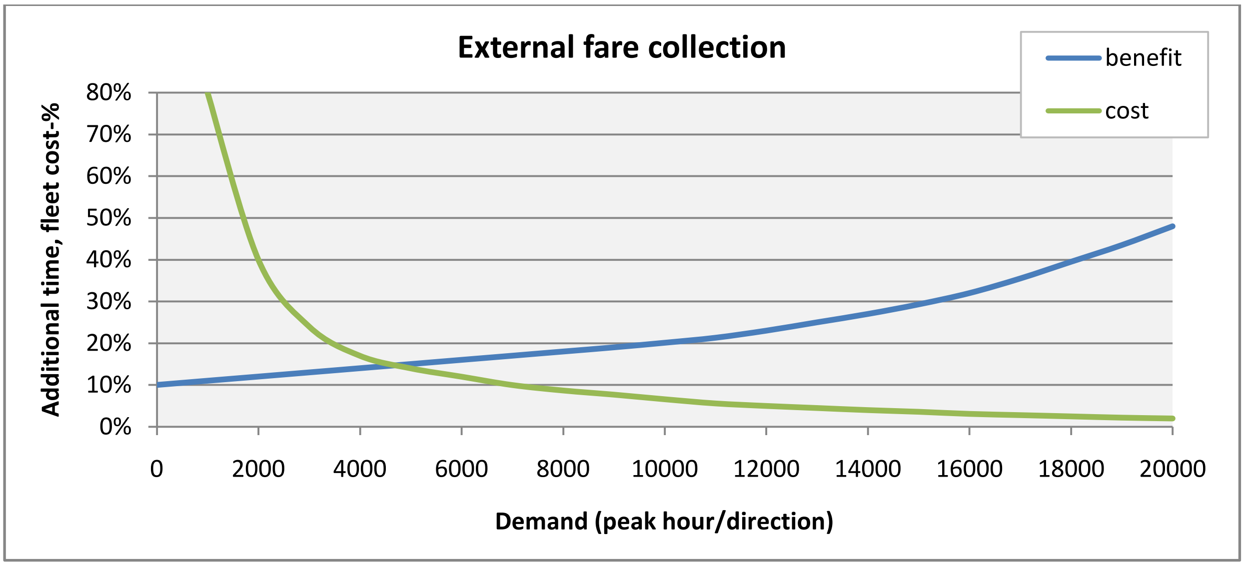

Figure 4.10 Offboard cost-benefit analysis (Litman *et al.*, 2007)

4.6.2) PLATFORM LEVEL BOARDING

In order to reduce boarding and disembarkation times further, state-of-the-art *platform-level boarding* can be introduced. This allows faster boarding times and easier access for passengers with disabilities. There are two possible techniques in this process: either a small gap between the station platforms and vehicles, or using boarding bridges that are connected to the vehicles and drop down once the vehicles have stopped.

4.6.3) VEHICLE ACCELERATION AND DECELERATION

The amount of time a vehicle takes to approach and accelerate away from the station is part of the equation for calculating the efficiency at stopping bays. The time consumed by vehicles accelerating and decelerating from stations is affected by the following factors (Litman *et al.*, 2007):

- Type of vehicle-platform interface
- Use of docking technology
- Vehicle weight and engine capacity
- Type of road surface.

There are many technological ways to improve the speed and accuracy of vehicles decelerating to align with the platform, but these are not discussed in this study.

4.6.4) Doorways

The number, size and placement of doorways play a vital role in the efficiency of boarding and disembarkation. According to Litman *et al.* (2007), boarding and disembarkation times can be reduced by 0.25 s/person when using multiple doorways and level boarding. Multiple doorways improve the efficiency of boarding and alighting because of the increase in capacity as well as reduced passenger congestion. Four 1.1 m–wide doorways have become standard on articulated vehicles. This is mainly owing to physical and practical reasons. Figure 4.11 shows the relationship between the number of doorways and the average boarding and disembarkation times per passenger; it is based on average boarding and disembarkation times taken from cases in Brazilian cities (Litman *et al.*, 2007).

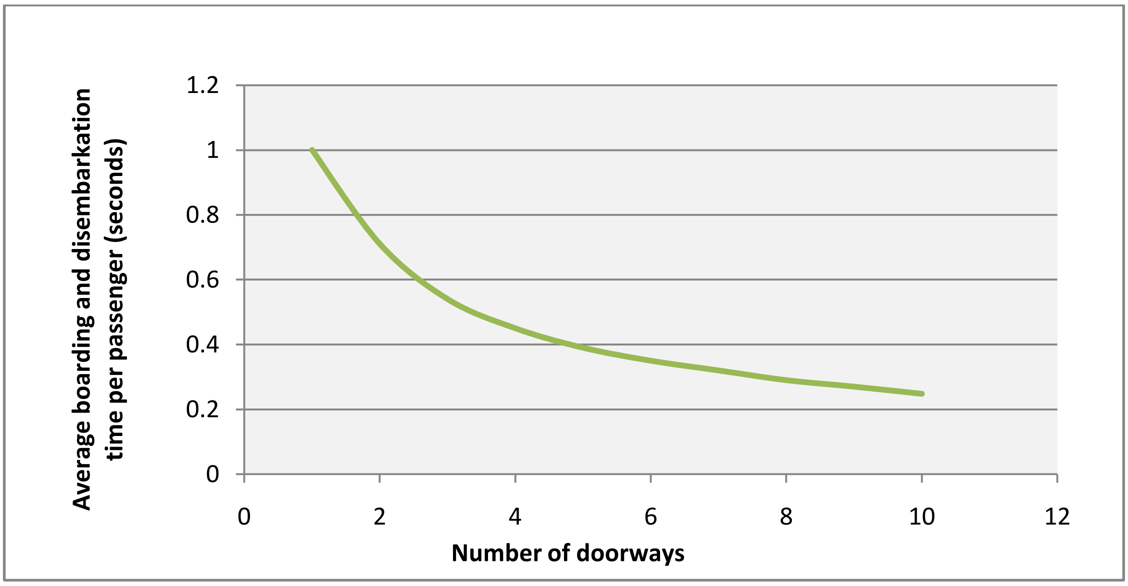

Figure 4.11 Impact of the number of doorways on average boarding and disembarkation times (Litman *et al.*, 2007)

The TransJakarta BRT system is an example of an inefficient system. It was designed to operate with standard size buses, single doors and partially blocked entrances by conductors. To resolve the capacity problems, the fleet size was increased by 36 buses. However, only eight buses helped increase the capacity; thereafter, the buses started queuing at the stations, bringing down the level of service. Table 4.2 presents the current situation as well as possible solutions to increase capacity. Shifting to articulated vehicles – with multiple, wide doorways – would add the most capacity to the doorways (Litman *et al.*, 2007).

Scenario	Average boarding time (seconds)	Capacity (pphpd)	Dwell time (seconds)	Average speed (kph)	Required fleet size (vehicles)
Present situation	2.5	2700	45	17	60
Improving boarding	1.7	3700	35	19	56
Vehicle with two doors	0.5	6000	22	21	51
Articulated vehicle (4-doors)	0.3	9600	18	23	26

Table 4.2 Scenarios for improving TransJakarta's capacity (Litman *et al.*, 2007)

4.7) STATION PLATFORM DESIGN

Platform size has a great impact on the system capacity. The optimum platform size is based on peak-hour boarding and alighting times. If a platform serves two directions, the sum of the capacity requirements of both directions must be factored into the platform sizing equations. The physical platform designs (sizes) of stations are largely a function of the boarding and alighting times as well as the frequency of services, which has already been addressed.

Station sizing has a great impact on the passenger comfort at stations and, as mentioned above, is largely dependent on the number of boarding and alighting passengers. The width of a station is the critical design parameter. At a station with only one stopping bay, the length of the station does not contribute a great deal to the platform capacity. In this situation, passengers gather around the doors to board. In the case of multiple stopping bays, the length of the station platform becomes important. (This issue is covered in Section 4.8).

The width at a standard station needs to accommodate all projected waiting passengers, include the required space for them to enter and exit the bus, and provide enough space for the infrastructure itself. The following equation is used to determine the required platform width at a standard station, with a single stopping bay in each direction:

Equation 4.9 Calculation of platform width

$$Wp = 1 + Wu + Wc + Wopp \qquad (4.9)$$

Where:

Wp	*Total platform width (m)*
1	*Width required for infrastructure*
Wu	*Width required for waiting passengers in one direction (m)*
Wc	*Width required for circulating passengers (m)*

Wopp *Width required for passengers waiting for vehicles going in the other direction*

As indicated previously, staggering stations could double the capacity of a given platform width (Litman *et al.*, 2007). In the case of staggered stations, the *Wopp* will be zero. Equation 4.9 is broken down into parts in subsequent equations.

The width required for circulating passengers (Wc) is based on the following standard: 2 000 passengers can pass through a 1 m-wide sidewalk per hour while a reasonable level of service is still provided (Litman *et al.*, 2007). Based on this standard, the following equation is used to calculate the width for circulating passengers:

Equation 4.10 Width required for circulating passengers

$$Wc = \frac{Pph}{2000\, passengers/hr} \qquad (4.10)$$

Where:

Pph *Number of circulating passengers expected per hour*

To calculate the width for passengers to move around (Wu), from Equation 4.9, we first need to calculate the minimum area for passengers to move around (Aw). This can be calculated according to the following equation:

Equation 4.11 Minimum area required for waiting passengers

$$Aw = \frac{Qp}{DwMax} \qquad (4.11)$$

Where:

Aw *Minimum area required for waiting passengers (m^2)*

Qp *Maximum number of passengers projected to queue*

DwMax *Capacity of a square metre to hold projected waiting passengers*

Pph and *Qp* are projected figures from modelling and demand-analysis, whereas *DwMax* is taken as a standard parameter of three passengers per square metre. This is owing to the fact that passengers do not feel comfortable when they are constrained to less than a third of a square metre.

Once the minimum area for waiting passengers is known, as well as the vehicle length, the platform width for waiting passengers (Wu) can be calculated (area = length × width) as follows:

Equation 4.12 Width required for waiting passengers in one direction

$$Wu = \frac{Aw}{Vehicle\ length} \qquad (4.12)$$

Where:

Aw	*Minimum area required for waiting passengers*

Equations 4.9 to 4.12 can be seen as a type of platform-sizing analysis for a standard station. The results of these equations are shown graphically in Figure 4.12, where Wopp from Equation 4.9 would be zero because this picture is an example based on a staggered station.

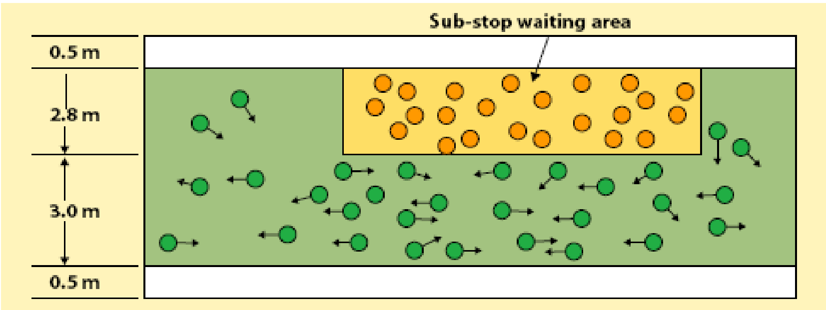

Figure 4.12 Result of platform sizing analysis (Litman *et al.*, 2007)

Some traffic-demand models can project a number of waiting passengers at a station based on an origin-destination matrix. From this, the current number of boarding passengers can be determined. If such information is not available, Equation 4.13 can be used, which gives a conservative estimate of the total number of boarding passengers.

Equation 4.13 Estimation of total boarding passengers at a stopping bay

$$Qp = \sum\left(\frac{PBi}{Fi}\right) = \sum PBBi \qquad (4.13)$$

Where:

Qp	*Maximum passenger queue expected*
Pbi	*Passengers boarding per hour on BRT route i*
Fi	*Frequency (BRT vehicles/hour) of route i*
Pbbi	*Average number of passengers boarding per BRT vehicle on line i*

For stations with single-stopping bays, the system-sizing equations above would be adequate. However, for stations with more than one stopping bay, additional space needs to be included to accommodate the vehicle movements. The minimum distance that vehicle A needs to pass vehicle B is equal to one half the length of vehicle A. For example, an 18 m bus requires at least 9 m between the stopping bays. This measurement can be used at low-frequency stations. Normally, stations use more length to allow vehicles to access stopping bays easily within less time. If space allows, an additional space behind each stopping bay, for another vehicle to wait, can be useful. However, at some point the addition of another stopping bay will be more efficient in order to mitigate the build-up of up queues behind stopping bays.

4.8) MULTIPLE-STOPPING BAYS AND EXPRESS SERVICES

It is clear that vehicle sizes, station interfaces, number of doorways, etc., contribute to higher capacity levels. With these considerations taken into account, corridor capacities at leading BRT systems in Curitiba and Quito were able to reach capacities in the range of 12 000 pphpd. However, a new capacity level was reached in 2000 when Bogotá's TransMilenio was built. Bogotá's capacity levels were approximately 45 000 pphpd. The main reason for this drastic increase was owing to an increase in the number of stopping bays used at a station. Referring back to the detailed capacity Equation 4.2 (p. 26), an increase in the value 'Nsp' (number of stopping bays) allowed Bogotá to reach capacity levels competing within the range of metro rail system's capacities.

Multiple-stopping bays serve two purposes: an increase in stopping bays reduces the saturation level ('X' from Equation 4.2) at stations, and secondly, different stopping bays can represent different services or routes at the same station.

As mentioned previously, a saturation level below 40% is desirable at any station. As soon as saturation levels exceed 40%, it is more likely that more stopping bays will be needed. To maintain saturation levels below 40% requires stopping bays to be spaced and scheduled properly. The saturation level for an individual stopping bay can be calculated using the following equation (Litman *et al*., 2007):

Equation 4.14 Calculating the saturation level of a stopping bay

$$X = Td \times F + [(Pb \times Tb) + (Pa \times Ta)] \qquad (4.14)$$

Where:

X	*Saturation level at stopping bay*
Td	*Dwell time (seconds)*
F	*Frequency (vehicles/hour)*

Pb	*Total number of passengers boarding (passengers)*
Tb	*Average boarding time per passenger (seconds)*
Pa	*Total number of passengers disembarking (passengers)*
Ta	*Average disembarkation time per passenger (seconds)*

Consequently, from Equation 4.13 it can be seen that the saturation level of a stopping bay is a function of the stopping bay's dwell time plus the total passenger boarding and disembarkation time per hour.

There are numerous ways to increase the capacity of a stopping bay when combing or clustering routes, or putting different types of services together. According the Litman *et al*. (2007), these include:

- Clustering routes with adjacent geographical coverage
- Clustering routes sharing different types of services, i.e. local and limited-stop services
- Frequencies can be carefully scheduled and spaced so that different routes can share the same stopping bay.

Multiple-stopping bays almost always require a passing lane. The second lane (which is alongside the lane connected to the station) allows vehicles to pass one another when entering and exiting the stopping bays. The length of the passing lane beyond the station depends on the station's saturation level.

Limited stop and express services can help expand corridor capacity. Limited stop services avoid the need to stop at each station, where express services pass through a station to one final destination. In Equation 4.2 (p. 26), limited or express services affect the term '1-Dir'. '*Dir*' represents the percentage of vehicles that operate either as limited-stop services or express services. For example, if 50% of vehicles operate as limited-stop vehicles, the capacity of the corridor will be increased.

A summary of the equations presented in this chapter is displayed on page 42.

4.9) CONVOYING

Passing lanes require a large amount of space and are not always permitted owing to political reasons or when roadway space is a limiting factor. In cases where the capacity requirements of a corridor require multiple-stopping bays, but passing lanes are not permitted, an alternative method exists, namely convoying. Convoy systems allow the use of multiple-stopping bays without passing lanes (Litman *et al*., 2007).

A convoy system can be described as a system where each vehicle that arrives at a station occupies the stopping bay that is the furthest away and the next vehicle the next stopping bay. This is known as a non-ordered convoy system (Litman *et al*., 2007). This type of system works best when all vehicles stopping at the station follow one route. Otherwise, with more than one route, customers will not know at which stopping bay their intended route will halt. This, however, can be overcome with the use of audio or visual indications of stopping-bay numbers and routes followed shortly before the arrival of a vehicle.

Another way a convoy system can operate is in an ordered manner (Litman *et al*., 2007). Here, designated stopping bays follow specific routes. Before entering the station, vehicles stop in an orderly manner and thereafter these enter the station in a specific sequence. A control centre with automatic vehicle-loading technology is essential. The management and control of vehicles in this type of system becomes difficult. The vehicles must enter the station in a specific way or there will be delays and vehicles will back up. The dwell and boarding times may also vary between different stopping bays, causing even further delays. In a convoying system, the vehicle with the lowest speed determines the entire system's speed. For these reasons, multiple-stopping bays are probably best implemented with the provision of a passing lane.

4.10) SERVICE AND OPERATING PLANS

This section addresses important service and operational elements influencing the performance of a BRT system, i.e. how *passengers* find value in, and perceive, the service. Customers want frequent, direct, easy-to-understand, comfortable, reliable, operationally efficient and, above all, rapid service (Hinebaugh & Diaz, 2009). To provide such a service to customers, while remaining focused on the elements affecting the system's speed and capacity performance, the following service and operational areas will be briefly discussed in this section. These include the service span, the service frequency and the method of schedule control.

The *service span* of a BRT system is the period of time in which the service is available. Service spans affect the segment of the market that the service can attract. There are generally two types of service spans. An *all day* service span runs from the morning until the end of service in the evening. This type of service normally runs at a minimum level of service (frequency) headways throughout the entire day, although the frequency of service could also be reduced during off-peak hours during the day. The other type of service is a *peak-hour* service, which runs only during peak hours. During other times, the use of local bus services is normally provided. It must be remembered that supplying the optimal amount of service during the day is a great challenge.

The *service frequency* affects the service regularity as well as the ability of passengers to rely on the BRT service (Hinebaugh & Diaz, 2009). A high service frequency reduces the waiting time for passengers but can also cause congestion at the stations. Therefore, the frequency is also limited to the capacity provided by vehicles, stations, etc.

There are two *methods of schedule control*. The first, i.e. *schedule-based control*, regulates vehicle operation according to a specific schedule. Specific times as to when and where vehicles stop on the route are given. This method is followed mainly to provide passengers with a schedule. *Headway-based control* is normally used on high-frequency services and focuses on maintaining an exact headway rather than meeting a specific schedule. The control is quite difficult and requires a combination of supervision and automated vehicle-location technology.

4.11) SUMMARY: CHAPTER 4

Chapter 4 provides information on the different components of a BRT system that determines, and has an influence on, the *capacity* (passengers peak hour per direction) of a system. It focuses on explaining *how* these components contribute to the capacity of a system by showing the calculations used when designing a system for a certain level of service. The components are made up of building blocks, which were defined at the beginning of the chapter. Thereafter, the components were introduced, as were the related calculations. These *deterministic* calculations are used for ascertaining design sizes and operating levels of BRT systems, such as the types of vehicles to be used, the station interfaces, the number of stopping bays, load factors, station design types and sizes, among others. Different methods of operation – such as convoying, service spans, service frequency and method of schedule control – were also explained. A summary of the equations presented in this chapter is displayed at the end of this chapter.

The 'real-world' BRT system used in this study is designed according to these *deterministic* calculations, and is built and modelled in this study using a known approach. This will serve as a reference model in this study. Since real-world systems usually exhibit complexity, time-dependency and variation, computer simulation is considered as a potential problem modelling tool. Several scenarios involving capacity investigations are anticipated, and simulation is useful for evaluating these issues. Chapter 5 provides information on *simulation.*

Summary of Chapter 4 equations			
Section	Equation	Equation name	Formula
Vehicle sizes	Equation 4.3	Calculating vehicle capacity from vehicle length	$Cb = 10 \times (L-3)$
Vehicle sizes	Equation 4.4	Impact of vehicle length on dwell time	$Td = 10 + (L/6)$
Vehicle sizes	Equation 4.5	Corridor capacity calculation	Equation 4.3 and 4.4 substituted into Eq. 4.2
Vehicle sizes	Equation 4.6	Equation 4.1 re-arranged: determining required vehicle capacity	$Cb = Co/(Lf \times F \times Nsp)$
Vehicle sizes	Equation 4.7	Calculating operational fleet size for a corridor	$Fo = (D \times Tc)/Cb$
Vehicle sizes	Equation 4.8	Calculating the total fleet size for a corridor (equation 4.7 + 10% contingency value)	$Ft = Fo + (Fo \times Cv)$
Station platform design	Equation 4.9	Calculation of platform width	$Wp = 1 + Wu + Wc + Wopp$
Station platform design	Equation 4.10	Width required for circulating passengers	$Wc = Pph / 2000$ passengers per hour
Station platform design	Equation 4.11	Minimum area required for waiting passengers	$Aw = Qp / DwMax$
Station platform design	Equation 4.12	Width required for waiting passengers in one direction	$Wu = Aw /$ Vehicle length
Station platform design	Equation 4.13	Estimation of total boarding passengers at a stopping bay	$Qp = \sum (PBi / Fi) = \sum Pbbi$
Multiple stopping bays and express services	Equation 4.14	Calculating the saturation level of a stopping bay	$X = Td \times F + [(Pb \times Tb) + (Pa \times Ta)]$

5) SIMULATION

Simulation is a powerful performance evaluating and analysis tool, which helps engineers and planners make timely and intelligent decisions about system designs and operations. It can be described as a tool for doing 'what-if' analysis, where simulation provides measures on any number of proposed scenarios and finally narrows the alternatives down to the best-possible solution. Simulation *evaluates* solutions and does not *generate* solutions. Information and concepts regarding simulation are discussed in this chapter.

This chapter begins by defining the terms *systems* and *modelling*, which are concepts underlying simulation. Thereafter, *simulation* is discussed as well as components and modelling concepts of simulation models. After the basics of simulation have been discussed, *discrete event simulation,* which is used to model scenarios, is explained and defined.

In any simulation study, a number of common steps need to be taken to ensure the success and creditworthiness of a model. These steps are briefly explained in Section 5.7, where after the advantages and disadvantages of simulation are addressed.

5.1) DEFINING A SYSTEM

A system can be broadly defined as a collection of elements that function together to achieve some objective (Blanchard, 1991). Service, economic, traffic and manufacturing systems are all examples of such systems.

5.2) DEFINING MODELLING

Modelling is the process of producing a model, which is a representation of a particular *system*. The model should be a close replication of a real-world or planned *system*. The purpose of modelling, according to Harrell and Tumay (1994), is to understand, predict, control and ultimately improve *system* behaviour.

Models are approximations of actual systems and therefore cannot be seen as true or false, but rather as useful or not useful. A useful model is a model that serves its intended purpose and can be characterised as follows (Harrel & Tumay, 1994):

- Includes only the elements that directly influence the problem being solved
- Is valid (sufficiently represents the system)
- Provides results that are meaningful and readily understood
- Is easily modified and expanded
- Is quick and inexpensive to build
- Is credible and reusable.

There are three types of models, namely symbolic models, analytical models and simulation models. *Symbolic models* are graphic representations of processes and other relationships. These are usually used to document processes or relationships, using methods such as flow diagrams, and facility layouts by using symbols such as rectangles and arrows to depict activity sequences and relationships. These models allow concepts to be portrayed, understood and easily documented.

Analytical models are mathematical formulas that yield quantitative solutions. These can be modelled by simple arithmetic calculations or complex linear programming algorithms, and provide optimum solutions for a given set of problems (Harrell & Tumay, 1994). This type of model often requires assumptions and cannot solve problems of great complexity. These are also often unable to account for the random behaviour that exists in most systems.

Simulation models are models that are built in order to experiment with imitated real-world systems. The following section explains simulation in more detail.

5.3) Defining simulation

With the rapid growth in computer development since World War 2, computer simulation was developed for the Manhattan Project to model the process of nuclear detonation. These simulations worked with inputs consisting of random-sampling probability distribution functions, where the models produce thousands of possible outcomes. This type of simulation is known as the Monte Carlo Simulation and is mostly used for studying systems with a significant amount of uncertainty in inputs. There are many types of simulation, but a feature common to all types of simulations is the attempt to generate model scenarios where all possible states of the model scenario can be captured.

The *Handbook of Simulation* (Banks, 1998) defines simulation as the "imitation of the operation of a real-world process, or system, over time. Simulation involves the generation of an artificial history of a system and the observation of that artificial history to draw conclusions concerning the operating characteristics of the real system that is represented".

Simulation does not solve problems, but can identify problems and evaluate alternative solutions or scenarios. Usually, models are built because it is impossible, impractical or too expensive to reconfigure and experiment with real-life systems. Therefore, simulation can be seen as a tool to evaluate the performance of an existing or proposed system, where experimental changes could be made and conditions could be altered to see what effect it would have on the outcome of a system. This comes down to the idea of simulation models answering 'what-if' questions.

Consequently, through simulation, operations of a system can be studied where deductions can then be made about properties concerning the behaviour of an actual system. There are different types of simulation models, which are addressed in Section 5.4.

Other performance-evaluation tools, besides simulation, include (Bekker, 2008):

- Queuing theory
- Linear programming
- Assignment algorithms
- Integer programming
- Markov chains
- Stochastic inventory models.

5.4) SIMULATION MODELS

System simulation models can be classified according to three traditional approaches:

- *Static* or *dynamic* models: In *static* models, time does not play a role. Most mathematical and statistical models, which represent a system at a fixed point in time, are *static*. On the other hand, models where time does play a role are known as *dynamic* models.

- *Discrete-event* vs. *continuous* simulation: A *discrete* model has dependant variables that change only at distinct points in simulated time, referred to as *event times* (Banks, 1998). Most manufacturing and service systems are discrete-event systems. Examples of *event times* in manufacturing could include times at which orders are placed, the part arrives and the parts depart. *Continuous* simulation is used to model systems of which the states change continuously as time passes. An example could be the change in temperature during one day. Some systems have both discrete- and continuous-modelling capabilities.

- *Stochastic* vs. *deterministic* simulation: A powerful feature of simulation is the ability to model random behaviour, variation or change. Most systems have some type of randomness. Models that are based on one or more variables, which are random in nature, are referred to as *stochastic* models (Harrell & Tumay, 1994). The output of such a model is also random and therefore the output is only an estimate of the true behaviour of a real-world system. Models that have no random input are known as *deterministic* models. If a simulation model is deterministic, the results after one simulation run of the model would be an exact measure of the systems' performance. If a simulation model is *stochastic,* the results after each simulation run would not be the same. Therefore, a *stochastic* model must run several times in order to estimate an average result of the system performance.

5.5) MODELLING CONCEPTS

There are several underlying concepts in simulation, which are briefly discussed in this section. These concepts include events, system-state variables, entities and attributes, resources, list processing, activities and delays.

Events are occurrences that change the state of a system. Examples of events include the arrival of a part at a workstation or the completion of a manufactured part.

System-state variables collectively describe the state of a system at any given point in time. Examples of such variables include:

- Number of entities in a queue
- State of a machine (idle or busy)

- Number of resources in use
- Current number of entities in the system.

These variables often have an effect on the decisions entities make when an event occurs. For example, when customers (entities) choose the shortest queue, they base it on the number of customers already in the queues.

Entities and attributes: Entities represent objects that are processed through a system, such as products, customers, documents, etc. Each entity may have attributes, which pertain to that entity alone. An example of an attribute for a specific entity could be the time of arrival. Another example of an attribute could be the colour (red, blue, green) of the entity.

Resources provide service to dynamic entities (entities which move). Entities can also request the use of more than one resource and if the amount requested is not available, the entity joins a queue until the required number of resources becomes available. When the resource is available, the entity uses the resource for a period of time, where after it is released and made available for use by the next entity. An example of a resource is a bank teller, which provides a service to customers.

List processing: Lists are used to represent the queues in which entities wait. Lists can be processed in more than one way, for example, according to First In First Out (FIFO), Last In First Out (LIFO), randomly, according to specific entity attributes, etc.

Activities and delays: Activities are tasks that are performed in a certain amount of time, which usually involves the use of a resource. Types of activities can include (Harrell & Tumay, 1994):

- Entity processes (check-in, treatment, inspection, fabrication, etc.)
- Entity moves
- Resource moves
- Resource setups
- Resource maintenance and repairs.

A delay has an indefinite duration, which is subject to system conditions. An example could be the waiting time in a queue, which is initially unknown, and depends on other events which may occur.

5.6) DISCRETE EVENT SIMULATION

Having briefly described simulation modelling concepts, *discrete event simulation* can now be defined as "a simulation which utilises a mathematical/logical model of a physical system where state variables change as events occur at discrete points in time" (Nance, 1993). Events occur as a result of activities and delays in the system. Entities – such as people, material and equipment – compete for resources and join queues where resources are occupied. Activities and delay times 'hold' entities for periods of time.

In addition, a basic explanation for discrete event simulation could be the management of events in time. A simulator triggers events, where queues and events are regulated and sorted by simulator time. As soon as events are finished, new events are processed and queued by the simulator.

Discrete event simulation is one of four modelling approaches in simulation. The others are known as *system dynamics modelling*, *dynamic physical systems modelling* and *agent-based modelling.* These types of models differ in elemental structures, where each type is better suited for a particular level of abstraction. The integration of these approaches is, however, also common and should therefore rather be viewed as modelling paradigms, as compared with fixed methods of modelling. Interested readers are invited to refer to *The study and application of Agent-based modelling* (Pieterse, 2007), which provides more information regarding the modelling paradigms. This project's field of study involves the use of discrete event simulation modelling, which is further discussed in this section.

In terms of the three traditional approaches, discrete event simulation can be classified as *dynamic* since time plays an essential role; *discrete*, because events occur at discrete points in time; and *stochastic*, as change and probabilities are inherent to the simulation model. In discrete simulation, time is advanced from one event to the next. This is known as the next-event approach. At each occurrence of an event, the system state is updated as are resources being used or released (freed).

Therefore, the goal of this type of modelling is to show the activities in which the entities (such as people) engage, thereby learning something about the dynamic behaviour of systems. Examples of computer-simulation software packages, which model discrete event simulations, are Arena, ProModel and GPSS/H.

Simulation and modelling principles have been addressed in this section. Together with these principles come common steps to be taken when conducting any simulation study. These steps are described in the next section.

5.7) STEPS IN A SIMULATION STUDY

A simulation study is initiated by a problem or a concerned area of investigation when designing a new system or investigating an existing system. Figure 5.1 is a schematic representation of a simulation study.

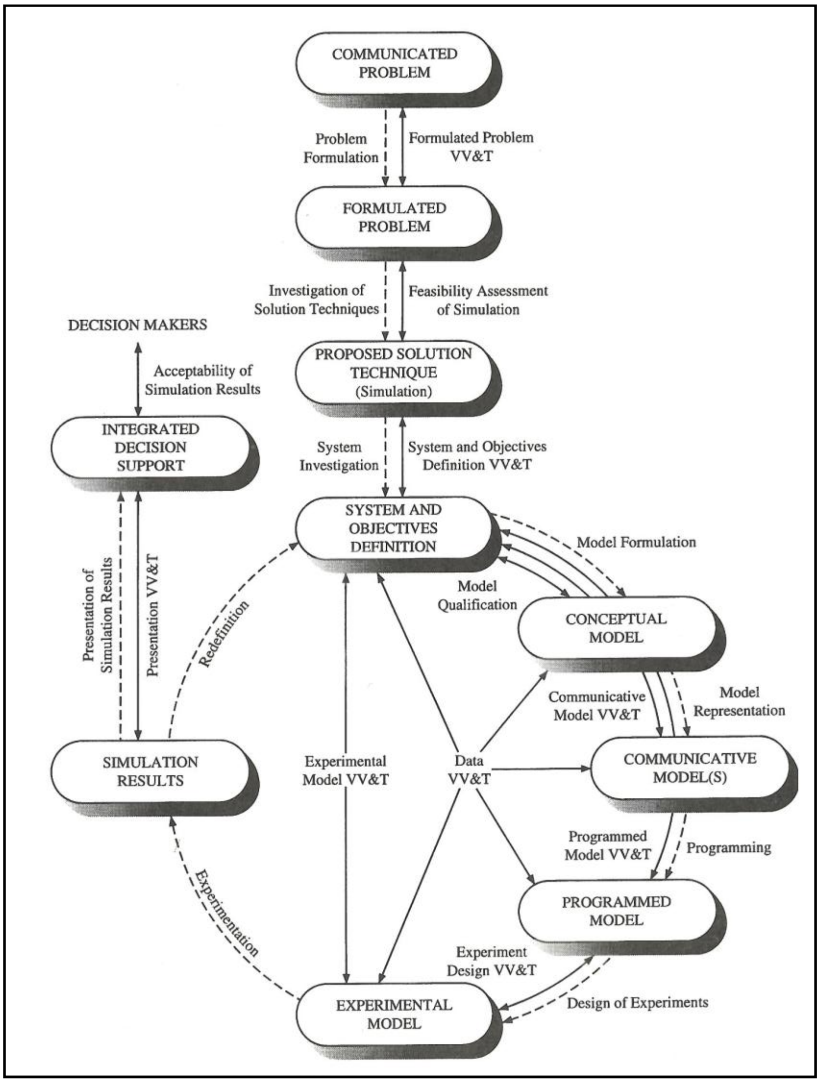

Figure 5.1 Schematic representation of a simulation study (Banks, 1998)

The iterative nature of simulation studies can be seen in Figure 5.1. The alteration of the system becomes the area of study, where after the cycle repeats again. The following steps are important when developing a model, experimenting and performing simulation analysis (Law & Kelton, 2000):

1. Problem formulation and definition: Every simulation begins with formulating a problem. It is therefore important to understand the problem as well as the study area. This will help to define the study goals, purposes of the study, limitations and constraints clearly.

2. Project planning: Planning of a simulation study is essential to ensure the success of the project. The main elements involved in planning are time, availability and cost of resources.

3. Defining the boundaries of the study area: Boundaries need to be defined for the study area to indicate what will be included and excluded. This simplifies the study area by separating it from the world as well as defining the boundaries within the system's environment. Boundaries also include the assumptions made throughout the study and should be agreed upon and accepted by the project team and clients.

4. Formulate a concept model: This step can be viewed as the planning part of the computer model. It is usually done on paper by using pseudo code or in diagram format. This step provides a better understanding of the problem, the model requirements and the level of detail.

5. Preliminary experiment: This step comprises the establishment of the following factors: level of confidence interval, time span, input variables, parameters to be studied, data required, entity attributes, scale of measurements, model resources and combinations of parameters, if necessary.

6. Investigation of parameters: Select the parameters that will be studied. These parameters are the output parameters on which the statistical analysis will be performed.

7. Obtain input data: The requirements of the model are established in the concept model and preliminary experimental design.

8. Translate the model into a simulation language: This step comprises computerising the concept model.

9. Verify the model: This step simply verifies that the built model works correctly. There are several actions, which could be done to check the model:
    - Syntax errors are corrected
    - Check the logic of the model
    - Check and correct *run-time errors,* which occur when the simulation is executed
    - Test various data sets and see how the model handles it
    - Obtain outside involvement and queries (outside ‘doubters’)
    - Conduct ‘walk-through checking’ by manually following each step.

10. Validate the model: Validation of a model confirms that the *right* model has been built for the *right* purpose. This can be validated through three different perspectives, namely the analyst, who designs and conducts confidence-building tests, the technical evaluator, who reviews the data and information of the model, and lastly the user, an outsider who does not understand the validation tests.

11. Rework the model where necessary: Through verification and validation, problems are exposed, which need to be changed. In this step, the changes are made where after the model must again be verified and validated. This is an iterative process and a very important step in a simulation study, which ensures that the model is an adequate representation of the real-world system before carrying on with the statistical analysis.

12. Initial simulation run: An initial simulation run is required to generate data for the preliminary statistical analysis. Preliminary confidence intervals will be determined, from which the actual number of replications can be determined.

13. Statistical analysis and production runs: Analysis is used to estimate the measures of performance for the scenarios that are being simulated.

14. Model modification and scenario analysis: The scenarios are modelled and output analysis is performed.

15. Documentation: Documentation is easiest when done right from the start. Alterations and additions are made as the process continues.

16. Implementation, maintenance and monitoring: The modeller must ensure that implementation is maintained and that feedback is obtained from the client to evaluate the success of the study.

5.8) ADVANTAGES OF USING SIMULATION

Various advantages of simulation are listed below (Banks, 1998):

- Simulation is a versatile and powerful tool, which can deal with complex systems.
- Many pitfalls can be avoided by using computer simulation to model a system before it is actually built.
- Improvements to, and fine tuning of, a system – which previously took months or years – can now be done in matter of hours or days.
- For service systems, simulation is a valuable tool for handling, for example, complex customer scheduling, staffing, resource management, customer flows and information flows.
- Simulation allows optimisation.
- Changes to a system can be investigated.
- Critical parameters in a system can be identified and studied.

5.9) DISADVANTAGES OF SIMULATION

Disadvantages of simulation include, for example (Banks, 1998):

- Simulation often entails the input of random variables, which can distort the imitation of the real-world system.
- Simulation can be expensive and is risky when simplifying a complex system with convenient assumptions.
- Easier solutions are often overlooked.
- Results can be misinterpreted.
- Simulation requires a certain level of expertise.

5.10) THE USE OF SIMULATION IN MANAGEMENT

Simulation is used in a wide range of practices and industries, among which include manufacturing, project management, engineering, financial institutes, research and development, insurance, oil and gas, transportation and the environment (see @Risk). Managers are confronted daily with problems which need to be solved and decisions that need to be made. A survey conducted by Christy and Watson (1983) found that the use of general-purpose simulation languages, such as FORTRAN is popular, but also found reasons why users and managers are reluctant to use other sophisticated simulation packages. They found that users are often not familiar with the quantitative techniques because of their lack of knowledge with the associated theory and computations. Other reasons why simulation is often overlooked include the lack of data, which is often not available, and the associated time required to perform the analysis. Individuals are easily put off by the requirements of simulation and therefore easily accept other methods of analysis which provides adequate results. Managers are also reluctant to use simulation because of the knowledge of simulation required, as well as the costs of simulation packages. They found that simulation needed attention to make it more transparent to users so that they feel less threatened by the techniques used in simulation.

Management decisions often have associated levels of risks and potential consequences leading from them. Simulation allows one to see different possible outcomes of decisions made and assesses the impact of these decisions. Moreover, the impact of the *risks* undertaken can be assessed, allowing for better decision making under uncertainty. Outcomes of different situations and extreme cases can be modelled, where graphs are easily generated of the results and the chances of occurrence. This is also an important method of communicating the findings to other stakeholders or decision makers. A few examples are provided where simulation is used as a tool for managerial decision making:

- Simulation supports the development of company policies and strategies.
- In a project management field, Monte Carlo simulation can be used by project managers to quantify the effects of risks and uncertainty in project schedules and budgets. This allows project managers to justify and communicate their arguments to other senior authorities when they are pushing for unrealistic expectations. It can also provide statistical indications of a project's performance, such as the target completion date and budget.

- Simulation is used as a tool for managing change. As stated by Barnett (2003), it is important in business process management to lead organisations and people carefully from their old ways of doing, to the new ways. Simulation is a tool which accelerates this change because of its ability to bring clarity to the reasons for change.
- In the manufacturing industry: Applications of simulation are used in the following categories which involve managerial decision making; facilities planning, developing methods of control, material handling, examining the logistics of change, company modelling and training operations staff (Robinson, 1994). For example, in an inventory management system, simulation can be used to determine inventory parameters, such as the levels of safety stock and re-order points.
- Simulation for hospital operations: Hospital managers are faced with problems concerning demand and resourcing problems, waiting lists, emergency protocols, cancellations etc. Simulation models have been developed to assist hospital managers explore solutions to the problems so they can gain knowledge for making insightful management decisions.

Other examples of areas where simulation is used in conjunction with management include:

- Simulation is often used in lean manufacturing to explore implementation strategies.
- Call centres use simulation as a decision support tool.
- Construction uses simulation for risk management.
- Simulation is used in leadership and management research.
- Simulation is used in software project management education.
- Simulation is frequently used in supply chain management.

5.11) SUMMARY: CHAPTER 5

Simulation is defined as the imitation of real-world processes or systems over time, and is the method chosen in this study to investigate BRT system parameters. The aim of this chapter is to provide the reader with the necessary information about simulation concepts, components, the process of simulation, as well as the reasons for using simulation.

This chapter started by addressing the underlying concepts of simulation, after which simulation is defined. A brief discussion on the history of simulation followed as does the classification of simulation.

The components of simulation models, e.g. events, variables, entities, attributes, lists, activities and delays, were presented. After the foundations of simulation were laid, the simulation paradigm used in this study, known as *discrete event simulation*, was introduced and explained. Steps in a simulation study followed, concerning any area of investigation of a new or proposed system. These steps are crucial and ensure the success and validity of the simulation study. This chapter ends by listing a number of advantages and disadvantages of using simulation, as well as the use of simulation in management.

Literature on *BRT systems* and *simulation* has been covered in previous chapters. In Chapter 6, the focus shifts to providing information about the *specific study problem*.

6) STUDY OBJECTIVES

The *capacity* of a BRT system is determined by many factors, such as the vehicle type, bus station designs, fare collection methods, lane configurations and bus operations. However, the issue governing all those mentioned above is the *number of passengers* who will make use of the service. These numbers are only *estimates* and so a level of uncertainty exists. As shown, the capacity of a station is calculated using *deterministic equations*, which do not include elements of uncertainty or change, and averages are used to represent the rates at which passengers arrive, board and disembark from the buses. Considering the above, the objectives of this study are now presented.

6.1) RESEARCH STATEMENT

The overall objective of the present study is to *build* and *use* a stochastic simulation model to investigate capacity parameters of a BRT station. This model must serve as a decision-support tool for planning BRT stations. The outcome of the research will determine if such a model can be built, and if it will be useful in practice.

6.2) SPECIFIC PROBLEM

The simulation model is based on the operations of the Thibault Station, a proposed BRT station in the Cape Town city centre. This model only concerns the events specific to the Thibault Station and is not affected by events occurring outside this scope.

The number of passengers waiting in queues is simulated during a day, so that the queue length fluctuations can be investigated. Passenger activities within the station, such as, procuring bus tickets and verification of tickets at turnstiles do not form part of the study scope.

6.3) Main objectives

The main objectives of this study are:

1) To simulate the processes of the Thibault Station using deterministic values provided by Pendulum Consulting. The simulation model must be built so that users can define and change important input parameters.
2) To develop a stochastic model from the deterministic model, in order to predict the outcome of operations of the Thibault Station under variable input data. The main objective is to model the *passengers arriving at the station* randomly to investigate the impact these changes will have on the capacity of the system. Users must be able to test different scenarios and therefore be able to define their specific input data to the model.
3) To construct scenarios from the stochastic model to determine the correctness of the model as well as demonstrate how the tool can be used to obtain valuable information.
4) Analyse capacity parameters by evaluating different scenarios.
5) Report findings on the stochastic model and the scenarios evaluated.

6.4) Summary: Chapter 6

The objectives of the study were outlined in this chapter. The executions of them are carried out from here and are presented in the following chapters, beginning with the conceptual model.

7) Concept Model

The concept model is explained in this chapter. The aim of the concept model is to create a logical representation of the system operations of the Thibault Station. This is a critical step and was done before the actual simulation as it helped in planning the simulation model. The concept model also ensures that the modeller understands the bus station concepts and processes clearly, thus helping the modeller to develop a model that is credible and adequate.

7.1) Focus of the concept model

This study focuses on the capacity planning of the BRT station in Cape Town, known as the Thibault Station. Thibault Station is an enclosed bus station with glass sliding doors, staffed ticket booths, pre-board fare verification (by means of turnstiles) and four platforms. A detailed architectural drawing of the Thibault Station is shown in Appendix A. The operations of the Thibault Station involve:

Passenger movement:

- There are two entrances to the station. Entrance 1 is the main entrance where passengers buy tickets from a ticket booth before proceeding to the platforms. Entrance 2, which does not have a ticket booth, is situated at the opposite end of the station. This entrance only allows access to passengers already in the possession of tickets. The majority of these passengers have monthly or seasonal tickets allowing them quicker access to the platforms. They could also enter through Entrance 1.
- Passengers verify their tickets at the turnstiles, after which they proceed to their desired platform waiting area.

Buses:

- The buses operate in a separate dedicated BRT bus lane, allowing no interference from other modes of traffic.
- There are two routes departing from the Thibault Station with different types of buses serving each route. The TO1 route uses bi-articulated buses with a passenger capacity of 120. The TO2 route uses smaller buses seating only 40 passengers.
- The buses operate according to a schedule, which is explained in Section 8.3 on p. 72.

- The service frequency changes throughout the course of the day. This is owing to the variation in demand during a day.

Infrastructure:

- Platforms: There are four platforms at the station where passengers depart. Platform 1 is allocated to TO1 buses and transfers passengers to the CBD. Platform 3 is also a TO1-allocated platform and routes out to Blaauwberg.
- TO2 buses stop at Platform 2 and proceed to the CBD. Platform 4, situated opposite Platform 2, is also a TO2-allocated bus stop, and transfers passengers to the Cape Town International airport.
- There are two parking berths at each platform, allowing parking space for an additional bus waiting for the platform. Please refer to the detailed architectural drawing in Appendix A for more information.

A basic illustration of the platform layouts and bus cycles is shown in Figure 7.1. This is only for the purpose of understanding the movement of the buses *to* and *from* their dedicated platforms. TO1 buses follow the cycle represented by the red lines, while TO2 buses follow the blue lines. It must be made clear that the 'drop-off stations' in Figure 7.1 represent the stations where buses depart and arrive. Because this study only concerns the activity involved between the dotted lines, drop-off stations were used in the model to represent all other stations that form part of a cycle. The important input data of each bus's cycle time and respective route times along the cycle are still incorporated into the model, despite the use of two drop-off stations representing *all* other stops during a cycle. The manner in which this is incorporated into the model is explained in Chapter 8.

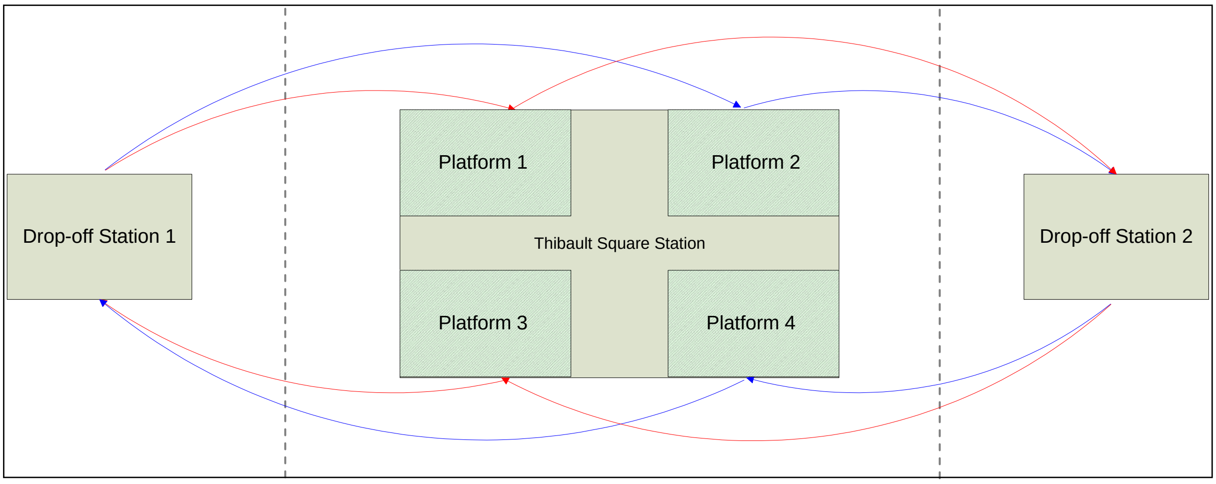

Figure 7.1 Thibault Station platform layout

The entities in the model are the passengers and the buses. These are the 'discrete units of traffic' in the simulation model, as stated by Brunner and Schriber (2005). The attributes of these entities are discussed in Chapter 8.

Model restrictions include:

- Vehicles only operate between 4:00 AM and 23:00 PM daily
- TO1 buses have a capacity of 120 passengers per bus
- TO2 buses have a capacity of 40 passengers per bus.

Model assumptions include:

- The various bus types always stop at their dedicated platforms. If buses arrive simultaneously at the same platform, or arrive while the parking berth is already occupied, that bus will stop behind the bus already occupying the designated parking berth, while waiting its turn.
- Dwell, boarding and disembarkation times are assumed to be incorporated into the passenger arrival times.
- Buses always arrive according to scheduled times.
- The bus capacities, already defined for the different types of buses, represent the passenger *seating* capacity and are taken as the *maximum* number of passengers that the vehicle can accommodate. Therefore, *standing* passengers are not included in the model.
- The number of boarding passengers can only be as large as the number of available seats of the particular bus.

7.2) REQUIRED INPUT DATA

In order to build the model, input data is needed. The required input data identified for arriving and departing buses are:

- Scheduled arrival times of buses
- Cycle times of buses
- The number of each bus type in use
- The number of passengers onboard
- The number of passengers disembarking from the bus.

Arriving passenger data:

- Arrival rates of passengers
- Passenger platform choice.

The actual data obtained for the simulation model is addressed in Chapter 8.

7.3) MODEL BOUNDARIES AND LEVEL OF DETAIL

The boundaries and level of detail to which the model conforms need to be defined for the purpose of scoping and simplifying the building of the simulation model. The events and activities of the system, which are included and excluded from the simulation model, are addressed.

7.3.1) THE MODEL BOUNDARIES

The aim of this study is to investigate the capacity of the Thibault Station, which is the environmental boundary. As mentioned above, the events affecting the capacity of the Thibault Station fall between the dotted lines of Figure 7.1, which form the physical boundary of the study (Law & Kelton, 2000). The attributes of arriving buses are included in the model. Please refer to Chapter 8 regarding the method of assigning these attributes to the arriving buses. Having already assumed that buses arrive at the correct time, other factors, such as the location and driving of the buses, are excluded from the model.

7.3.2) THE LEVEL OF DETAIL

The capacity of the buses, the space available in the station, and the queues in which passengers wait are the main focus areas of the study. Activities such as the purchasing of tickets before proceeding through the turnstiles, or the time spent walking inside the station, are not taken into account. This could be integrated into the inter-arrival times of passengers.

7.4) THE CONCEPT MODEL

The concept model illustrates the basic logic and functioning of the system and is a repeat of how the system has been described in this chapter. The concept model is displayed in two parts. Part A illustrates the activities of the *buses* whereas Part B concerns the activities involving the *passengers* arriving at the Thibault Station. In the simulation model, these two parts must be carefully integrated to represent the entire operation of the system.

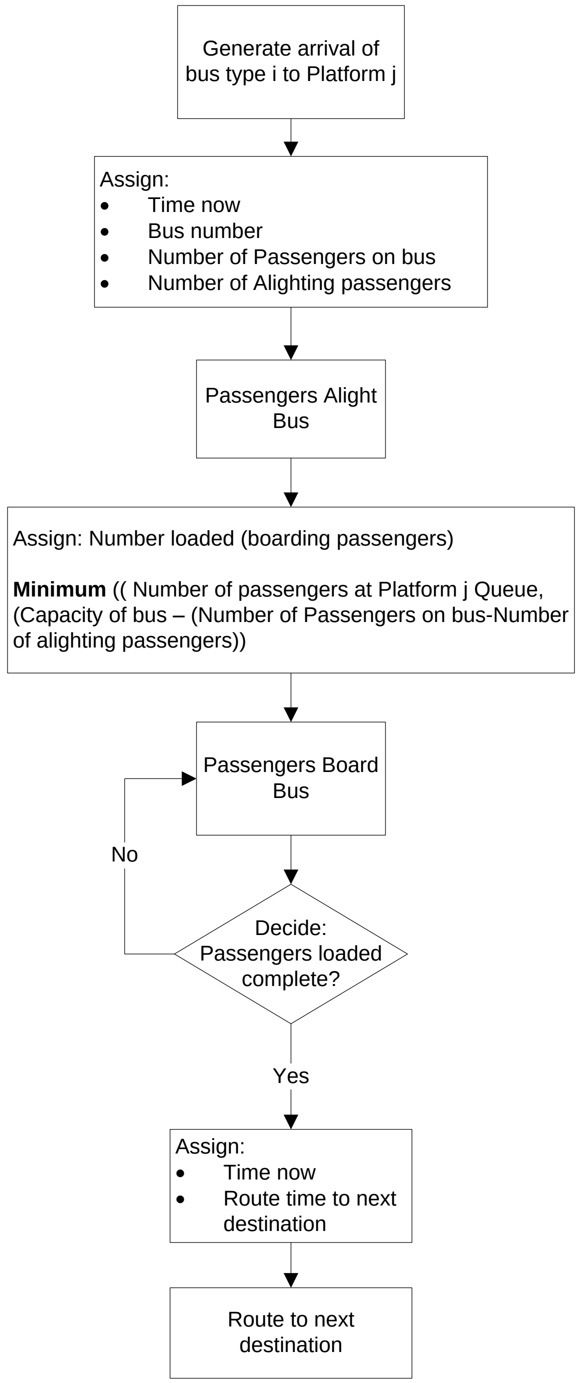

Figure 7.2 Concept Model Part A: Activities involving the buses

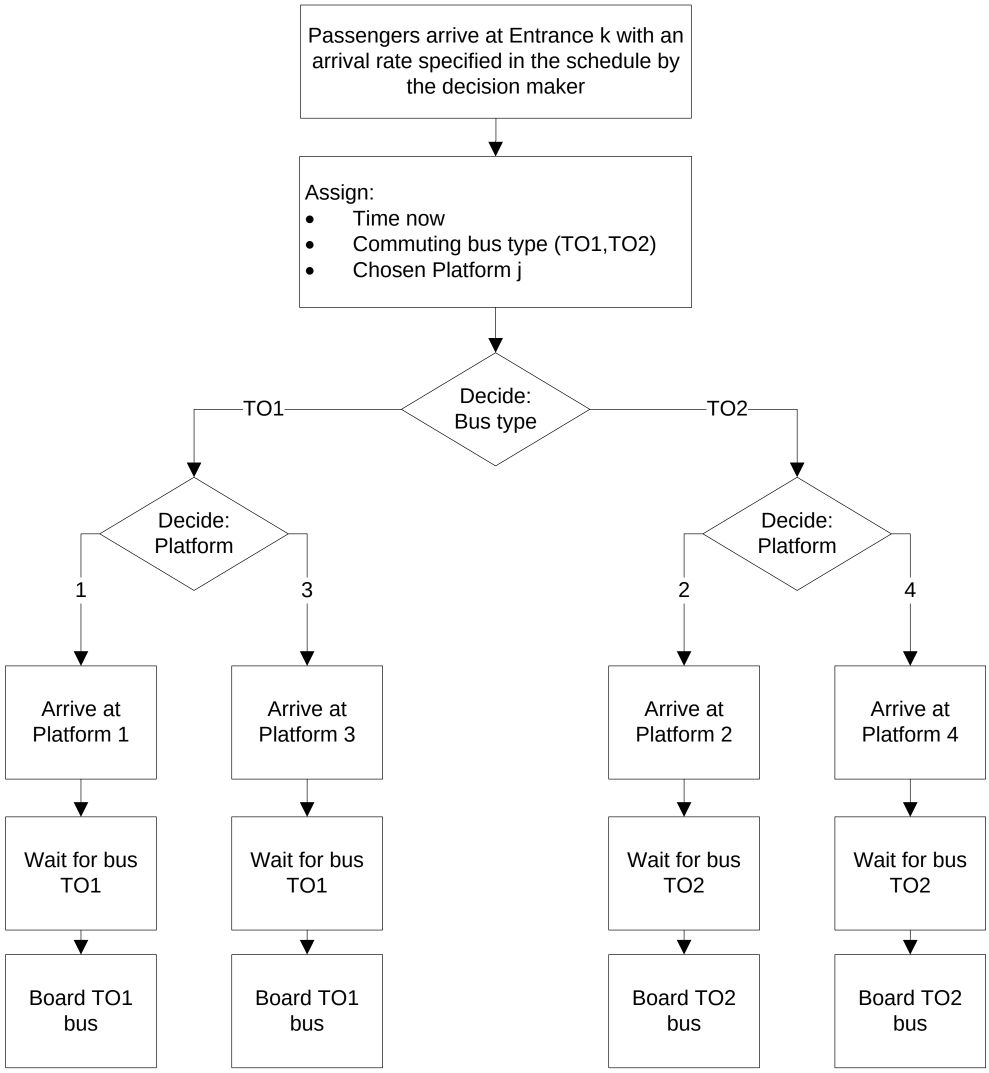

Figure 7.3 Concept Model Part B: Passenger activities

7.5) Performance measures

The operations of the Thibault Station form a terminating system as buses operate between specific times in a day. Because the method of operation and designs at the Thibault Station are based on calculations from deterministic equations, the simulation model is built to behave in a deterministic manner, therefore only running for a single day using no random input.

Having documented the operations of the Thibault Station in the concept model, performance measurements, which provide valuable information on the capacity levels experienced at the station, were decided on. These were chosen to be:

- Average platform queue length
- Frequency of averaged queue lengths
- Average waiting time in queue
- Maximum waiting time in queue.

The performance measurements contain the most important information for assessing the capacity of the station. It is thus imperative to ensure that the statistical calculations performed to obtain these performance measures are correctly calculated and implemented into the model so that the results are statistically credible. The following statistical issues arose concerning the implementation of the performance measures. The first issue concerns the use of *averages* where the performance measurement *average platform queue length,* which is calculated hourly, is discussed. This is not a 'normal' average like the *average waiting time in a queue,* which is taken over the *number of passengers* (this is discrete), but rather an average taken over *time,* which is known as a *time weighted average*. The meaning of time weighted averages is briefly explained by means of basic statistics. For in-depth statistical explanation, readers can refer to Law (2007). A time weighted average is an average that takes into account the *time* a queue remains at a certain length. This is mathematically denoted as:

$$\hat{q}(x) = \frac{1}{T(x)} \sum_{i=0}^{\infty} iT_i \qquad (7.1)$$

Where

i *the number of passengers in the queue*

T_i *the time during the simulation that the queue length is i*

$T(x)$ *the time required to observe the x delays (in this case it would be 1 hour), where x is the number of passengers who have completed their delays*

This equation calculates the product of the queue length and the time it remains at a certain length repetitively for all changes in the queue length and adds these together. A basic illustration of this concept is shown in Figure 7.4.

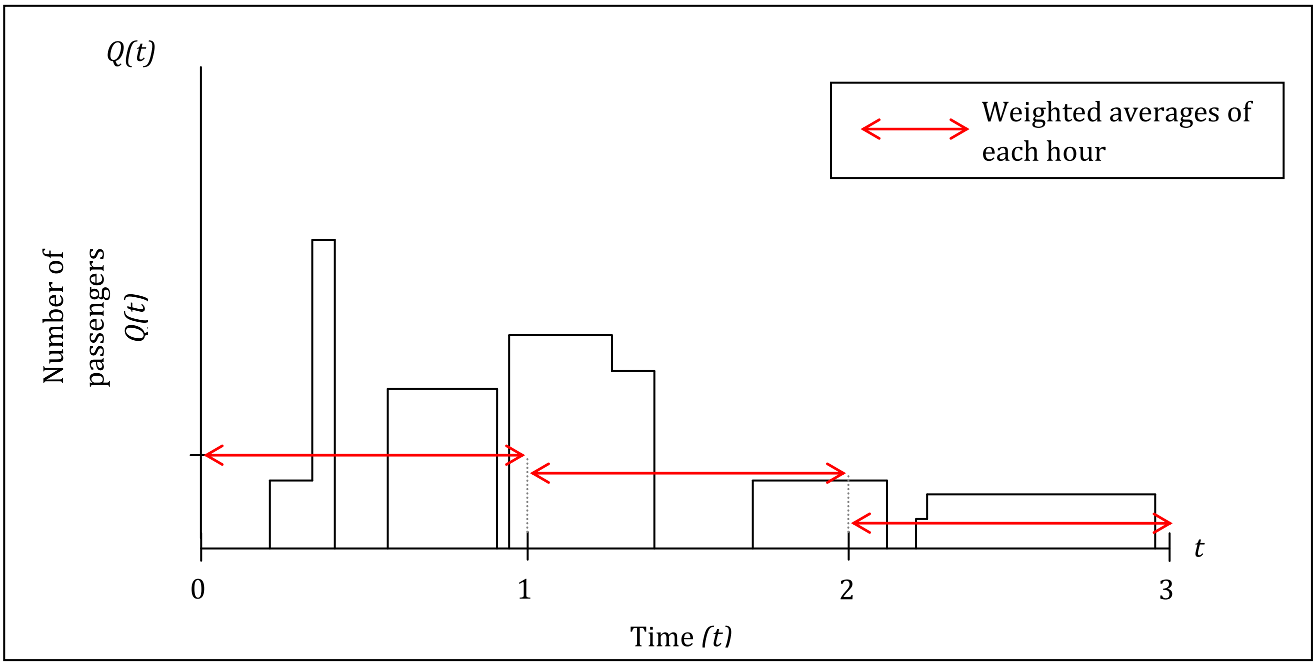

Figure 7.4 Weighted averages calculated hourly

Equation 7.1 is equivalent to the mean area of the curves of Figure 7.4 and can therefore be written as:

$$\hat{q}(x) = \frac{1}{T(x)} \int_0^{T(x)} Q(t)dt \qquad (7.2)$$

Where

$\hat{q}(x)$ *the average number of passengers in a queue*

$T(x)$ *the time required to observe the x delays*

$Q(t)$ *the number of passengers in a queue at time t*

This equation is preferable since the integrator can accumulate the small rectangles through time.

The following statistical matter concerns the use of *point estimators* and *half widths* for the stochastic models developed in Chapter 10 and are discussed next. By using *point estimates* together with a *half width,* valuable results are obtained of *expected values over a number of replications*. These terms are briefly explained.

Unbiased point estimators are used to estimate the true population parameter μ. Equation 7.3 shows how an unbiased point estimator is calculated.

$$\bar{\bar{X}}(n) = \frac{1}{n}\sum_{i=1}^{n} \bar{X}_i \qquad (7.3)$$

Where

$\bar{\bar{X}}(n)$ *is the point estimator over 'n' number of simulation replications*

$\bar{X}_i$ *is the average value for the* i^{th} *replication*

If a large number of independent replications is performed, where the observations of each replication results in an averaged $\bar{X}_i$, then the *average* of the $\bar{X}_i$ will be $\bar{\bar{X}}(n)$ which is referred to as the point estimator of μ.

Because $\bar{X}_i$ is a random variable with a variance Var[$\bar{X}_i$], the $\bar{X}_i$ will not be the same. While in one replication $\bar{X}_i$ may be close to the expected μ, another replication may estimate an $\bar{X}_i$, which differs largely from the expected μ. It is thus necessary to assess *how close* the point estimator $\bar{\bar{X}}(n)$ is to μ. The usual way to assess the *precision* of a point estimator is by including a confidence interval for μ. In this study, the confidence level is taken as 95% (*1-* α), which will provide a point estimate of a population parameter μ as well as a confidence interval half width, giving an idea of how precise this estimate is.

The half width is a more informative estimator that specifies the range in which $\bar{X}_i$ is expected. If the parameter to be estimated is μ, then the half width is [*L*,*U*], where *L* is the lower limit and *U* the upper limit of the half width, so that $P(L \leq \mu \leq U) = 1 - \alpha$. The value (1 - α) is known as the level of confidence, and α is the level of significance.

Therefore, for the performance measurement *average platform queue length* to be statistically viable, is must be calculated in the simulation as a *weighted average* as shown in Figure 7.4, and to ensure the correctness of the expected value of μ, point estimators with a half width are necessary, as shown in Equation 7.3.

7.6) SUMMARY: CHAPTER 7

A concept model of the Thibault Station has been described and illustrated in this chapter. The concept model describes the entities and activities involved with the operations of the Thibault Station which will be simulated. This forms a crucial part of the modeller's knowledge and understanding of the system before proceeding to the simulation and analysis of the model results.

The performance measurements of the system were also chosen and explained with information provided on statistical issues concerning the feasibility of the chosen performance indicators.

The concept model is simulated using Arena software and is used as the 'base' model for this study. It is further referred to in the document as the 'deterministic model'. The actual input data used in the deterministic model is explained in Chapter 8.

8) BUILDING THE SIMULATION MODEL

The simulation model is based on the concepts discussed in Chapter 7 and is built with the aim of *serving as a tool to investigate and analyse matters influencing the capacity of the Thibault Station*. The chapter begins by introducing strategic considerations for building the model, after which the actual data obtained are discussed. In Section 8.3, the method of incorporating the input data into the model is explained, where extracts from input spreadsheets are presented. The model was implemented in Arena (Rockwell, 2010), and the chapter concludes with an illustration and description of the Arena simulation model.

As noted previously, the model is built with the aim of serving as a decision support tool for BRT station capacity investigations. Although this model is based on the operations of the Thibault Station – that being Thibault's *specific* platform layout, bus schedule, passenger arrival rates and so on – the focus still remains on building a model that can be applied to *any* BRT station. Therefore, the following strategic considerations were identified: these are guidelines of what the simulation model must resemble for it to be used as a tool applicable on *any* BRT station.

8.1) STRATEGIC CONSIDERATIONS FOR APPLICATION IN MANAGEMENT

The simulation model must reflect the following strategic considerations to assist the manager when planning similar systems. Specifically, the manager must be able to evaluate various operational scenarios without the need for re-programming the model.
The model must be:

- Manageable
- Flexible
- Accessible
- Changeable.

A major facilitator for including these strategic considerations in the simulation model is Microsoft Excel. Simulation input data can be read into the spreadsheets, which are then linked to Arena. The input data can also be changed on the spreadsheets, and when the simulation model is run, the updated Excel data are read by the model. The Excel models, which were built for the input data to the simulation, are discussed in Section 8.3. The following section deals with the actual data obtained from Pendulum Consulting.

8.2) DATA OBTAINED FOR THE SIMULATION MODEL

Important data obtained from Pendulum Consulting are presented below. The data presented will assist with the understanding and reasoning of the developed Excel models (in Section 8.3), which serve as input data for the simulation model.

8.2.1) PEAK HOUR INFORMATION

Peak hour data are important estimates and have a significant influence on station design factors. This is owing to the large number of commuters in the system at peak hours. The station's layout must therefore be designed to provide sufficient capacity for these high levels of expected commuters. The data in Table 8.1 have been verified using the capacity equations from Chapter 4 and shows that the deterministic equations presented there are authentic and used in practical situations. Refer to Appendix B for the capacity calculations.

Route Code	**TO1**	**TO2**
Length-one way (km)	29	25
Cycle time (min)	121	98
Vehicle length (m)	18	12
Vehicle capacity	120	40
Fleet size (buses)	21	16
Frequency (veh/h)	10.9	9.3
Headway (min)	6	6

Table 8.1 Peak hour information

8.2.2) BUS SCHEDULE

The bus schedule during a day has been defined based on different demand profiles, so the numbers in Table 8.2 are percentages of the frequency of buses at peak hours. For example, between 4 and 5am, the TO1 route will operate at 10% of that specified in peak-hour frequency (veh/h) shown in Table 8.1. These percentages are further used as an indication of the estimated passenger arrival rates and are explained in Section 8.3.

Time of day	TO1	TO2
4 - 5am	10%	10%
5 - 6am	30%	30%
6 - 7am	90%	70%
7 - 8am	100%	90%
8 - 9am	60%	100%
9 - 10am	30%	100%
10 - 11am	20%	90%
11 - 12pm	20%	90%
12 - 1pm	30%	80%
1 - 2pm	30%	80%
2 - 3pm	30%	80%
3 - 4pm	30%	90%
4 - 5pm	60%	100%
5 - 6pm	100%	100%
6 - 7pm	80%	90%
7 - 8pm	40%	80%
8 - 9pm	10%	70%
9 - 10pm	10%	50%
10 - 11pm	10%	10%

Table 8.2 Bus schedule demand profiles

8.2.3) THE ACTUAL BUS FREQUENCIES USED DURING THE DAY FOR EACH ROUTE

The numbers in Table 8.3 were used in the first implementation phase of the Thibault Station and are therefore used in the simulation model. These are reduced from that of the demand percentages shown in Table 8.2. There are a number of reasons for the reduced figures provided by Pendulum Consulting. Some include certain policies restricting the number of buses implemented in the first phase, the lack of available funds, a starting and safety strategy to limit the number of vehicles in case the demand estimates are incorrect, and other system flaws that could be discovered at early stages of operation.

Time of day	TO1	TO2
4-5am	3	3
5-6am	4	4
6-7am	5	4
7-8am	5	3
8-9am	5	4
9-10am	3	4
10-11am	3	4
11-12pm	3	4
12-1pm	3	4
1-2pm	3	4

Time of day	TO1	TO2
2-3pm	3	4
3-4pm	3	4
4-5pm	4	4
5-6pm	6	4
6-7pm	5	4
7-8pm	4	4
8-9pm	2	3
9-10pm	2	2
10-11pm	2	2

Table 8.3 Reduced bus frequencies

Next, the input data for the simulation model, as well as the developed Excel spreadsheets, are explained.

8.3) INPUT DATA AND INPUT SPREADSHEETS FOR THE SIMULATION MODEL

An objective stated in Chapter 6 is to develop a *deterministic* simulation model of the Thibault Station as *deterministic equations* were used for the Thibault Station's capacity planning and system sizing. This section presents the input data for this model.

The data in Section 8.2 is incorporated into the simulation model by means of the developed Excel spreadsheets. There are two kinds of spreadsheets developed, namely the *User Interface* spreadsheets and the *Arena* spreadsheets. The *User Interface* spreadsheets are discussed in this section as these are the spreadsheets the users are concerned with. These spreadsheets allow the users to change the data so that different scenarios can be investigated. The *Arena spreadsheets* contain the same information as the *User Interface* spreadsheets but are converted into a format that is accessible by the Arena software. As users change data on the *User Interface* spreadsheets, the *Arena spreadsheets* are automatically changed, which in turn are linked to the *Arena Simulation Model.* A schematic drawing of the different interfaces is shown in Figure 8.1.

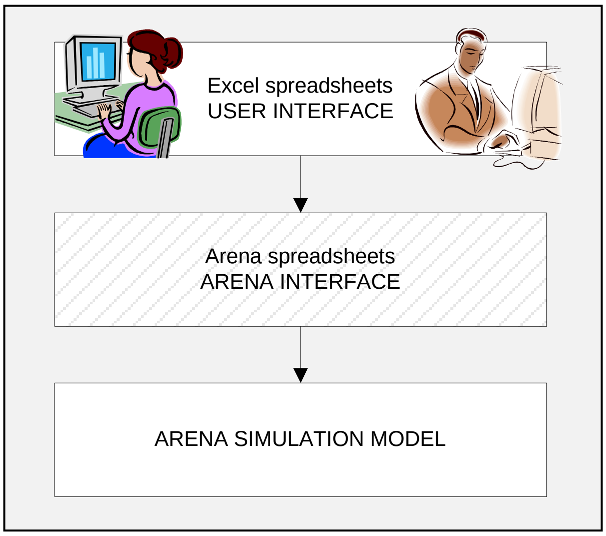

Figure 8.1 The interfaces used at different levels of operation

The input data related to the *arrival of buses* are explained first. An Excel spreadsheet was developed for each route, which also serves as a method of assigning the attributes to the arriving buses. An extract from the spreadsheet developed for the TO1 route is shown in Figure 8.2, with only the first two hours of the day displayed.

Bus Schedule TO1
Using estimated cycle times to assign scheduled arrivals and fleet size

Daily operating hour	Bus freq/hr	Estimated cycle times(Min)	Assigned bus number	Arrival times(min) at the different stations					
				P1	DO1	P3	DO2	Arrival time back at P1	
4-5	3	80 min		00:00	00:20	00:40	01:00	01:20	
			1	04:00	04:20	04:40	05:00	05:20	1
			2	04:20	04:40	05:00	05:20	05:40	2
			3	04:40	05:00	05:20	05:40	06:00	3
5-6	4	100 min		00:00	00:25	00:50	01:15	01:40	
			4	05:00	05:25	05:50	06:15	06:40	4
			5	05:15	05:40	06:05	06:30	06:55	5
			1	05:30	05:55	06:20	06:45	07:10	1
			2	05:45	06:10	06:35	07:00	07:25	2

Figure 8.2 Snapshot of a TO1 bus schedule

For a bus schedule to be prepared, the following data are needed:

- Bus frequency for every hour: In Figure 8.2, a frequency of three buses is used in the first hour with a bus arriving every twenty minutes.
- Estimated cycle times: For the first hour, an estimated cycle time of 80 minutes is used. This determines the inter-arrival time between the buses of that particular hour.

Once these figures are entered into the spreadsheet, the paths as well as the expected arrival times at the various stations can be followed. The simulation model reads the 'expected' arrival times as constants, therefore leaving no room for variation, fulfilling the deterministic model requirements. The buses can now be allocated to a schedule using either a mathematical allocation programme or by self-allocation. Because this study is not concerned with scheduling of buses, and does not involve intricate bus movement around the station, the schedule was self-assigned keeping the fleet size as low as possible. Refer to Appendix C1 for the entire spreadsheet of route TO1. The spreadsheet for the TO2 route is similar to that above and is included in Appendix C2.

The layout of the station was discussed in Chapter 7, and the bus operations and its input data in the previous section. The remaining capacity factor to deal with is the number of *passengers*. The *frequency* of buses passing through the station as well as the *physical design* of the station is governed by passenger demand estimates. Therefore, Excel spreadsheets have been designed for the input data of passenger estimates. The numbers on these spreadsheets can be adjusted so that the *effect of different volumes of passengers* on the designed capacity of the station, as well as the sufficiency of the bus capacities and frequencies, can be evaluated. Passenger estimates can also be gradually increased to determine what the capacity (pphpd) of a proposed station is. The method to achieve this is discussed in Chapter 10.

Figure 8.3 shows the *User Interface* spreadsheet used for specifying estimated percentages of passengers entering the station.

Passenger demand profiles	
Thibault Station at Full Capacity (Pph at Peak hour)	**800**
% of station capacity of TO1 bus service	80%
% of station capacity of TO2 bus service	20%

USERS CAN CHANGE THESE NUMBERS

Time of day	% Passenger estimates of full capacity		Estimated number of passengers		% of TO1 passengers enter Ent1&Ent2 to P1&P3				% of TO2 passengers enter Ent1&Ent2 to P2&P4			
	TO1 Busses	TO2 Busses	TO1 Busses	TO2 Busses	Entrance 1		Entrance 2		Entrance 1		Entrance 2	
					P1	P3	P1	P3	P2	P4	P2	P4
4-5am	10%	10%	64	16	35%	30%	25%	10%	40%	30%	20%	10%
5-6am	30%	30%	192	48	35%	30%	25%	10%	40%	30%	20%	10%
6-7am	90%	70%	576	112	35%	30%	25%	10%	40%	30%	20%	10%
7-8am	100%	90%	640	144	35%	30%	25%	10%	40%	30%	20%	10%
8-9am	60%	100%	384	160	35%	30%	25%	10%	40%	30%	20%	10%
9-10am	30%	100%	192	160	35%	30%	25%	10%	40%	30%	20%	10%
10-11am	20%	90%	128	144	35%	30%	25%	10%	40%	30%	20%	10%
11-12pm	20%	90%	128	144	35%	30%	25%	10%	40%	30%	20%	10%
12-13pm	30%	80%	192	128	35%	30%	25%	10%	40%	30%	20%	10%
13-14pm	30%	80%	192	128	35%	30%	25%	10%	40%	30%	20%	10%
14-15pm	30%	80%	192	128	35%	30%	25%	10%	40%	30%	20%	10%
15-16pm	30%	90%	192	144	35%	30%	25%	10%	40%	30%	20%	10%
16-17pm	60%	100%	384	160	35%	30%	25%	10%	40%	30%	20%	10%
17-18pm	100%	100%	640	160	35%	30%	25%	10%	30%	30%	20%	20%
18-19pm	80%	90%	512	144	35%	30%	25%	10%	40%	30%	20%	10%
19-20pm	40%	80%	256	128	35%	30%	25%	10%	40%	30%	20%	10%
20-21pm	10%	70%	64	112	35%	30%	25%	10%	40%	30%	20%	10%
21-22pm	10%	50%	64	80	35%	30%	25%	10%	40%	30%	20%	10%
22-23pm	10%	10%	64	16	35%	30%	25%	10%	40%	30%	20%	10%
Column	1	2	3	4	5	6	7	8	9	10	11	12

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USERS CAN CHANGE THESE NUMBERS

Figure 8.3 Passengers-arrival specification spreadsheet

This spreadsheet requires the following data:

- Thibault Station at full capacity: An estimate of the number of passengers inside the station at peak-hour traffic.
- Percentage of the station's capacity required for the TO1 service: The percentage of passengers making use of the TO1 service.
- Percentage of the station's capacity required for the TO2 service: The percentage of passengers making use of the TO2 service.
- Column 1 and 2 require the hourly percentage of peak-hour capacity estimates. In this example, the demand-profile percentages from Table 8.2 have been used. These percentages are actually an indication of the *number of buses* required at each hour. However, it can also be seen as an indication of the *number of passengers* expected at those hours. For example, if the frequency of vehicles between 4 and 5am is 10% of that of peak-hour frequency, one can argue that only 10% of the total number of passengers expected at peak hour will make use of the service during those hours. This example shows that all the factors affecting the capacity of the system are linked.
- Column 3 and 4 are automatically calculated by multiplying the capacity of the station with the specified percentages.
- Columns 5 to 12 are further estimates of the percentage of the passengers entering from either entrance 1 or 2 as well as their desired platform choice. For example, between 4 and 5am, 35% of the passengers who make use of the TO1 service will enter through Entrance 1 and proceed to Platform 1.

The Arena spreadsheet forms part of the spreadsheet shown in Figure 8.3. In columns 13 to 20, the percentages specified by the user are simply converted into arrival rates, which are read by Arena. The simulation model time maps the time intervals in the spreadsheets, i.e. one row of data is processed every simulated hour. Refer to Appendix D for the full passenger-demand estimate spreadsheet.

The last *User Interface* spreadsheet deals with the number of passengers on an arriving bus and the number of passengers embarking from that bus. An extract of this spreadsheet is displayed in Figure 8.4.

Specifying the number of passengers on an arriving bus and the number of alighting passengers							
Time	Load factor: % of bus capacity which is full	Bus capacity	**Passengers on bus at P1**	% of Passengers alighting the bus	**Number of alighting passengers at P1**	**Passengers on bus P3**	**Number of alighting passengers P3**
			TO1				
4-5am	5%	120	**6**	25%	**2**		
			6		**2**		
			6		**2**	**6**	**2**
5-6am	15%	120	**18**	25%	**5**	**18**	**5**
	USERS CAN CHANGE THESE NUMBERS		**18**	USERS CAN CHANGE THESE NUMBERS	**5**	**18**	**5**
			18		**5**	**18**	**5**
			18		**5**	**18**	**5**

Figure 8.4 Snapshot of the passengers-alighting specification spreadsheet

Figure 8.4 shows time slots for each arriving bus at the station, where a number representing the 'Passengers on bus' and the 'Number of alighting passengers' of that bus is allocated. Users can test a system by altering the load factors, bus capacity and percentage of disembarking passengers. They can also enter the figures in more detail, giving specific values to each arriving bus. In this case, values are kept constant throughout each hour. The same values were assigned to P3, which also holds for platforms 2 and 4. The complete spreadsheet, on which Figure 8.4 is based, is included in Appendix E.

In the following section, the Arena simulation model is illustrated and briefly explained without elaborating on the detailed coding of the model.

8.4) THE ARENA SIMULATION MODEL

An overview of the model logic in Arena is shown in the following figures. A few model concepts from Chapter 7 are discussed to provide a basic understanding of the model logic and to see how parts A and B from the concept model are implemented in the model.

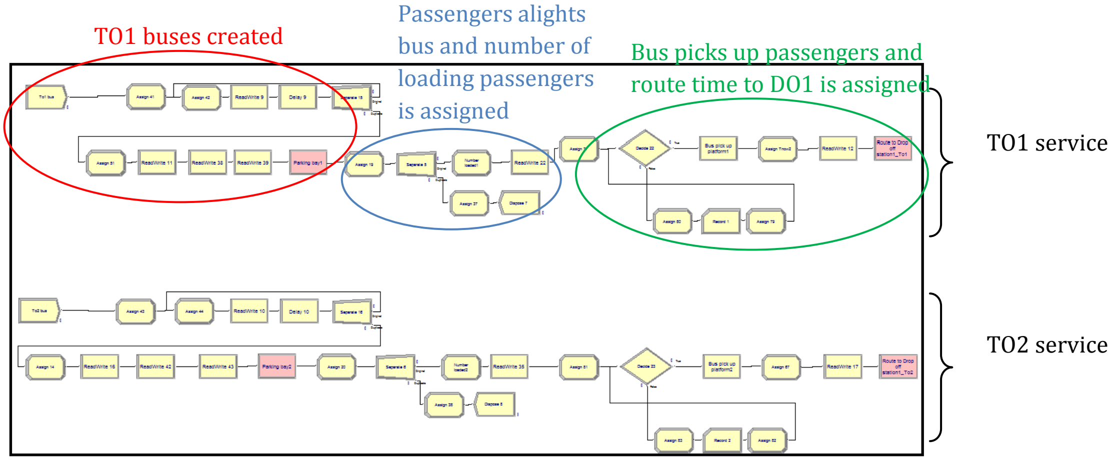


Figure 8.5 Arena modules used for executing bus operations at platform 1 and 2

Bus arrivals are created according to the schedule on the Excel spreadsheet. As buses arrive at the platforms, passengers disembark the vehicles, where after the number of passengers able to board the bus is assigned. The bus boards passengers on a 'first–come-first-served' basis and if the bus becomes full during boarding, the remaining passengers in the queue wait for the next scheduled bus. After passengers have boarded the bus, the route time to the next destination is assigned and the bus leaves the platform. This procedure also holds for the operations at platform 3 and 4, which are illustrated in Figure 8.6.

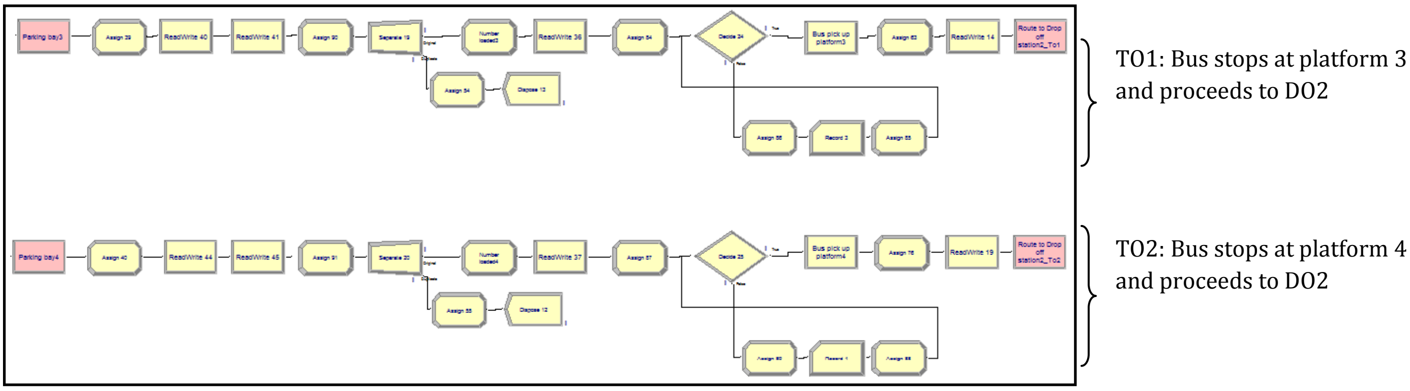


Figure 8.6 Modules used for bus operations at platform 3 and 4

The model logic of buses stopping at the drop-off stations is shown in Figure 8.7. These operations are similar to those taking place at the other platforms. The *bus* model logic follows that of Figure 7.1, routing from station to station, alighting and picking up passengers.

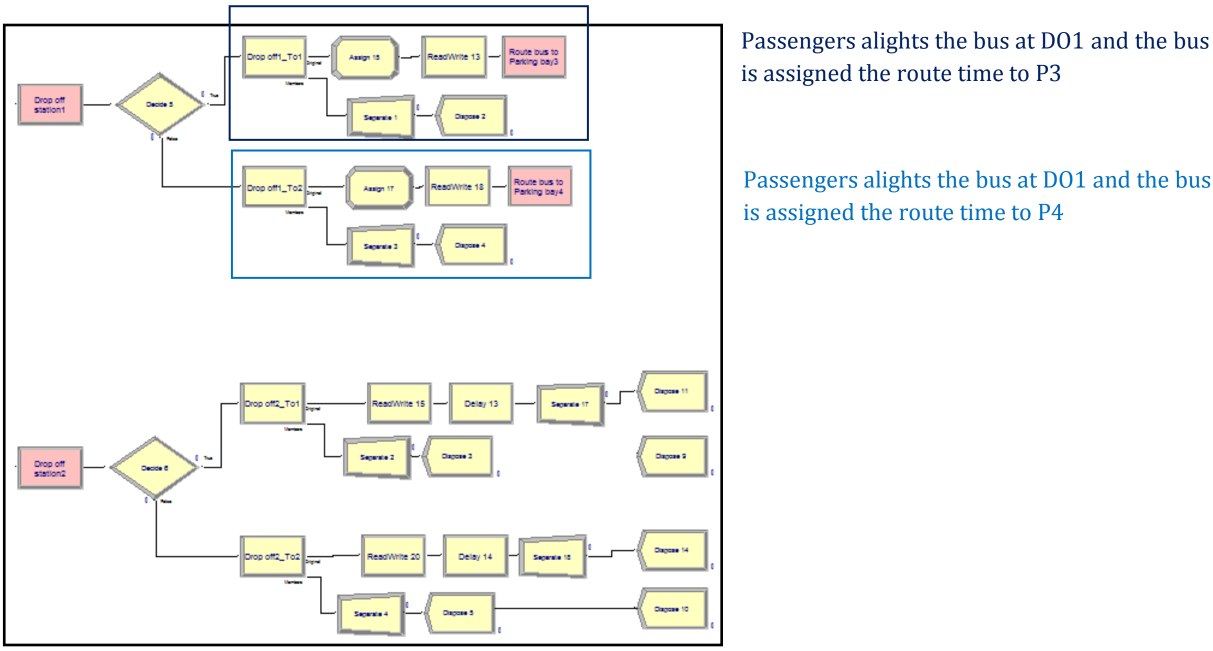


Figure 8.7 Modules used for bus operations at the drop-off stations

Next, the model logic for the *passengers* is shown. The model logic is executed when passengers arrive at the station through *Entrance 1* as shown in Figure 8.8. The same model logic is also used for passengers arriving through *Entrance 2*.

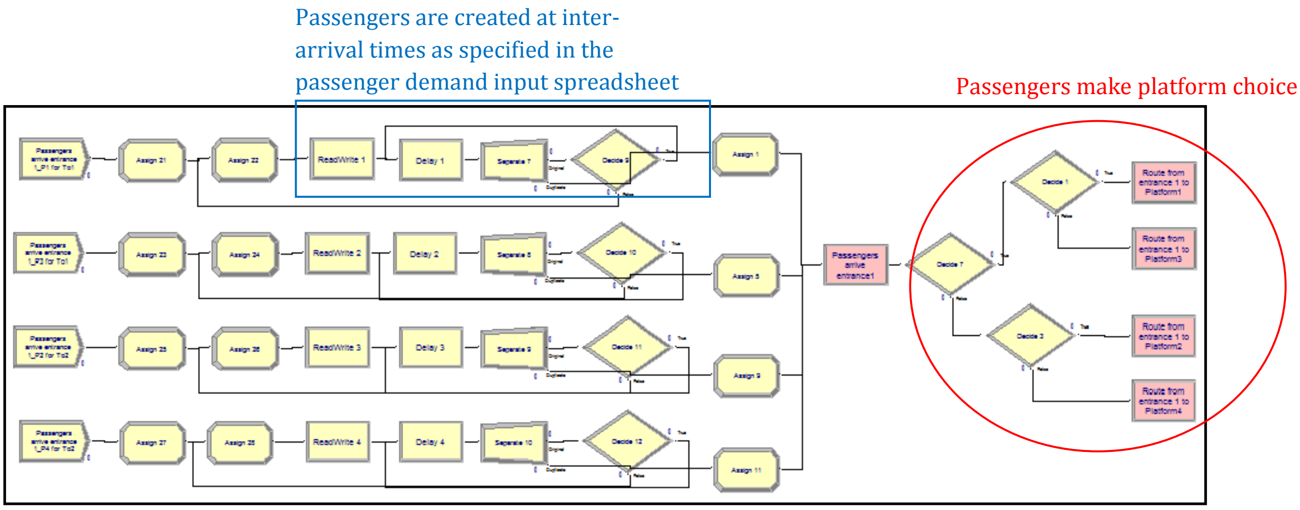


Figure 8.8 Modules used to execute passenger operations

The model logic of passengers waiting in the queue at platform 1 is shown below.

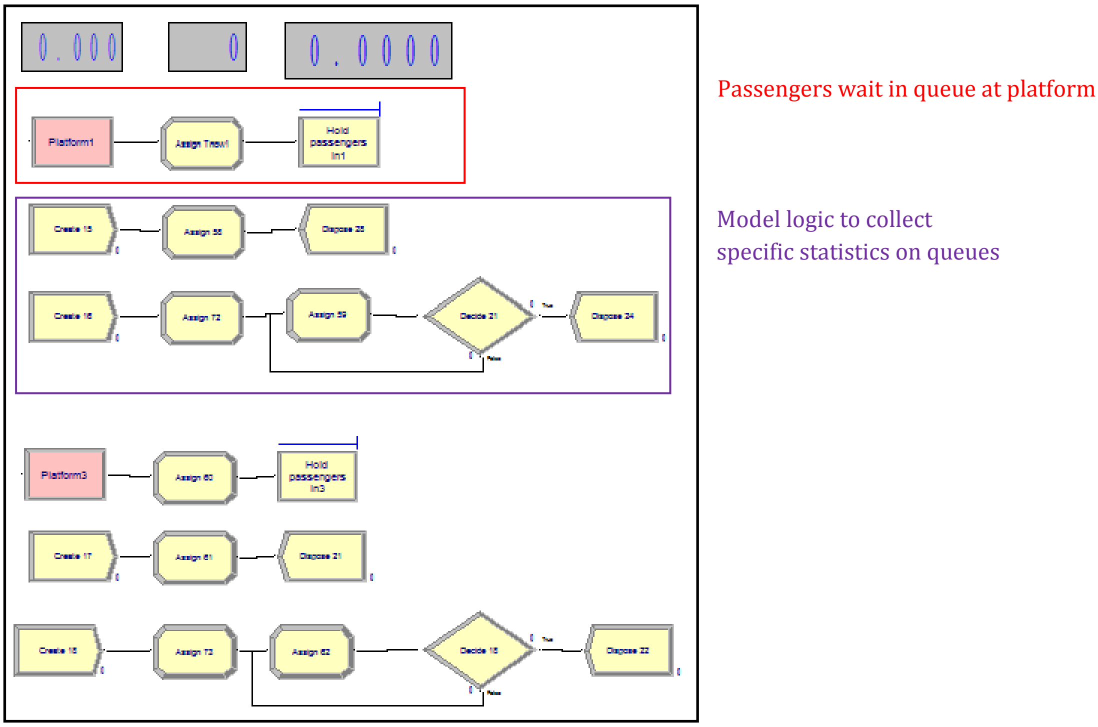


Figure 8.9 Modules used to execute queue operations

Although the detail of implementation is omitted, the previous figures should give the reader an idea of the model implementation in a specific simulation package.

8.5) SUMMARY: CHAPTER 8

This chapter explains the *reasons and methods* used for *building and using* the simulation model. It starts by providing strategic guidelines of how the simulation model must be built for it to fulfil its management goals. This is followed by discussing the data obtained from Pendulum Consulting, where after the format and design of the simulation model's input data spreadsheets were explained. Extracts from the input data spreadsheets are shown with information provided on the contents and use thereof. The chapter concludes by giving a brief illustration and explanation of the actual simulation model built in Arena. Chapter 9 shows techniques used to verify and validate the correctness and reasonableness of the model.

9) VERIFICATION AND VALIDATION

The verification and validation of the simulation model forms part of the simulation steps discussed in Section 5.7 on p. 49. To recap, *verification* concerns the ability of the model to comply with the model specifications and assumptions made in the conceptual model, therefore investigating the *correctness* of the simulation model. *Validation* on the other hand confirms that the *right* model has been built for the *right* purpose. These were both done continuously throughout the building process and are discussed in this chapter. The verification and validation techniques presented here are based on Law (2007).

9.1) VERIFICATION OF THE SIMULATION MODEL

Verification is also known as *debugging* the simulation model and the techniques used to do this are discussed in this section. The verification of the model is fairly simple since the input and operations of the model are deterministic, allowing one to know what the output should be and in some instances require hand calculations to see if the model is operating as intended. The following techniques were used to verify the simulation model:

- Correcting *error* messages in the simulation, which prevent the simulation model from running.
- Running the model under different input parameter values to test the reasonableness of the output parameters: different input data were inserted into the spreadsheets to see whether the simulation model will run under extreme values and how this was reflected in the output of the model.
- More than one person reviewing the simulation model: a structured 'walk-through the simulation model' was conducted for objective criticism, helping with model debugging and finally gaining confidence in the correctness of the model.
- A powerful technique used for debugging a discrete-event simulation is known as 'tracing'. This method required the state of the simulation to be displayed right after an event has taken place and the simulation was then compared to hand calculations to see whether it operates as intended. By using a 'module break' before, after or at the point in time where an event occurs, the system is 'paused' and specific information about the state of the system can be obtained, such as certain statistical counters, state variables, contents of the events list and many more. The 'command function' in

Arena is commonly used to specify the required information. An example of how the module breaks, and how command functions can easily be used to verify the functioning of the *drop-off* and *pickup* of passengers, is shown below:

Example: Using module breaks and command functions to obtain information used to prove the correctness of the bus operations

Investigating the operations of a TO2 bus with a passenger capacity of 40:

1) The command function is used to show the number of passengers waiting in the queue *before* the bus picked up the passengers: sh nq(Hold passenger in queue2.queue) = 20

2) The command function is used to show the number of passengers on the arriving bus: sh (Passengers in bus) = 30

3) The command function is used to show the number of passengers alighting from the bus: sh (Passengers alight) = 7

   We therefore know, by applying simple mathematics, that the number of remaining passengers inside the bus is: 30 – 7 = 23. Because the bus can only take 40 passengers, we now know that the bus may only pick up 17 passengers out of the 20 passengers waiting in the queue.

4) The command function used to show the number of passengers that the bus picked up: sh (Number loaded) = 17

   The number loaded is correct. We can also check the number of remaining passengers in the queue which should be three.

5) The command function is used to show the number of passengers in the queue right after the bus has departed: sh nq(Hold passengers in queue2.queue) = 3

Furthermore, an example where seven passengers arrived on the bus with a capacity of 40, and two disembarked, while there were five passengers waiting in the queue: By using the same command functions mentioned above, it was verified that the bus picked up the five passengers waiting in the queue, with zero passengers remaining in the queue. The bus departed with 10 passengers inside the bus.

We have now been able to verify that the *drop-off* and *pickup* functions of TO2 buses work correctly.

Another method used for 'tracing' is through defining variables which are displayed (animated) in the simulation model workspace. If a module break is placed at a point where these variables are influenced, the values are updated and shown each time an event occurs at that point, thereby easily monitoring its value. An example of this is shown in Figure 9.1 and 9.2. A module break is placed over the Assign module, and above the modules appear two boxes containing the values of variables. The first box displays the value of the queue length, whereas the second box displays the current time weighted average queue length for that hour. In Figure 9.1 the queue length is 3, and the time weighted average of the queue is 7.836.

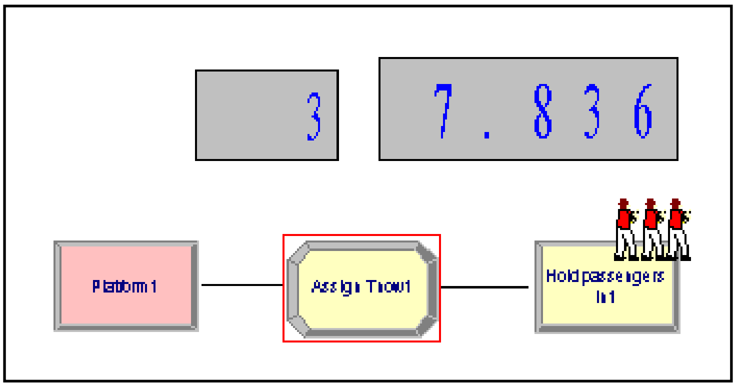


Figure 9.1 An example of tracing variables (3.201 hrs)

The model was run again, until it 'stopped' at the module break at 3.206 hrs (simulation time) where an event occurred. In this case, another entity joined the queue which is shown in Figure 9.2. The queue length variable increased to four passengers, and the time weighted average adjusted accordingly. The queue length is also animated above the queue module. If the queue length exceeds a certain number, the animation fails to illustrate all the entities. The use of variable boxes indicating the values are also useful in these instances.

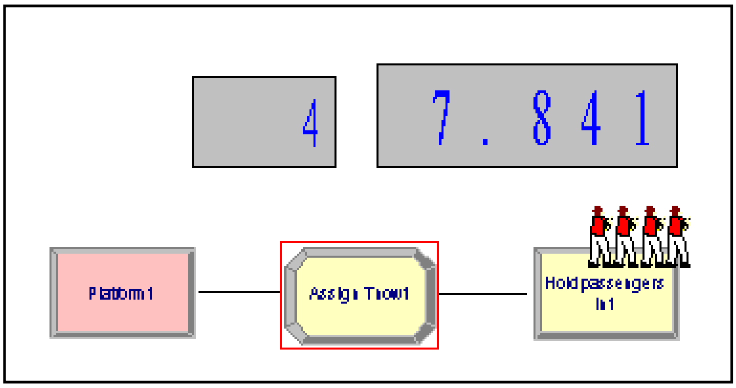


Figure 9.2 An example of tracing variables (3.206 hrs)

- Method of observation: Following entities as these flow through the simulation model is a good method of inspecting the model logic and functioning thereof. Module breaks and command functions are used to obtain information on entity-specific attributes. Module breaks are also used to capture the times of entity creations, which are then verified by comparing these times to those specified on the input data spreadsheets. An example of how this method was used for verification is shown in Table 9.1.

Functions	Verification techniques		
	Module break	**Command function**	**Input data spreadsheets used to compare the values obtained from the command function**
TO1 Buses			
Buses arrive according to schedule	Parking bay 1 module	Step function (to view times)	Bus schedule TO1 spreadsheet
Buses drop-off and pickup correct amounts	Number loaded and Pickup module	Sh (Passengers on bus) Sh (Alighting passengers) Sh (Number loaded)	N/A
Bus attributes are correct	Assign module	Vi en # (shows all entity att)	Bus schedule TO1 spreadsheet
TO2 Buses			
Buses arrive according to schedule	Parking bay 2 module	Step function (to view times)	Bus schedule TO2 spreadsheet
Buses drop off and pick up correct amounts	Number loaded and Pickup module	Sh (Passengers on bus) Sh (Alighting passengers) Sh (Number loaded)	N/A
Bus attributes are correct	Assign module	vi en # (shows all entity attributes)	Bus schedule TO2 spreadsheet
Passengers			
Passengers arrive according to schedule	Passengers arrive at entrance 1 Passengers arrive at entrance 2 module	Sh (att_Time_arrival)	Passenger arrival estimate spreadsheet
Passengers wait in queues	Hold passengers in queue x module		
Passengers enter buses	Hold passengers in queue x module	Sh nq(Hold passengers in queuex.queue)	N/A

Table 9.1 Using the method of observation to verify system operations

The verification methods mentioned in the section were used in conjunction with one another to verify all the simulated events of the Thibault Station.

9.2) VALIDATION OF THE SIMULATION MODEL

Validation of the simulation model is an essential *process*, which determines whether or not the model is a true and adequate representation of the proposed system for the particular objectives stated in Chapter 6. Validation was performed throughout the development of the model to establish whether the *right model was built for the right purpose.* The techniques used to increase the validity and credibility of the simulation model is described below.

- Interviews were conducted to gain valid information for the model and discussions were held with subject matter experts (SME) about the simulation model logic, functioning and performance measurements chosen for the model.
- Assumptions made before building the model (mentioned in Chapter 7) were discussed and agreed upon together with the SMEs.
- Quantitative techniques used to validate components of the simulation model: *Sensitivity analysis* was the method used to determine that *passenger activities* have a significant impact on the performance measures of the system. Further information on the sensitivity of *passenger activities* and the use of common random numbers to experiment with the performance of this model are discussed in Chapter 10.
- Results validation: SMEs were used to validate the output of the simulation model as well as the reasonableness of the results as expected from the proposed system.
- A common method known as the *face validity* of a system was executed by SMEs. This involves identifying problems in the model logic, functioning and correctness of the system. A system is said to have *face validity* if the simulation results are consistent with the *perceived* system behaviour. Table 9.2 includes face validation functions investigated by SMEs.

The SMEs were system planners from Pendulum Consulting as well as an expert in the simulation field.

Functions	Criteria	
Bus functions:		
Bus schedule	Do the buses arrive according to the schedule?	√
	Are the bus numbers correctly assigned?	√
	Do the buses rotate correctly in their specific sequence?	√
	Are the bus attributes correctly assigned to buses completing a cycle?	√
Boarding and disembarkation procedures	Is the correct number of disembarking passengers assigned to the bus?	√
	Is the correct number of passengers remaining on the bus (i.e. disembarking the bus) assigned to the bus?	√
	Is the remaining capacity of the bus correctly calculated after passengers have disembarked from the bus?	√
	Do the buses pick up passengers from the correct queues?	√
	Do the buses leave when passengers are loaded?	√
Passenger functions:		
Arrivals	Are passenger arrivals according to schedule?	√
	Do passengers arrive correctly from entrance 1 and 2?	√
	Are passengers assigned their correct bus type?	√
	Are passengers assigned their correct platform choice?	√
Queues	Do passengers wait in the correct queue?	√
Boarding and disembarkation procedures	Is the correct number of passengers disembarking the bus?	√
	Is the correct number of passengers entering the bus?	√
	If the capacity of a bus only allows a certain number of passengers from the queue to board, is the number of passengers remaining in the queue after boarding correct?	√
Other functions:		
Overall functioning	Does the model terminate correctly after 19 hours of operations?	√
	Does the functioning of the model follow that portrayed by the concept model?	√

Table 9.2 Face validation issues

9.3) SUMMARY: CHAPTER 9

The verification and validation techniques used to establish the credibility of the model were presented in this chapter. This is an important process, which is continuously done throughout the development of the model to assure the objectives of the study and the value of the output performance measurements are indeed achieved at the end of the study.

The deterministic model's building process was described in Chapter 8, while the verification and validation of the model was established in this chapter. We can now confidently proceed to Chapter 10, which involves the development of stochastic models *from* the deterministic model to investigate the difference in output performance measurements when including elements of randomness into the model. The validation and verification methods presented in this chapter were also applied to the stochastic models.

10) Stochastic Modelling of the System

The base model, built from the concept model presented in Chapter 7, is referred to as the *deterministic model.* It has already been established *how* this system behaves, but not under conditions which include elements of uncertainty. Consequently, random behaviour is brought into the study by developing *stochastic models* of the Thibault Station. The detail of the stochastic models is explained in this chapter, where after an example of using a stochastic model for testing the capacity levels of the Thibault Station is shown. Before proceeding to the detail of the models, the processes chosen to be modelled stochastically are substantiated and briefly discussed.

There is usually some element of uncertainty present in real-world systems, and it is often the randomness itself that leads to important system behaviour. *This is the reason for developing stochastic models of the Thibault Station where the flow of passengers was chosen to be modelled randomly so that the impact on the model results and station capacity can be examined.*

As mentioned before, the bus operations and design of the station are governed by the estimated passenger demand, and because inter-arrival times of passengers involve significant amounts of uncertainty, these were chosen to be modelled stochastically. Random numbers were assigned to the following passenger activities:

1. Inter-arrival times of passengers
2. The number of alighting passengers.

The focus remains on investigating the impact *inter-arrival times of passengers* (1) have on the capacity of the station since arriving passengers *wait in queues*, which reveal important information regarding the capacity levels of the station. It is also necessary that the number of disembarking passengers and those remaining seated are modelled randomly so that the actions concerning the *passengers waiting in queues* are completely random and not affected by deterministic numbers as defined on the input data spreadsheets used in the deterministic model. Therefore, the *alighting passenger data spreadsheet* is not used in the stochastic models but is rather replaced by random numbers, which are elaborated on later in this chapter.

10.1) STOCHASTIC MODELS

The uniform distribution was chosen as the input probability distribution to model the inter-arrival times of passengers. This distribution was chosen since there was no statistical pattern of the arrival times in the *passenger-arrival specification spreadsheet* to which a distribution could be fitted. The inter-arrival times specified on this spreadsheet are still used as the basis of the arrival rates but are adjusted to random numbers by using the uniform distribution. This is done so that the passenger demand profiles throughout a day (i.e. peak hour volumes and other estimated fluctuations) are still taken into account. The probability density function of this distribution is shown in Figure 10.1.

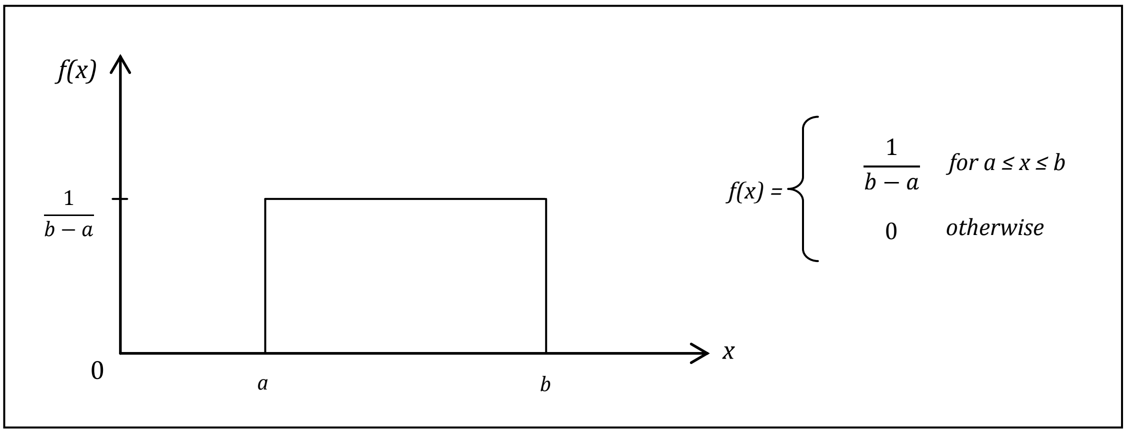


Figure 10.1 Probability density function of the uniform distribution

The uniform distribution is used when all values over a finite range [a,b] are equally likely to be considered; in other words, all values in the range have the same probability of being chosen. The way the uniform distribution is implemented into the stochastic models is explained next.

10.1.1) STOCHASTIC MODEL 1

In this model, the inter-arrival times are taken from the *passenger arrival specification* spreadsheet over which a uniform range is placed to induce variation of these numbers. The aim of Stochastic model 1 is to keep the inter-arrival times the same as specified on the *passenger arrival specification* spreadsheet and increase the range of the uniform distribution by 25% for each scenario to examine the effect these increases have on the output of the model, relative to the inter-arrival time mean for that period. Figure 10.2 shows the four scenarios, each with an increased uniform range. The inter-arrival time of *each observation* is adjusted by the uniform distribution to behave randomly.

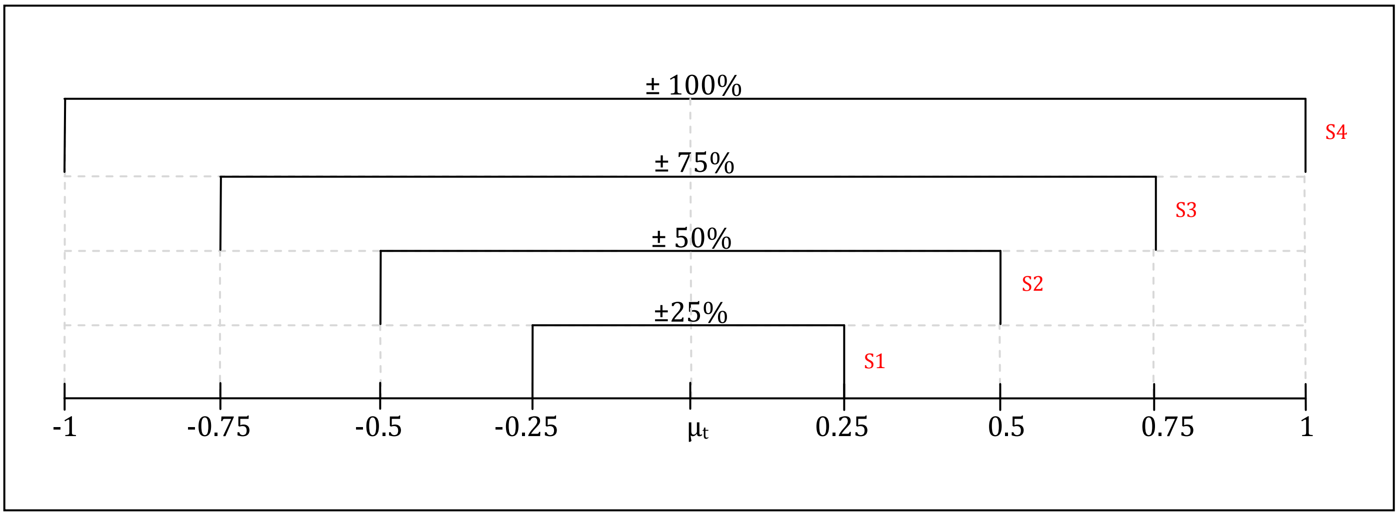


Figure 10.2 The developed scenarios of Stochastic model 1

The following is used to calculate the inter-arrival times for the various scenarios:

Scenario 1:	*(UNIF[-0.25,0.25] × (inter-arrival time)) + (inter-arrival time)*
Scenario 2:	*(UNIF[-0.5,0.5] × (inter-arrival time)) + (inter-arrival time)*
Scenario 3:	*(UNIF[-0.75,0.75] × (inter-arrival time)) + (inter-arrival time)*
Scenario 4:	*(UNIF[-1,1] × (inter-arrival time)) + (inter-arrival time)*

The more the range increases for the respective scenarios, the larger the difference between the *original* inter-arrival time and the *random* inter-arrival time could become. The outcomes of the scenarios are discussed in Chapter 11.

10.1.2) STOCHASTIC MODEL 2

The model is designed to investigate two cases. Instead of keeping the inter-arrival times constant and varying the range of the distribution, the range of the inter-arrival times are shifted while the size of the range is kept constant at 25%. This can be seen in Figure 10.3.

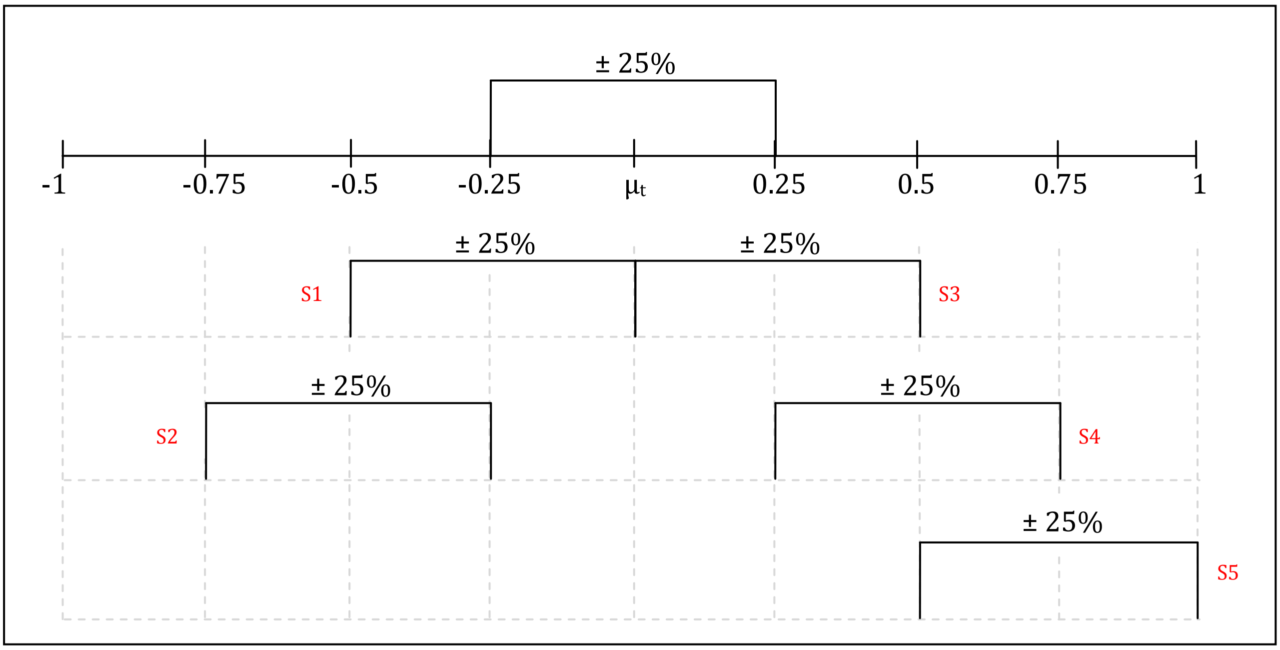


Figure 10.3 The developed scenarios of Stochastic model 2

The inter-arrival times of passengers in this model are calculated as follows:

Scenario 1: ((inter-arrival time) - (inter-arrival time × 0.25)) + (UNIF[-0.25,0.25] × (inter-arrival time))

Scenario 2: ((inter-arrival time) - (inter-arrival time × 0.5)) + (UNIF[-0.25,0.25] × (inter-arrival time))

Scenario 3: ((inter-arrival time) + (inter-arrival time × 0.25)) + (UNIF[-0.25,0.25] × (inter-arrival time)

Scenario 4: ((inter-arrival time) + (inter-arrival time × 0.5)) + (UNIF[-0.25,0.25] × (inter-arrival time))

Scenario 5: ((inter-arrival time) + (inter-arrival time × 0.75)) + (UNIF[-0.25,0.25] × (inter-arrival time))

One reason for developing the scenarios is to validate the correctness of the model by comparing the scenarios against each other. For example, the inter-arrival times of Scenario 2 must be smaller than those of Scenario 1. This must result in longer overall queue lengths in Scenario 2, compared to Scenario 1. The outcomes of such cases were investigated and are presented in the next chapter. These scenarios are therefore used to declare the correctness of the stochastic model.

The second reason for developing this stochastic model is to examine the effect the uniform distribution has on the model outcome if the inter-arrival times are adjusted slightly with the range of the uniform distribution kept constant.

As stated before, the passengers disembarking the bus and those remaining seated have to be modelled randomly to ensure variation throughout the activities affecting the number of passengers boarding a bus. This figure can be obtained by multiplying a random number with the capacity of a bus and round the result. The method used to assign values to disembarking passengers and those remaining seated are shown for the TO1 buses with a capacity of 120:

'RA' is a random number from the uniform continuous distribution between 0 and 1
Passengers arriving on the bus = Int(RA × 120)
Passengers alighting the bus = RA × (passengers arriving on the bus)
Boarding passengers = MIN (Passengers in the queue, (Capacity of the bus−(passengers arriving on the bus − passengers alighting the bus))
The same method was applied for the TO2 buses with a capacity of 40.

The outcomes of the generated numbers were compared to those from the *deterministic model.* The impact the random numbers had on the system was minimal and were therefore accepted since the values must still closely resemble those of the *deterministic model* but include variation (because the student is mainly concerned with the impact *boarding* passengers have on the capacity levels of the station and therefore wanting to keep the other factors unchanged). This method of assigning random numbers to disembarking and seated passengers were used in both stochastic models developed. The results of *Stochastic model 1* are used to verify the method used for assigning these random numbers.

10.2) OUTPUT DATA ANALYSIS

Simulation output data of stochastic processes are *random* and therefore conclusions about the model's true characteristics must be carefully dealt with. The chosen performance measurements as well as related statistical issues have been discussed in Chapter 7 but additional information regarding the replication run length and statistical analysis is addressed in this section.

Each simulation run produces only *estimates* of a model's true output characteristics and it is therefore necessary that several independent replications are run for improved estimates. A major cornerstone of statistical theory, also known as the *second fundamental theorem of probability,* is the *central limit theorem,* which states that if the sample size (replications) increases the distribution of the sample average of these random variables will be normally distributed with a mean μ and a variance σ^2. This basically reassures us that our estimates will be reasonable. In the stochastic models, which are terminating systems, the number of replications is set to 50 (i.e. 50 observations) where one replication represents a day of 19 hours. This number of replications provides an acceptable 95% half width.

The Output analyser of Arena and Excel were used to analyse output data and present performance indications of the models developed. The results from the stochastic models are presented in Chapter 11.

10.3) SUMMARY: CHAPTER 10

The stochastic models were primarily developed because these are believed to be a closer representation of the real-world system than that of the designed model currently in use, which is deterministic and does not include elements of uncertainty. Several scenarios were constructed and explained in this chapter. The aim is to investigate the performance of these scenarios and the impact these have on the capacity of the proposed Thibault Station designs. The reader will subsequently be shown *how* the model can be used in various ways to obtain significant information and the consequences of decisions made. The outcomes of the scenarios are provided in Chapter 11 together with performance measurements, analysis and findings of the results obtained.

11) RESULTS AND ANALYSIS

The outcomes of the independent simulation runs of the stochastic models provided sufficient estimated values of the performance measurements at a confidence level of 95%. These values were used to assess the capacity levels of the Thibault Station. The various methods used to obtain information from the models are presented subsequently.

First, the results of the scenarios developed from *Stochastic model 1* are shown, followed by the analysis thereof. After this, the same procedure is followed for the scenarios developed from the second stochastic model. The results from these models are discussed as well as the methods used to obtain important information from the results for decision-making purposes. The chapter concludes with a method to present information to the user, enabling him/her to weigh up different platform sizes against different capacity levels. This method is showed by comparing two scenarios against one another.

11.1) STOCHASTIC MODEL 1: SCENARIO RESULTS AND ANALYSIS

For the convenience of the reader, the figures from Chapter 10, illustrating the different scenarios investigated, are repeated below.

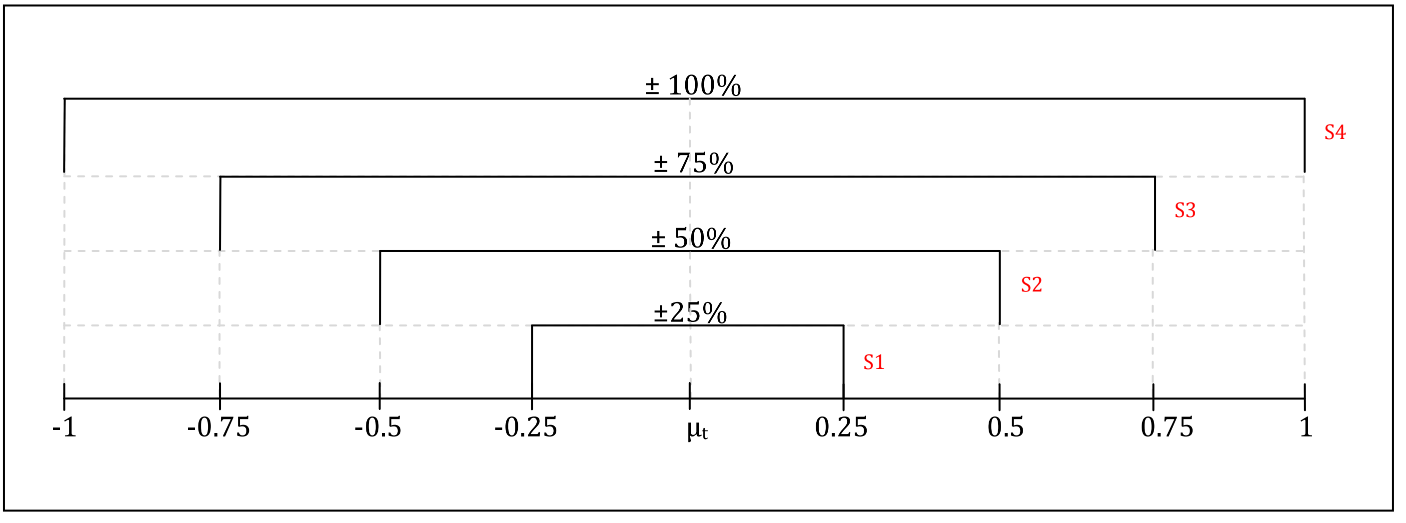


Figure 11.1 The developed scenarios of Stochastic model 1 (repeat)

The results from the various scenarios are listed on Excel spreadsheets and contain long lists of numerical data. It was therefore chosen to present the results by means of graphs presenting the hourly averaged queue lengths of the different platforms over a day. This also allows one to draw conclusions from the graphs by comparing the scenarios against one another. The average queue lengths for the scenarios are displayed in Figure 11.2 and contain four graphs, each representing a different platform queue of the Thibault Station.

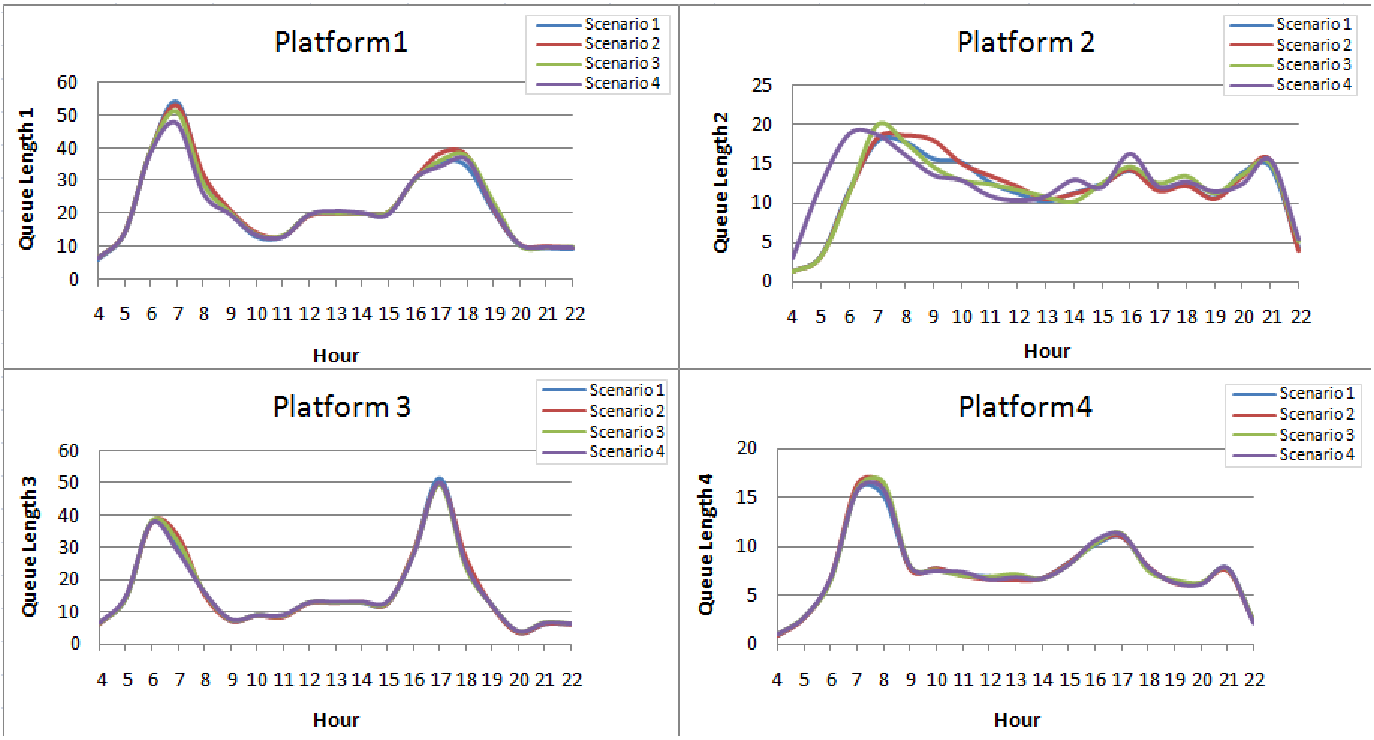


Figure 11.2 Stochastic model 1: average platform queue lengths

Further results obtained from the queues are shown in Table 11.1.

Average waiting times in queues (hrs)				
	Queue 1	*Queue 3*	*Queue 2*	*Queue 4*
Scenario 1	0.14	0.16	0.17	0.16
Scenario 2	0.14	0.16	0.17	0.16
Scenario 3	0.14	0.16	0.17	0.16
Scenario 4	0.14	0.15	0.17	0.16
Max. waiting times in queues (hrs)				
	Queue 1	*Queue 3*	*Queue 2*	*Queue 4*
Scenario 1	0.52	0.62	0.64	0.65
Scenario 2	0.54	0.62	0.63	0.67
Scenario 3	0.53	0.62	0.65	0.68
Scenario 4	0.51	0.62	0.68	0.66
Daily average number of passengers in queues (hrs)				
	Queue 1	*Queue 3*	*Queue 2*	*Queue 4*
Scenario 1	22	17	12	8
Scenario 2	23	17	12	8
Scenario 3	22	16	12	8
Scenario 4	22	16	12	8

Table 11.1 Stochastic model 1: scenario results

The different scenarios show no significant differences when compared in Figure 11.2. The reason for this observation is the fact that no elements in the simulation model affect the arrival rates of passengers. Therefore, the uniform distribution being placed over the *original inter-arrival times* ends up assigning values over the *different* ranges, but the same expected values, and because of the equal probability of numbers being allocated on each side of the range, the final averaged values over these *ranges* end up being similar to the *original inter-arrival time* values.

Although the system was not greatly impacted by using the uniform distribution to induce random variation to the inter-arrival times, the model is still valuable and can be used to assess the *correctness* of certain parts of the model by comparing it against the *deterministic model*. The method used for assigning the random numbers to *passengers alighting* from the bus and those *remaining seated* is *verified* by comparing the stochastic model against the deterministic model. Recall that it is required that the number of passengers alighting and those remaining seated must be modelled randomly, but at the same time not completely change the way the system behaves so that we can observe the impact that different *inter-arrival times* of passengers *entering* the station have on the capacity of the system. Scenario 2 from Stochastic model 1 was used in the comparison illustrated in Figure 11.3.

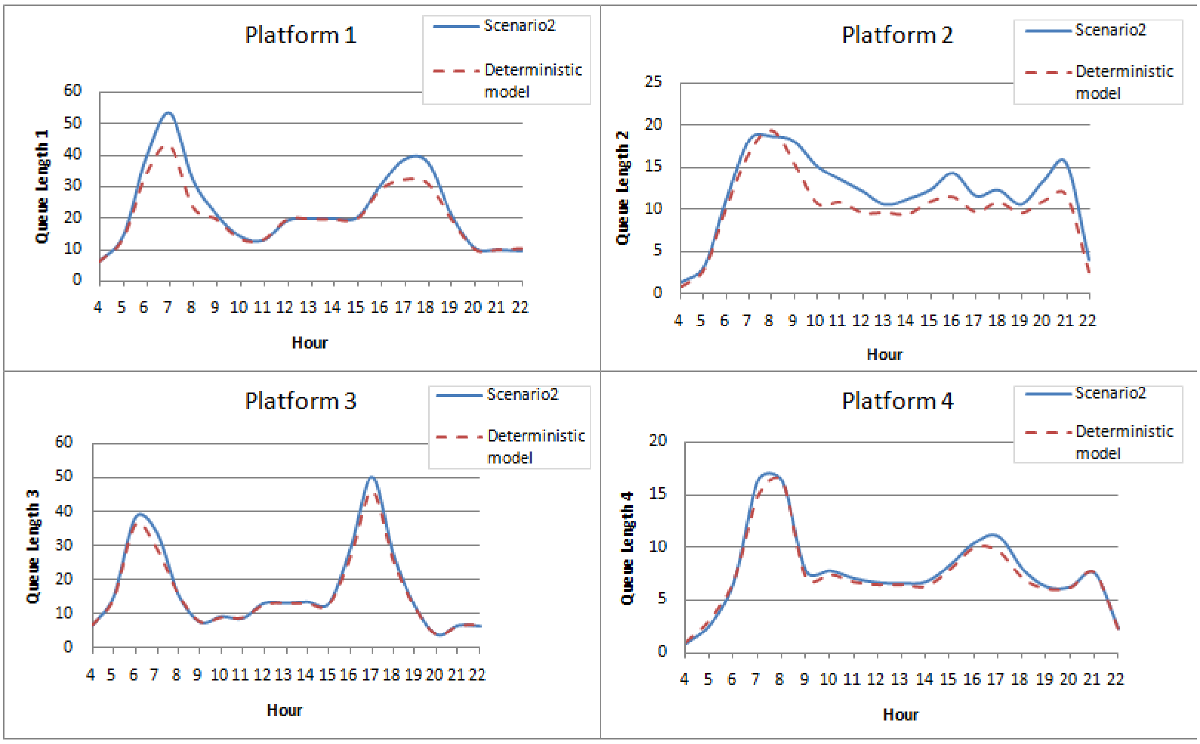


Figure 11.3 Comparison of the average queue lengths of Scenario 2 and the deterministic model

Figure 11.3 shows minimal variation between the queue lengths of the stochastic model and the deterministic model. This proves that the passengers alighting from the bus are modelled randomly but at the same time does not have a significant impact on the system's performance.

Further investigations of the stochastic model were conducted by developing scenarios presented in Section 11.2.

11.2) Stochastic model 2: scenario results and analysis

Figure 11.4 shows the various scenarios that are examined in this section.

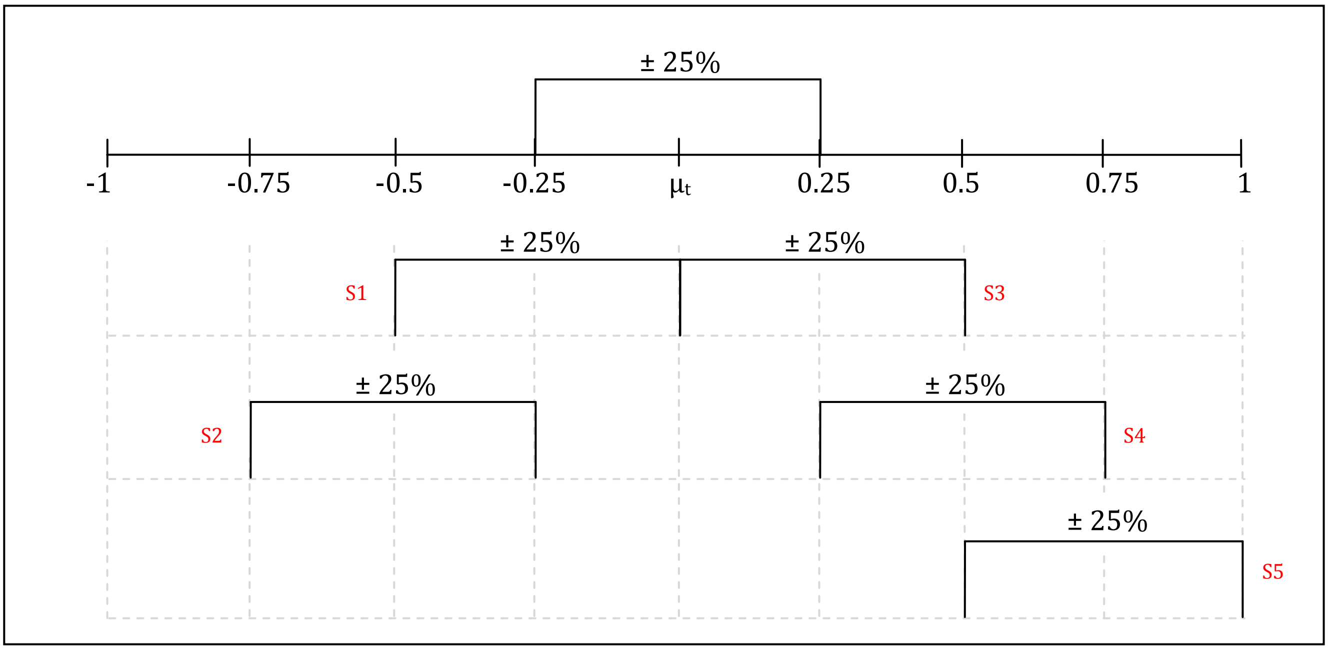


Figure 11.4 The developed scenarios of Stochastic model 2 (repeat)

Stochastic model 2 was developed to see how the system reacts when the *means* of the inter-arrival times are changed by 25% together with a constant uniform distribution of 25% placed over these times. The effect the variation has on the performance of the system is investigated. The investigations of this section are divided into two parts, where Scenario 1 and 2 are compared against each other, and Scenarios 3, 4 and 5 are compared. Figure 11.5 shows the graphs illustrating the average queue lengths for Scenario 1 and 2, after which Table 11.2 shows more results.

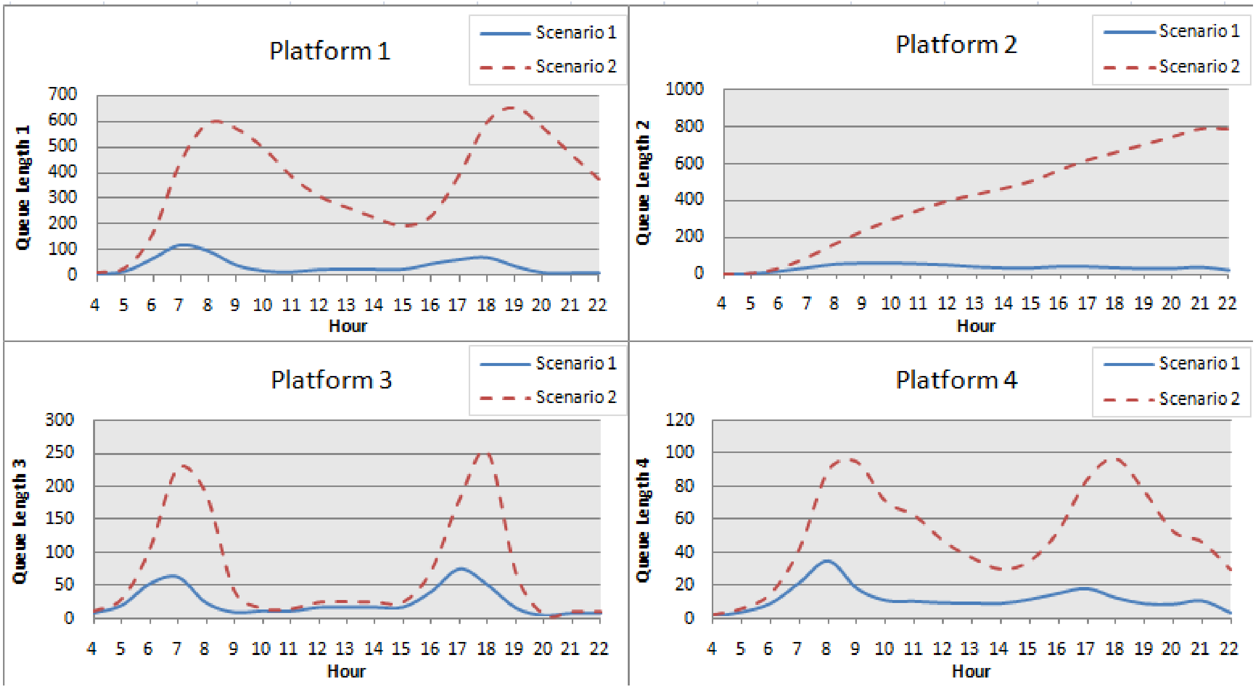


Figure 11.5 Stochastic model 2: average platform queue lengths (S1,S2)

Average waiting times in queues (hrs)				
	Queue 1	*Queue 3*	*Queue 2*	*Queue 4*
Scenario 1	0.19	0.18	0.39	0.19
Scenario 2	1.09	0.34	2.68	0.53
Max waiting times in queues (hrs)				
	Queue 1	*Queue 3*	*Queue 2*	*Queue 4*
Scenario 1	0.64	0.65	1.08	0.74
Scenario 2	3.23	0.84	6.25	1.28
Daily average number of passengers in queues (hrs)				
	Queue 1	*Queue 3*	*Queue 2*	*Queue 4*
Scenario 1	40	25	36	12
Scenario 2	366	72	418	51

Table 11.2 Stochastic model 2: Scenario 1 and 2 results

By adjusting the inter-arrival times by 25%, the considerable difference in queue lengths from Scenario 1 and 2 can be seen. There is a significant statistical difference at peak hours, when the question arises: if the inter-arrival times are incorrectly estimated by 25%, will the station be able to handle such demand? The simulation model can be used to test the impact different estimates have on the station. An example is outlined in Section 11.3 on p. 99.

In addition, from Figure 11.5 it can be concluded that platform 2 cannot handle the demand experienced in Scenario 2. The graph is constantly increasing because the rate at which passengers arrive is more than what the buses can handle. In this case, the fleet size should be reconsidered.

Table 11.2 shows the major differences in waiting times for the respective scenarios. The daily average number of passengers in the queues is also shown in the table, where a clear indication of the increase in passengers can be seen between the two scenarios. The decrease of 25% in the arrival times had an average impact of an increase by a factor 4 in waiting times and an increase by a factor 8 on the queue lengths experienced at platform 1. [Note: the buses are already running close to maximum capacity for Scenario 1, considering the waiting times and queue lengths presented above. For Scenario 2, the fleet size remains the same to illustrate the impact a decrease in inter-arrival times has on the performance of the system.]

The comparison of Scenario 3, 4 and 5 follows with the average queue lengths portrayed in Figure 11.6.

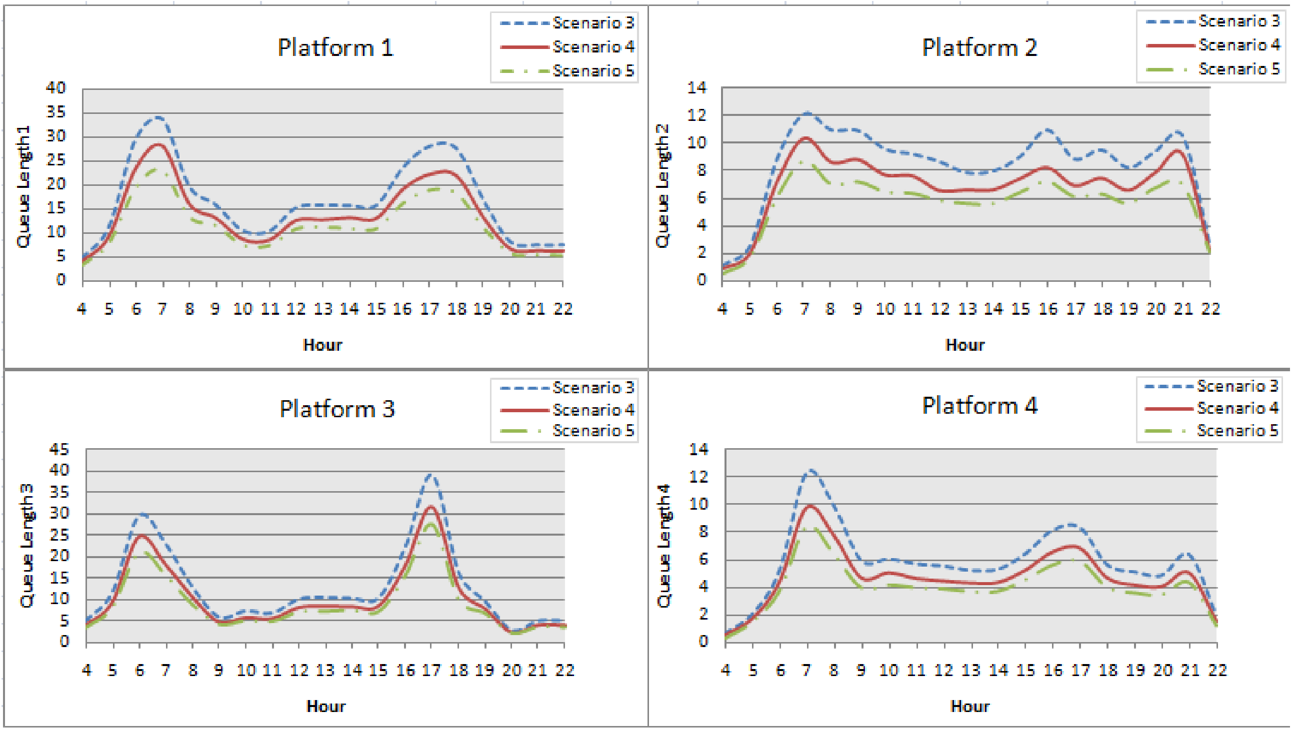


Figure 11.6 Stochastic model 2: average platform queue lengths (S3, S4 and S5)

Average waiting times in queues (hrs)				
	Queue 1	*Queue 3*	*Queue 2*	*Queue 4*
Scenario 3	0.13	0.15	0.15	0.15
Scenario 4	0.12	0.14	0.14	0.14
Scenario 5	0.12	0.14	0.14	0.14
Max waiting times in queues (hrs)				
	Queue 1	*Queue 3*	*Queue 2*	*Queue 4*
Scenario 3	0.50	0.61	0.55	0.65
Scenario 4	0.50	0.59	0.55	0.62
Scenario 5	0.51	0.57	0.51	0.62
Daily average number of passengers in queues (hrs)				
	Queue 1	*Queue 3*	*Queue 2*	*Queue 4*
Scenario 3	17	13	8	6
Scenario 4	14	10	7	5
Scenario 5	12	9	6	4

Table 11.3 Stochastic model 2: Scenario 3,4 and 5 results

In these scenarios, the inter-arrival rates are lower and fewer passengers enter the station. The results show no significant effects on the performance of the system. Because the station was already operating at a high performance level – and as fewer passengers enter the station in Scenarios 3, 4 and 5 – the station and its operations are able to accommodate the passengers.

The use of Arena's Output Analyzer, together with Excel, can be used to perform a type of analysis on the results that assist in obtaining even more in-depth information about the system. The method used to achieve this is explained in Section 11.3 and is based on an example, which uses Scenario 1 and 2.

11.3) Using Output Analyzer and Excel to generate frequency statistics

The results of Scenario 1 and 2 from Section 11.2 (p. 96) are used to explain the method to obtain the frequency statistics for the queue lengths and, most importantly, discuss the results obtained. Results from Scenario 1 are discussed in detail, after which these results are compared to those in Scenario 2.

Arena's Output Analyzer was used to obtain *time frequencies* from the modelled queues at the Thibault Station. This example only presents the results for queues 1 and 3 because these are situated opposite one another in the station and therefore jointly determine the capacity or space requirements for that area of the station. The example focuses on capacity issues related to those queues; however, the results for queue 2 and 4 follow the same procedure and are included in Appendix F. A basic illustration of the layout of the platforms is shown in Figure 11.7, from where the joint capacity contribution for that area of queues 1 and 3 can be seen.

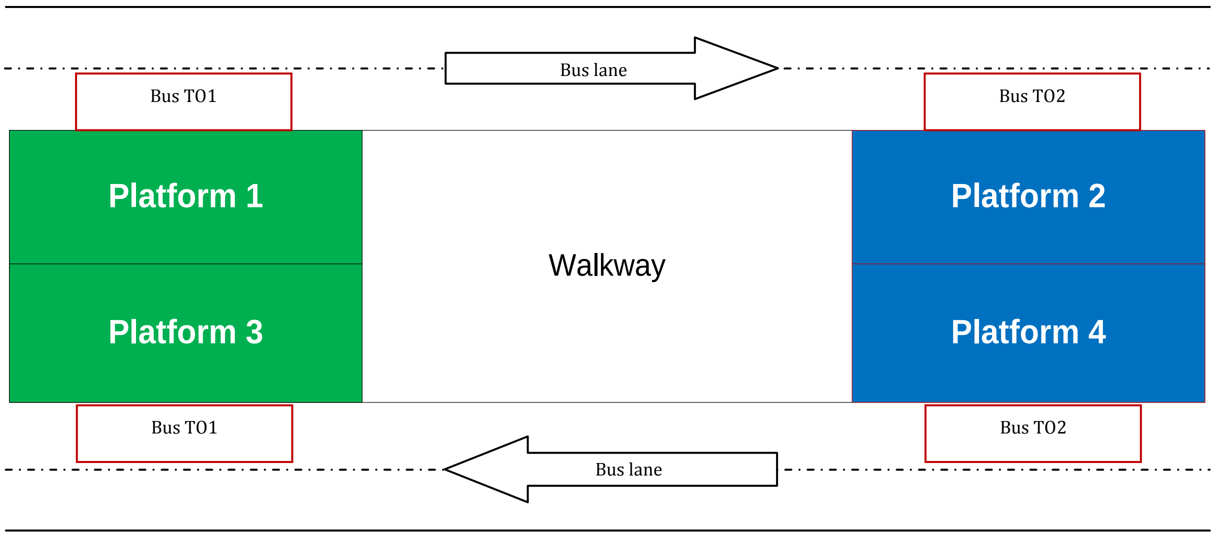
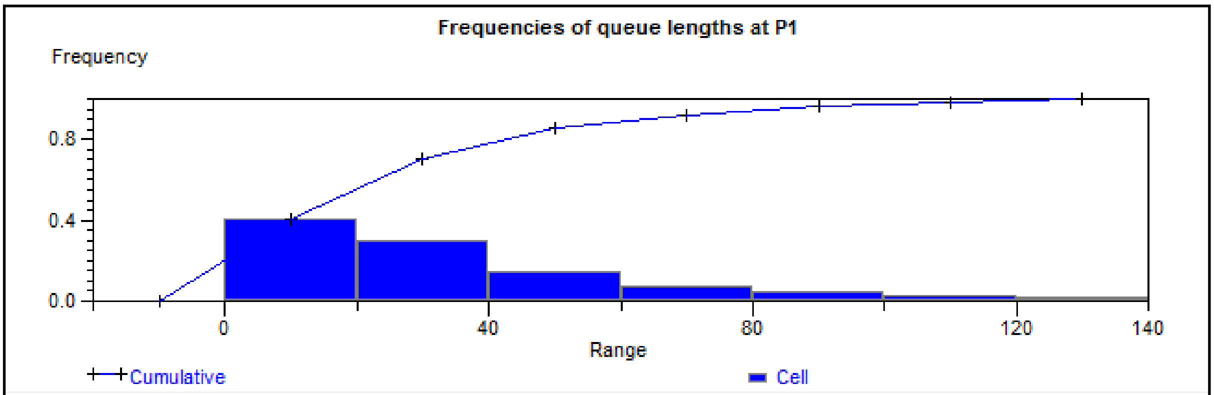


Figure 11.7 A Basic illustration of the queue areas at the Thibault Station

Firstly, the results are shown for Scenario 1 of Stochastic model 2. The *time frequencies* of queue length 1 are shown in Figure 11.8.



Histogram Summary
Frequencies of queue lengths at P1

Cell	Cell Limits From	To	Abs. Freq. (Time) Cell	Cumul.	Rel. Freq. Cell	Cumul.
1	-Infinity	0	0	0	0	0
2	0	20	7.701	7.701	0.4053	0.4053
3	20	40	5.698	13.4	0.2999	0.7052
4	40	60	2.798	16.2	0.1473	0.8525
5	60	80	1.336	17.53	0.07034	0.9228
6	80	100	0.7739	18.31	0.04073	0.9636
7	100	120	0.4293	18.74	0.02259	0.9862
8	120	+Infinity	0.2631	19	0.01385	1

Figure 11.8 Time frequencies for queue 1 (Scenario 1)

The histogram shown in Figure 11.8 illustrates the time (percentage of day) at which queue 1 remained at a certain length within a range. This time-persistent data of queue 1 is used to calculate the frequency information shown in the lower half of the figure. The queue ranges are shown together with the time the queue remained at that length, as well as the cumulated time. The histogram summary from Figure 11.8 is repeated below in order to show the user examples of how the data can be interpreted:

Histogram Summary
Frequencies of queue lengths at P1

Cell	Cell Limits From	To	Abs. Freq. (Time) Cell	Cumul.	Rel. Freq. Cell	Cumul.	
1	-Infinity	0	0	0	0	0	
2	0	20	7.701	7.701	0.4053	0.4053	
3	20	40	5.698	13.4	0.2999	0.7052	2
4	40	60	2.798	16.2	0.1473	0.8525	3
5	60	80	1.336	17.53	0.07034	0.9228	
6	80	100	0.7739	18.31	0.04073	0.9636	
7	100	120	0.4293	18.74	0.02259	0.9862	
8	120	+Infinity	0.2631	19	0.01385	1	

1 4

Figure 11.9 Time frequencies explanation

- Queue 1 remains at a queue length ranging between 20 and 40 passengers for 5.69 hours of the day. See **1** in Figure 11.9.
- For 40.53 % of the *operating time* in a day, the queue length will range between 0 and 20 passengers. See **2** in Figure 11.9.
- For 70.52 % of the *operating time* in a day, the queue length will be less than 40 passengers. See **3** in Figure 11.9.
- For 17.53 hours of the 19 hour day, the queue length will be less than 80 passengers. See **4** in Figure 11.9.

The cumulated time is represented by the curved line in the histogram, which effectively sums up the figure. Interpretations of this line could lead to important decisions, which are discussed later.

The *passenger frequencies* of queue 1 were calculated using Excel and are displayed in Table 11.4.

Queue length	Passenger frequency	Relative frequency	Upper limit	Cumulative frequency
0 < X ≤ 20	1098	0.27	**X ≤ 20**	0.27
20 < X ≤ 40	1051	0.26	**X ≤ 40**	0.52
40 < X ≤ 60	776	0.19	**X ≤ 60**	0.71
60 < X ≤ 80	527	0.13	**X ≤ 80**	0.84
80 < X ≤ 100	357	0.09	**X ≤ 100**	0.93
100 < X ≤ 120	189	0.05	**X ≤ 120**	0.97
X >120	108	0.03		1

Table 11.4 Passenger frequencies for queue 1 (Scenario 1)

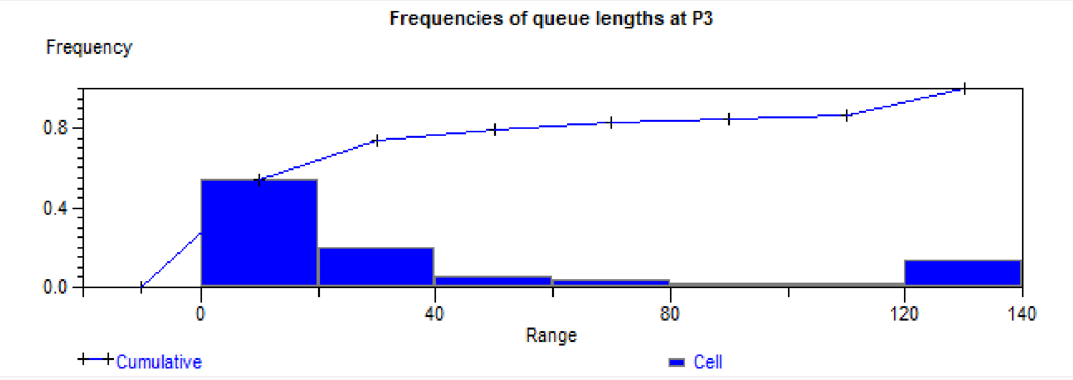
The *passenger frequencies* show the number of observations (passengers) counted in the specified ranges. Valuable conclusions can be made by using the *passenger frequencies* together with the *time frequencies.* The following is an example for a queue length between 20 and 40:

- For 70.52% of the *operating time,* there could be up to 52% of the *total number of passengers* making use of the service that day, where they will stand in a queue comprising less than 40 passengers.

Or

- *Up to 52% of the total number passengers* will make use of the service 70.52% of the *operating time,* where they will stand in a queue comprising less than 40 passengers. This means that the rest of the expected passengers (48%) will make use of the service in only 29.48% of the operating hours, which is 5.6 hours of the day.

The same results were generated for queue 3. Figure 11.10 shows the *time frequencies* of queue length 3, after which the *passenger frequencies* for queue 3 are displayed in Table 11.5.



Histogram Summary
Frequencies of queue lengths at P3

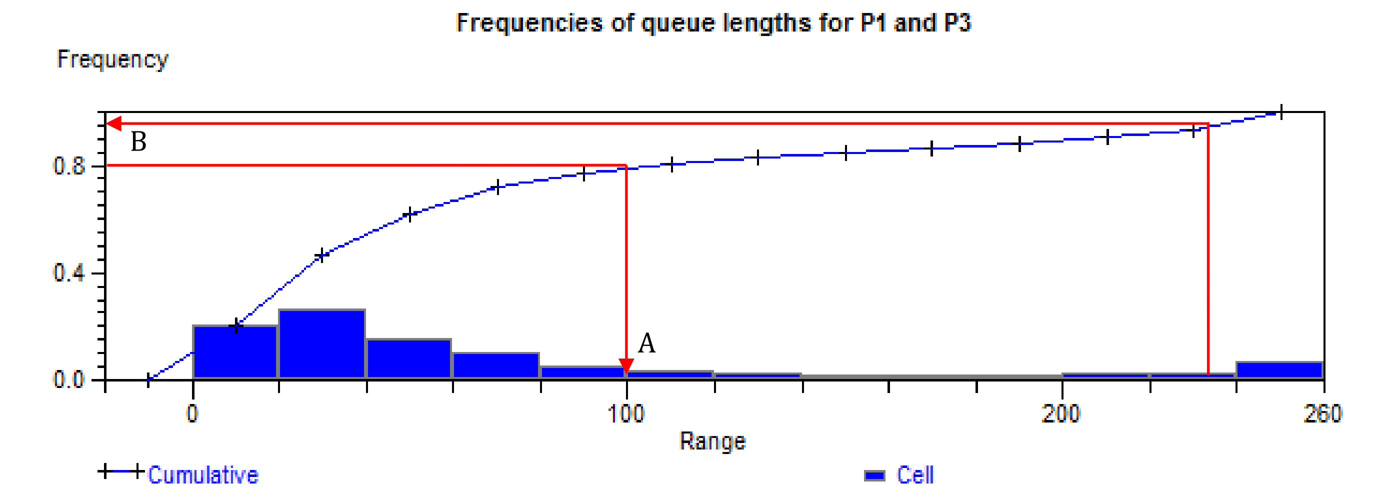
Cell	Cell Limits From	To	Abs. Freq. (Time) Cell	Cumul.	Rel. Freq. Cell	Cumul.
1	-Infinity	0	0	0	0	0
2	0	20	10.34	10.34	0.544	0.544
3	20	40	3.782	14.12	0.199	0.7431
4	40	60	0.9866	15.11	0.05193	0.795
5	60	80	0.6529	15.76	0.03436	0.8294
6	80	100	0.3253	16.08	0.01712	0.8465
7	100	120	0.4139	16.5	0.02179	0.8683
8	120	+Infinity	2.503	19	0.1317	1

Figure 11.10 Time frequencies for queue 3 (Scenario 1)

Queue length	Passenger frequency	Relative frequency	Upper limit	Cumulative frequency
0 < X ≤ 20	920	0.33	X ≤ 20	0.33
20 < X ≤ 40	490	0.18	X ≤ 40	0.51
40 < X ≤ 60	225	0.08	X ≤ 60	0.59
60 < X ≤ 80	154	0.06	X ≤ 80	0.65
80 < X ≤ 100	98	0.04	X ≤ 100	0.68
100 < X ≤ 120	114	0.04	X ≤ 120	0.72
X >120	766	0.28		1

Table 11.5 Passenger frequencies for queue 3 (Scenario 1)

As stated at the beginning of the section, the combination of both queues (queue 1 and 3) is required to gain important information regarding the *overall capacity* of that area in the station. The data above were statistically combined, after which the results were generated. Figure 11.11 shows the *time frequencies* followed by the *passenger frequencies* presented in Table 11.6.



Histogram Summary

Frequencies of queue lengths for P1 and P3

Cell	Cell Limits From	Cell Limits To	Abs. Freq. (Time) Cell	Abs. Freq. (Time) Cumul.	Rel. Freq. Cell	Rel. Freq. Cumul.
1	-Infinity	0	0	0	0	0
2	0	20	3.787	3.787	0.1993	0.1993
3	20	40	5.01	8.797	0.2637	0.463
4	40	60	2.923	11.72	0.1539	0.6168
5	60	80	1.949	13.67	0.1026	0.7194
6	80	100	1.036	14.7	0.05451	0.7739
7	100	120	0.5984	15.3	0.03149	0.8054
8	120	140	0.4346	15.74	0.02288	0.8283
9	140	160	0.301	16.04	0.01584	0.8441
10	160	180	0.3132	16.35	0.01648	0.8606
11	180	200	0.384	16.74	0.02021	0.8808
12	200	220	0.4856	17.22	0.02556	0.9064
13	220	240	0.4765	17.7	0.02508	0.9315
14	240	+Infinity	1.302	19	0.06855	1

Figure 11.11 Time frequencies for the combination of queue 1 and queue 3 (Scenario 1)

Queue length	Passenger frequency	Relative frequency	Upper limit	Cumulative frequency
0 < X ≤ 20	723	0.11	**X ≤ 20**	0.11
20 < X ≤ 40	961	0.14	**X ≤ 40**	0.25
40 < X ≤ 60	857	0.12	**X ≤ 60**	0.37
60 < X ≤ 80	687	0.1	**X ≤ 80**	0.47
80 < X ≤ 100	463	0.07	**X ≤ 100**	0.54
100 < X ≤ 120	380	0.06	**X ≤ 120**	0.59
120 < X ≤ 140	313	0.05	**X ≤ 140**	0.64
140 < X ≤ 160	210	0.03	**X ≤ 160**	0.67
160 < X ≤ 180	226	0.03	**X ≤ 180**	0.7
180 < X ≤ 200	284	0.04	**X ≤ 200**	0.74
200 < X ≤ 220	268	0.05	**X ≤ 220**	0.8
220 < X ≤ 240	352	0.05	**X ≤ 240**	0.85
X > 240	1028	0.15		1

Table 11.6 Passenger frequencies for the combination of queue 1 and queue 3 (Scenario 1)

The same interpretations of the data given for queue 1 hold for Figure 11.11 and Table 11.6.

Consider the *cumulative line* of Figure 11.11. The following gives examples of how this information could be used as a basis for *design decisions:*

- *Different alternatives can be weighed up against one another:* For a space to accommodate passengers *80% of the operating time*, the cumulative line shows that it must be designed and built to fit approximately 100 passengers. The other 20% of the time, the space will *not* be able to accommodate the expected demand where these passengers must wait at alternative waiting areas. This is known as the 80th percentile at which the station is built, and is illustrated in Figure 11.11 by the red line indicated as A.

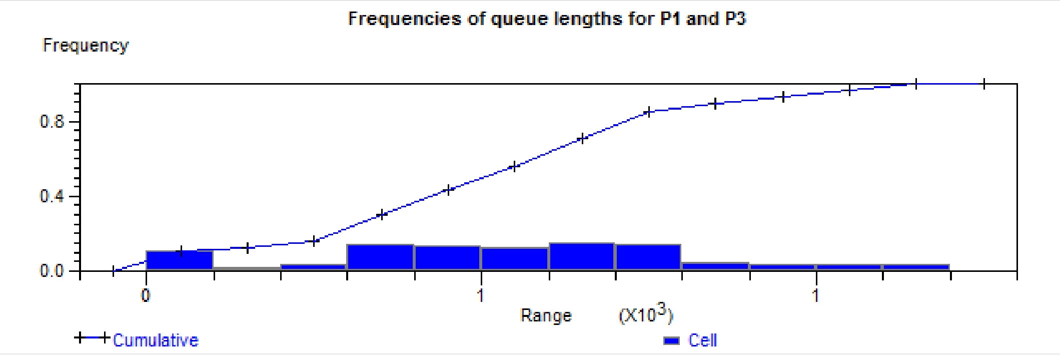
  Knowing this information, the space requirements for that area can be calculated. The basic minimum space requirement for a single standing passenger is 0.3 m^2. For a passenger facility, an area of 0.75 m^2 is used as a buffer zone for each pedestrian. These are standard practices, which are taken from the *Highway Capacity Manual* (Transportation Research Board, 2000), and by using these, the space required to accommodate passengers 80% of the time is calculated as follows: $100 \times 0.75\ m^2 = 75\ m^2$.

- *Conversely, the cumulative line could also be used to obtain information about the percentile for a specific space:* If the proposed station is designed with an approximately 176 m^2 waiting area, the number of passengers it can hold is calculated ($176 \div 0.75\ m^2$) as 235. Referring back to the graph, the cumulative line shows a 95th percentile (operating time) for 235 passengers. The red line labelled B shows how this value can be read from the graph. This means that an area of 176 m^2 will be sufficient to accommodate passengers 95% of the time.

Passenger percentiles can be used in addition or alternatively, to support decisions made regarding the designing of a station. An example of using an 80% passenger percentile is given, which is taken from Table 11.6: To accommodate 80% of *all passengers* (for queue 1 and 3), the station platform must be built to hold 220 passengers. Figure 11.11 can be used in addition, which shows that 80% of the passengers constitute to 90% of the operating time.

A trade-off exists between the *percentile* for which a station is designed and the *cost* of the station. *Is the designer going to design a station at the 80th percentile, which will be less expensive, and accommodate fewer passengers, or at the 90th percentile which will accommodate more passengers?* A larger percentile will require more space, which in turn increases the costs. These graphs are useful for such decisions.

The information presented for Scenario 1 is valuable for decision-making purposes; however, it will also be valuable to compare this scenario (1) against Scenario 2 to see what impact a 25% difference in inter-arrival rates will have on the proposed station design. This is a good method of testing the sensitivity of the passenger estimates. The results of Scenario 2 for queue 1 and queue 3 *combined* are presented in Figure 11.12 and Table 11.7.



Histogram Summary
Frequencies of queue lengths for P1 and P3

	Cell Limits		Abs. Freq. (Time)		Rel. Freq.	
Cell	From	To	Cell	Cumul.	Cell	Cumul.
1	-Infinity	0	0	0	0	0
2	0	100	2.05	2.05	0.1079	0.1079
3	100	200	0.2604	2.31	0.01371	0.1216
4	200	300	0.6863	2.996	0.03612	0.1577
5	300	400	2.759	5.755	0.1452	0.3029
6	400	500	2.516	8.271	0.1324	0.4353
7	500	600	2.272	10.54	0.1196	0.5549
8	600	700	2.925	13.47	0.154	0.7089
9	700	800	2.629	16.1	0.1384	0.8473
10	800	900	0.9193	17.02	0.04838	0.8956
11	900	1000	0.6546	17.67	0.03445	0.9301
12	1000	1100	0.7288	18.4	0.03836	0.9685
13	1100	1200	0.5964	19	0.03139	0.9998
14	1200	+Infinity	0.002891	19	0.0001522	1

Figure 11.12 Time frequencies for the combination of queue 1 and queue 3 (Scenario 2)

The 80th time percentile of Figure 11.12 requires a space that holds between 700 and 800 passengers. The 80th time percentile of Scenario 1 requires a space that could hold only up to 120 passengers. There is a vast difference between the scenarios. If the station was built according to Scenario 1 and the passenger estimates were incorrectly estimated, the impact could be catastrophic, for the same number of buses.

Queue length	Passenger frequency	Relative frequency	Upper limit	Cumulative frequency
$0 < X \leq 100$	615	0.06	$X \leq 100$	0.06
$100 < X \leq 200$	257	0.03	$X \leq 200$	0.09
$200 < X \leq 300$	509	0.05	$X \leq 300$	0.13
$300 < X \leq 400$	1238	0.12	$X \leq 400$	0.26
$400 < X \leq 500$	1304	0.13	$X \leq 500$	0.38
$500 < X \leq 600$	1373	0.13	$X \leq 600$	0.52
$600 < X \leq 700$	1544	0.15	$X \leq 700$	0.67
$700 < X \leq 800$	1152	0.11	$X \leq 800$	0.78
$800 < X \leq 900$	489	0.05	$X \leq 900$	0.83
$900 < X \leq 1000$	484	0.05	$X \leq 1000$	0.88
$1000 < X \leq 1100$	675	0.07	$X \leq 1100$	0.94
$1100 < X \leq 1200$	602	0.06	$X \leq 1200$	1
$X > 1200$	1	0		1

Table 11.7 Passenger frequencies for the combination of queue 1 and queue 3 (Scenario 2)

This method generates easily understandable graphs for displaying significant information about a system's performance measurements, the impacts which could be experienced and the capacity capabilities for different parameters. Outcomes of alternatives can easily be generated, investigated and compared against each another.

The examples presented in this chapter showed *how* the stochastic model can be used as a tool to *investigate* and *evaluate* many different aspects relating to the capacity of a station.

11.4) THE SIGNIFICANCE OF THE STOCHASTIC MODEL

In Chapter 4, equations were presented which are used to determine the capacity requirements for a BRT corridor. These *deterministic* equations are mainly focused on calculating capacity requirements for corridors, and determine the capacity of a system usually over a number of stations along a certain route. Thereafter, stations are usually designed according to a level of service to provide sufficient facilities for the estimated capacities. However, these equations can also be used to determine capacity requirements for a single station. As mentioned before, these equations were used to verify data provided by Pendulum Consulting for the Thibault station. They deal largely with factors such as the dwell times, boarding and alighting times, saturation levels, renovation rates, the number of stopping bays and average number of boardings over a corridor, which are elements relating to the entire operation of a BRT system. In practice the capacity of an entire BRT system is investigated and determined whereby the system is then designed to operate optimally as a whole.

In real life systems there is a time-dependency of operations and almost always variation. Therefore, the stochastic model represents the operations at a BRT station more realistically, and allows factors affecting the capacity of a station, such as the flow of passengers, the queue lengths, the frequency and capacity of buses to be investigated considering time-dependency and variation. The major advantage of the stochastic model is that percentiles of e.g. queue lengths can be estimated. The decision maker can thus chose to design a station for the 80th percentile, while she is limited to unknown percentiles when using the values of the deterministic model. Different scenarios can be constructed so that the impact certain actions have on the capacity of a station can be investigated. A review of the chapter is given below.

11.5) SUMMARY: CHAPTER 11

The results and analysis of Stochastic models 1 and 2 were reviewed in this chapter. The various scenarios developed from Stochastic model 1 were explained and discussed in Section 11.1. Subsequently, the results and interpretations from the developed scenarios of Stochastic model 2 were addressed. The chapter then continues by using two scenarios from Stochastic model 2 to portray a method used to obtain frequency statistics for the various queues. Section 11.3 discusses the method used to generate these statistics as well as the importance thereof. It also shows the valuable deductions and conclusions, which could be made from the generated frequency statistics. The significance of the stochastic model is discussed in Section 11.4.

The aim of the chapter was not only to make the model results known, but also communicated the interpretations and usefulness of the model results. More of the final model conclusions are discussed in Chapter 13. The following chapter addresses aspects of management related to the developed model.

12) MANAGEMENT ASPECTS OF THE STUDY

The simulation model was built to serve as a tool for investigating, planning and designing BRT stations. This model is beneficial in many ways, as has already been pointed out in this study, but another feature of the model is its ability to be used for *management* decisions.

Model capabilities and results were discussed in the previous chapter and are now linked to *management decisions* that may arise from these. A few aspects of management, which are unique to the model, are highlighted in the current chapter. The following areas of management are addressed:

- Operations management
- Strategic management
- Financial management.

12.1) OPERATIONS MANAGEMENT

Operations management concerns the operations or processes involved in the study, where the responsibilities of ensuring that these operations are efficient, as well as meeting the customer's requirements, are fulfilled. Input processes such as the customers entering the station and the flow, as well as output processes such as buses picking up passengers and transferring them, need to work according to customer specifications. Operations management therefore involves the management of operations and ensuring the correct system is designed, evaluated and achieved as intended. The simulation model is an effective support tool that can evaluate the service of the system.

Operations management also entails the correct number of resources being used, with the model providing the ability to measure the utilisation of resources. Another applicable management operation is the scheduling of buses. Arena is a user-friendly, easily understandable software program, which is compatible with many other programmes. Schedules can be assigned in Arena, imported or changed in the model, after which the adequacy can be tested and evaluated.

12.2) STRATEGIC MANAGEMENT

The aim of achieving long-term objectives – such as development phases, plans or programmes – of a project is seen as a form of strategic management. The simulation model can be used to predict the performance in certain cases, which can support the decision-making of long-term objectives and help set strategic goals.

Examples of *how* and *where* the simulation model can be used to support strategic management decisions are:

- Station planning: A system's future or ideal performance can be estimated. This can be a good indication of what the system is capable of and can therefore be used to support and set goals of a proposed system. Alternatively, the simulation model can also be used to test the suitability of set goals: are these realistic and achievable?
- Long-term planning: Future passenger growth estimates can be modelled and investigated to evaluate or determine whether the station's capacity will be able to handle such demand, while the required number of buses can be estimated for a given level of service.
- Different types of analysis can be performed: Sensitivity analysis can be used to evaluate the importance and effect certain parameters have on the performance of the system. 'What if' analysis is also a useful method, which can be used to anticipate the outcomes of different scenarios or future performances.

Strategic management is an ongoing process. The simulation model is a great facilitator to determine and reassess whether certain strategic objectives have been met. It is also useful in evaluating the success of implemented goals and supports the decisions of whether goals have been met or should be newly set.

12.3) FINANCIAL MANAGEMENT

Financial management can be seen as the *management* ensuring that financial objectives are achieved. There are three key elements namely financial planning, financial control and financial decision-making.

Financial planning concerns the management necessary to ensure that enough funding is available. The simulation model can be used to determine the effect and requirements future capacity estimates and growth rates hold for a station's physical design and levels of service. It can be used to determine the required additional resources for expansion and other growth-related impacts. The simulation model can therefore be used to assess a system, providing management with performance indications and requirements of future developments, which will assist them in making funding decisions.

Financial control helps to ensure that the business meets their objectives. The model can assist in evaluating the performance of a system, so that the following key question can be answered: are assets being used efficiently? Utilisation indicators and other performance measurements obtained from the simulation model are good indications of whether or not a system is achieving its objectives.

Financial decisions are continuously made throughout projects. Major decisions are made at the beginning phases such as the planning and designing phases of systems. The simulation model can be used to weigh different station designs against one another and estimate their related performances. Cost-benefit analysis can be done based on the performance and costs alternative designs hold.

12.4) SUMMARY: CHAPTER 12

Chapter 12 showed the relevancy of the simulation model to *management.* Operations management, strategic and financial management aspects were discussed.

Operations management is essential for planning and designing systems. A few aspects were highlighted, which showed how the model can support operational management decisions. Thereafter, the suitability, feasibility and acceptability of long-term objectives were discussed, which form part of strategic management options. Examples were given of how the simulation model can be used to evaluate these options. Lastly, the relevance and importance of financial management aspects – such as financial planning, financial control and financial decision-making – were addressed.

The following chapter summarises the findings and conclusions of this project.

13) Conclusions and Project Summary

The purpose of this work was to build a model that can be used as a *tool* for investigating matters affecting the *capacity* of a BRT station. The main objective was to develop a *simulation model* of which the input data to the model can be changed by designers, allowing different alternatives or scenarios to be investigated, after which an *analysis* of the system's performance measurements can be done. This will provide the user with important knowledge of the system's performance, which will assist him/her in making insightful planning or design decisions.

A literature study was conducted to obtain the necessary information related to the study area. BRT systems were placed into the public transportation perspective by providing background information on the development of BRT systems, after which more in-depth research and investigation was done specifically on BRT systems and the capacity thereof. *Simulation* was chosen as the performance evaluation tool used to assess the capacity of the BRT station.

The simulated model is based on a proposed BRT station situated in the City of Cape Town, which is known as the Thibault Station. Pendulum Consulting provided the data required to model the operations of the station. The development phases of the model involved a conceptual model of the Thibault Station, the simulation of the model in Arena, the verification and validation of the model, the stochastic modelling of the system, followed by the analysis and results generated from the model. The aim of the building process was to develop the model so that *designers* will be able to use the model to do capacity analysis. Excel input spreadsheets linked to the simulation model enabled this.

The stochastic models developed from the deterministic model are believed to provide realistic results, since they take into account elements of randomness which are present in the operations and activities of bus stations. The most valuable information was obtained from the key performance measurements which were identified as the percentiles of queue lengths, the waiting times and the frequency statistics. The methods presented in the study for investigating and analysing the stochastic scenarios showed the *capabilities* of the model and the usefulness to future users.

The following conclusions were drawn from the study:

- The use of a stochastic model enables the operations of a bus station to be modelled more realistically since elements of randomness are included in the model, which makes it a closer representation to that of the real-world system. The results generated are therefore more credible than those generated from deterministic models.
- The use of time-weighted averages is imperative for analysing the capacity of a station. Basing decisions on arithmetic averages will be misleading.
- Stochastic model 1 – showed by using the *uniform distribution* and increasing the *range* over the original inter-arrival time values, with no other activities in the simulation model affecting the rate at which passengers arrive – shows no significant impact on the system design and should not be used to induce variation into inter-arrival times.
- Stochastic model 2 revealed that comparing different alternatives (scenarios) can lead to useful system performance analysis.
- By using the average queue length statistics and both the *time frequency* and *passenger frequency* statistics, information is obtained which supports decision-making for many capacity related issues when planning or designing a station.
- The stochastic model can be used for:
  - Sensitivity analysis: Users can change input parameters and examine the effect these have on other system elements.
  - Risk analysis: The model can predict what can happen, and also how likely it is to happen. Contingency and safety factors can be evaluated.
  - 'What-if' analysis: Input parameters can be changed to discover how the system will react under certain conditions.
  - Management decision: The model is used as a tool to investigate certain actions. The model generates results, which can determine or support a management decision.

Participating users will be trained by the student in how to use the model, and more specifically the input data spreadsheets, so that they can investigate different scenarios and generate results.

The stochastic model presented in the study provides support to the decision maker on capacity designing parameters of BRT stations.

The following suggestions are made for future work:

- Building a corridor by duplicating the simulation model:
  The model developed in this study can be used as a basis for expanding the simulation model into an entire BRT corridor, consisting of more than one station. The model can be duplicated and linked, on which numerous capacity studies could be done.
- Integrating an optimal bus schedule into the simulation model:
  This study did not focus on implementing an optimal bus schedule into the simulation model. A mathematical programming language can be used to develop an optimal bus schedule. This could then be linked to the simulation model on which further investigations could be done, such as the costs related to the optimal bus schedule requirements versus the efficiency thereof.
- Develop a fully generic stochastic simulation model:
  The current stochastic model is based on the station configuration of the Thibault Station, that being four platforms and four waiting queues which are modelled. For other station configurations model adjustments would need to be made. The same holds for the input data spreadsheets which were developed for the model. Although the spreadsheets are user-friendly and values are easily adjustable, the bus schedule spreadsheets are designed for a cycle consisting of four station stops in a cycle. For a cycle consisting of less or more station stops, Excel and Arena adjustments are needed. A more generic approach could be valuable in future studies.

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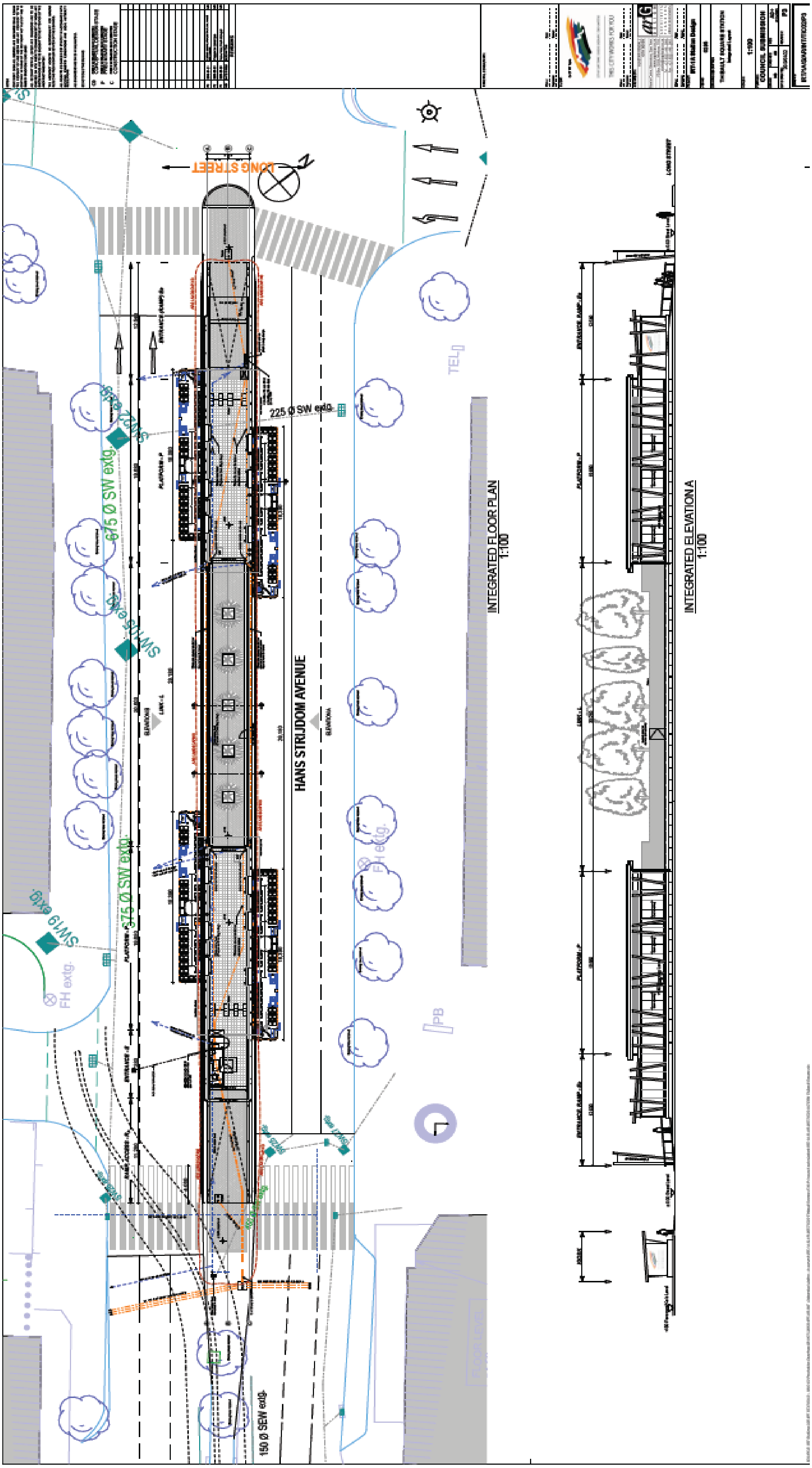
Appendix A: Architectural drawing of the Thibault Station


LONG STREET
HANS STRIJDOM AVENUE
INTEGRATED FLOOR PLAN
1:100
INTEGRATED ELEVATION A
1:100
675 Ø SW extg.
225 Ø SW extg.
150 Ø SEW extg.
FH extg.
SW19 extg.
TEL
PB
THE CITY WORKS FOR YOU

APPENDIX B: CAPACITY CALCULATIONS OF THE THIBAULT STATION

BRT capacity calculations	Calculation using Pendulum data	Pendulum's parameters
$H = \dfrac{60}{F/Nps}$ *Include eq*	$H = \dfrac{60}{10/1}$ $= 6\ min$	*TO1: Headway (min) = 6 min*
$Co = Cb \times LF \times F \times Nsp$ *Equation 4.1*	$Co = 120 \times 1 \times 10.9 \times 1$ $= 1308\ passengers/hour$	$TO1: Co = 1307\ passengers/hour$
$Co = Cb \times LF \times F \times Nsp$ *Equation 4.1*	$Co = 40 \times 1 \times 9.3 \times 1$ $= 372\ passengers/hour$	$TO2: Co = 370\ passengers/hour$
$Fo = (D \times Tc)/Cb$ *Equation 4.7*	$Fo = (1307 \times 2.0167)/120$ $= 21.98\ vehicles$	$TO1: Fleet\ size: 21\ vehicles$
Using an alternative equation: $Fo = F \times Tc$	$Fo = 10.9 \times 2.0167$ $= 21.98\ vehicles$	$TO1: Fleet\ size: 21\ vehicles$
$Fo = (D \times Tc)/Cb$ *Equation 4.7*	$Fo = (370 \times 1.633)/40$ $= 15.1\ vehicles$	$TO2: Fleet\ size: 16\ vehicles$
Using an alternative equation: $Fo = F \times Tc$	$Fo = 10.9 \times 2.0167$ $= 15.1\ vehicles$	$TO2: Fleet\ size: 16\ vehicles$

APPENDIX C1: INPUT DATA SPREADSHEET FOR THE TO1 BUS SCHEDULE

Bus Schedule TO1

Using estimated cycle times to assign scheduled arrivals and fleet size

Daily operating hour	Bus freq/hr	Estimated cycle times(Min)	Assigned bus number	Arrival times(min) at the different stations					
				P1	DO1	P3	DO2	Arrival time back at P1	
4-5	3	80 min		00:00	00:20	00:40	01:00	01:20	
			1	04:00	04:20	04:40	05:00	05:20	1
			2	04:20	04:40	05:00	05:20	05:40	2
			3	04:40	05:00	05:20	05:40	06:00	3
5-6	4	100 min		00:00	00:25	00:50	01:15	01:40	
			4	05:00	05:25	05:50	06:15	06:40	4
			5	05:15	05:40	06:05	06:30	06:55	5
			1	05:30	05:55	06:20	06:45	07:10	1
			2	05:45	06:10	06:35	07:00	07:25	2
6-7	5	120min		00:00	00:30	01:00	01:30	02:00	
			3	06:00	06:30	07:00	07:30	08:00	3
			6	06:12	06:42	07:12	07:42	08:12	6
			7	06:24	06:54	07:24	07:54	08:24	7
			8	06:36	07:06	07:36	08:06	08:36	8
			4	06:48	07:18	07:48	08:18	08:48	4
7-8	5	120min		00:00	00:30	01:00	01:30	02:00	
			5	07:00	07:30	08:00	08:30	09:00	5
			1	07:12	07:42	08:12	08:42	09:12	1
			9	07:24	07:54	08:24	08:54	09:24	9
			2	07:36	08:06	08:36	09:06	09:36	2
			10	07:48	08:18	08:48	09:18	09:48	10
8-9	5	120min		00:00	00:30	01:00	01:30	02:00	
			3	08:00	08:30	09:00	09:30	10:00	3
			6	08:12	08:42	09:12	09:42	10:12	6
			7	08:24	08:54	09:24	09:54	10:24	7
			8	08:36	09:06	09:36	10:06	10:36	8
			4	08:48	09:18	09:48	10:18	10:48	4
9-10	3	92min		00:00	00:23	00:46	01:09	01:32	
			5	09:00	09:23	09:46	10:09	10:32	5
			1	09:20	09:43	10:06	10:29	10:52	1
			9	09:40	10:03	10:26	10:49	11:12	9
10-11	3	80min		00:00	00:20	00:40	01:00	01:20	
			10	10:00	10:20	10:40	11:00	11:20	10
			6	10:20	10:40	11:00	11:20	11:40	6
			8	10:40	11:00	11:20	11:40	12:00	8
11-12	3	80min		00:00	00:20	00:40	01:00	01:20	
			4	11:00	11:20	11:40	12:00	12:20	4
			9	11:20	11:40	12:00	12:20	12:40	9
			10	11:40	12:00	12:20	12:40	13:00	10
12-13	3	80min		00:00	00:20	00:40	01:00	01:20	
			8	12:00	12:20	12:40	13:00	13:20	8
			4	12:20	12:40	13:00	13:20	13:40	4
			9	12:40	13:00	13:20	13:40	14:00	9
13-14	3	80min		00:00	00:20	00:40	01:00	01:20	
			10	13:00	13:20	13:40	14:00	14:20	10
			8	13:20	13:40	14:00	14:20	14:40	8
			4	13:40	14:00	14:20	14:40	15:00	4
14-15	3	80min		00:00	00:20	00:40	01:00	01:20	
			9	14:00	14:20	14:40	15:00	15:20	9
			10	14:20	14:40	15:00	15:20	15:40	10
			8	14:40	15:00	15:20	15:40	16:00	8
15-16	3	80min		00:00	00:20	00:40	01:00	01:20	
			4	15:00	15:20	15:40	16:00	16:20	4
			9	15:20	15:40	16:00	16:20	16:40	9
			10	15:40	16:00	16:20	16:40	17:00	10
16-17	4	92min		00:00	00:23	00:46	01:09	01:32	
			8	16:00	16:23	16:46	17:09	17:32	8
			1	16:15	16:38	17:01	17:24	17:47	1
			4	16:30	16:53	17:16	17:39	18:02	4
			9	16:45	17:08	17:31	17:54	18:17	9
17-18	6	120min		00:00	00:30	01:00	01:30	02:00	
			10	17:00	17:30	18:00	18:30	19:00	10
			2	17:10	17:40	18:10	18:40	19:10	2
			3	17:20	17:50	18:20	18:50	19:20	3
			5	17:30	18:00	18:30	19:00	19:30	5
			8	17:40	18:10	18:40	19:10	19:40	8
			1	17:50	18:20	18:50	19:20	19:50	1
18-19	5	112min		00:00	00:28	00:56	01:24	01:52	
			7	18:00	18:28	18:56	19:24	19:52	7
			4	18:12	18:40	19:08	19:36	20:04	4
			9	18:24	18:52	19:20	19:48	20:16	9
			11	18:36	19:04	19:32	20:00	20:28	11
			12	18:48	19:16	19:44	20:12	20:40	12
19-20	4	92min		00:00	00:23	00:46	01:09	01:32	
			10	19:00	19:23	19:46	20:09	20:32	10
			2	19:15	19:38	20:01	20:24	20:47	2
			3	19:30	19:53	20:16	20:39	21:02	3
			5	19:45	20:08	20:31	20:54	21:17	5
20-21	2	80min		00:00	00:20	00:40	01:00	01:20	
			7	20:00	20:20	20:40	21:00	21:20	7
			11	20:30	20:50	21:10	21:30	21:50	11
21-22	2	80min		00:00	00:20	00:40	01:00	01:20	
			2	21:00	21:20	21:40	22:00	22:20	2
			5	21:30	21:50	22:10	22:30	22:50	5
22-23	2	80min		00:00	00:20	00:40	01:00	01:20	
			11	22:00	22:20	22:40	23:00	23:20	11
			2	22:30	22:50	23:10	23:30	23:50	2
			5	23:00					5

Appendix C2: Input data spreadsheet for the TO2 bus schedule

Bus Schedule TO2

Using estimated cycle times to assign scheduled arrivals and fleet size

Daily operating hour	Bus freq/hr	Estimated cycle times(Min)	Assigned bus number	Arrival times(min) at the different stations					
				P2	DO1	P4	DO2	Arrival time back at P2	
4-5	3	60 min		00:00	00:15	00:30	00:45	01:00	
			1	04:00	04:15	04:30	04:45	05:00	1
			2	04:20	04:35	04:50	05:05	05:20	2
			3	04:40	04:55	05:10	05:25	05:40	3
5-6	4	72 min		00:00	00:18	00:36	00:54	01:12	
			1	05:00	05:18	05:36	05:54	06:12	1
			4	05:15	05:33	05:51	06:09	06:27	4
			2	05:30	05:48	06:06	06:24	06:42	2
			3	05:45	06:03	06:21	06:39	06:57	3
6-7	3	80 min		00:00	00:20	00:40	01:00	01:20	
			5	06:00	06:20	06:40	07:00	07:20	5
			1	06:20	06:40	07:00	07:20	07:40	1
			4	06:40	07:00	07:20	07:40	08:00	4
7-8	3	87min		00:00	00:29	00:58	01:27	01:56	
			2	07:00	07:29	07:58	08:27	08:56	2
			3	07:20	07:49	08:18	08:47	09:16	3
			5	07:40	08:09	08:38	09:07	09:36	5
8-9	4	87min		00:00	00:29	00:58	01:27	01:56	
			1	08:00	08:29	08:58	09:27	09:56	1
			4	08:15	08:44	09:13	09:42	10:11	4
			6	08:30	08:59	09:28	09:57	10:26	6
			7	08:45	09:14	09:43	10:12	10:41	7
9-10	4	80min		00:00	00:20	00:40	01:00	01:20	
			2	09:00	09:20	09:40	10:00	10:20	2
			8	09:15	09:35	09:55	10:15	10:35	8
			3	09:30	09:50	10:10	10:30	10:50	3
			5	09:45	10:05	10:25	10:45	11:05	5
10-11	4	80min		00:00	00:20	00:40	01:00	01:20	
			1	10:00	10:20	10:40	11:00	11:20	1
			4	10:15	10:35	10:55	11:15	11:35	4
			6	10:30	10:50	11:10	11:30	11:50	6
			7	10:45	11:05	11:25	11:45	12:05	7
11-12	4	72min		00:00	00:18	00:36	00:54	01:12	
			3	11:00	11:18	11:36	11:54	12:12	3
			5	11:15	11:33	11:51	12:09	12:27	5
			1	11:30	11:48	12:06	12:24	12:42	1
			4	11:45	12:03	12:21	12:39	12:57	4
12-13	4	72min		00:00	00:18	00:36	00:54	01:12	
			6	12:00	12:18	12:36	12:54	13:12	6
			7	12:15	12:33	12:51	13:09	13:27	7
			3	12:30	12:48	13:06	13:24	13:42	3
			5	12:45	13:03	13:21	13:39	13:57	5
13-14	4	72min		00:00	00:18	00:36	00:54	01:12	
			4	13:00	13:18	13:36	13:54	14:12	4
			6	13:15	13:33	13:51	14:09	14:27	6
			7	13:30	13:48	14:06	14:24	14:42	7
			3	13:45	14:03	14:21	14:39	14:57	3
14-15	4	72min		00:00	00:18	00:36	00:54	01:12	
			5	14:00	14:18	14:36	14:54	15:12	5
			4	14:15	14:33	14:51	15:09	15:27	4
			6	14:30	14:48	15:06	15:24	15:42	6
			7	14:45	15:03	15:21	15:39	15:57	7
15-16	4	80min		00:00	00:20	00:40	01:00	01:20	
			3	15:00	15:20	15:40	16:00	16:20	3
			5	15:15	15:35	15:55	16:15	16:35	5
			4	15:30	15:50	16:10	16:30	16:50	4
			6	15:45	16:05	16:25	16:45	17:05	6
16-17	4	96min		00:00	00:24	00:48	01:12	01:36	
			7	16:00	16:24	16:48	17:12	17:36	7
			2	16:15	16:39	17:03	17:27	17:51	2
			3	16:30	16:54	17:18	17:42	18:06	3
			5	16:45	17:09	17:33	17:57	18:21	5
17-18	4	96min		00:00	00:24	00:48	01:12	01:36	
			4	17:00	17:24	17:48	18:12	18:36	4
			6	17:15	17:39	18:03	18:27	18:51	6
			8	17:30	17:54	18:18	18:42	19:06	8
			7	17:45	18:09	18:33	18:57	19:21	7
18-19	4	80min		00:00	00:20	00:40	01:00	01:20	
			2	18:00	18:20	18:40	19:00	19:20	2
			3	18:15	18:35	18:55	19:15	19:35	3
			5	18:30	18:50	19:10	19:30	19:50	5
			4	18:45	19:05	19:25	19:45	20:05	4
19-20	4	72min		00:00	00:18	00:36	00:54	01:12	
			6	19:00	19:18	19:36	19:54	20:12	6
			8	19:15	19:33	19:51	20:09	20:27	8
			2	19:30	19:48	20:06	20:24	20:42	2
			3	19:45	20:03	20:21	20:39	20:57	3
20-21	3	60 min		00:00	00:15	00:30	00:45	01:00	
			5	20:00	20:15	20:30	20:45	21:00	5
			6	20:20	20:35	20:50	21:05	21:20	6
			8	20:40	20:55	21:10	21:25	21:40	8
21-22	2	60min		00:00	00:15	00:30	00:45	01:00	
			3	21:00	21:15	21:30	21:45	22:00	3
			6	21:30	21:45	22:00	22:15	22:30	6
22-23	2	60min		00:00	00:15	00:30	00:45	01:00	
			3	22:00	22:15	22:30	22:45	23:00	3
			6	22:30	22:45	23:00	23:15	23:30	6

APPENDIX D1: PASSENGER-ARRIVAL SPECIFICATION SPREADSHEET (USER INTERFACE)

Passenger demand profiles												
Thibault Station at Full Capacity (Pph at Peak hour)			**800**									
% of station capacity of TO1 bus service			80%		USERS CAN CHANGE THESE NUMBERS							
% of station capacity of TO2 bus service			20%									
Time of day	**% Passenger estimates of full capacity**		**Estimated number of passengers**		**% of TO1 passengers enter Ent1&Ent2 to P1&P3**				**% of TO2 passengers enter Ent1&Ent2 to P2&P4**			
	TO1 Busses	**TO2 Busses**	**TO1 Busses**	**TO2 Busses**	**Entrance 1**		**Entrance 2**		**Entrance 1**		**Entrance 2**	
					P1	**P3**	**P1**	**P3**	**P2**	**P4**	**P2**	**P4**
4-5am	10%	10%	64	16	35%	30%	25%	10%	40%	30%	20%	10%
5-6am	30%	30%	192	48	35%	30%	25%	10%	40%	30%	20%	10%
6-7am	90%	70%	576	112	35%	30%	25%	10%	40%	30%	20%	10%
7-8am	100%	90%	640	144	35%	30%	25%	10%	40%	30%	20%	10%
8-9am	60%	100%	384	160	35%	30%	25%	10%	40%	30%	20%	10%
9-10am	30%	100%	192	160	35%	30%	25%	10%	40%	30%	20%	10%
10-11am	20%	90%	128	144	35%	30%	25%	10%	40%	30%	20%	10%
11-12pm	20%	90%	128	144	35%	30%	25%	10%	40%	30%	20%	10%
12-13pm	30%	80%	192	128	35%	30%	25%	10%	40%	30%	20%	10%
13-14pm	30%	80%	192	128	35%	30%	25%	10%	40%	30%	20%	10%
14-15pm	30%	80%	192	128	35%	30%	25%	10%	40%	30%	20%	10%
15-16pm	30%	90%	192	144	35%	30%	25%	10%	40%	30%	20%	10%
16-17pm	60%	100%	384	160	35%	30%	25%	10%	40%	30%	20%	10%
17-18pm	100%	100%	640	160	35%	30%	25%	10%	30%	30%	20%	20%
18-19pm	80%	90%	512	144	35%	30%	25%	10%	40%	30%	20%	10%
19-20pm	40%	80%	256	128	35%	30%	25%	10%	40%	30%	20%	10%
20-21pm	10%	70%	64	112	35%	30%	25%	10%	40%	30%	20%	10%
21-22pm	10%	50%	64	80	35%	30%	25%	10%	40%	30%	20%	10%
22-23pm	10%	10%	64	16	35%	30%	25%	10%	40%	30%	20%	10%
Column	1	2	3	4	5	6	7	8	9	10	11	12

USERS CAN CHANGE THESE NUMBERS

USERS CAN CHANGE THESE NUMBERS

APPENDIX D2: PASSENGER-ARRIVAL SPECIFICATION SPREADSHEET (ARENA INTERFACE)

Record numbers								R 1	R 2	R 5	R 6	R 3	R 4	R 7	R 8
Number of TO1 passengers enter Ent1&Ent2 to P1&P3				Number of TO2 passengers enter Ent1&Ent2 to P2&P4				Interarrival times(min) of TO1 passengers Ent1&Ent2 to P1&P3				Interarrival times(min) of TO2 passengers Ent1&Ent2 to P2&P4			
Entrance 1		Entrance 2		Entrance 1		Entrance 2		Entrance 1		Entrance 2		Entrance 1		Entrance 2	
P1	**P3**	**P1**	**P3**	**P2**	**P4**	**P2**	**P4**	**P1**	**P3**	**P1**	**P3**	**P2**	**P4**	**P2**	**P4**
22	19	16	6	6.4	4.8	3.2	1.6	2.68	3.13	3.75	9.38	9.38	12.50	18.75	37.50
67	58	48	19	19.2	14.4	9.6	4.8	0.89	1.04	1.25	3.13	3.13	4.17	6.25	12.50
202	173	144	58	44.8	33.6	22.4	11.2	0.30	0.35	0.42	1.04	1.34	1.79	2.68	5.36
224	192	160	64	57.6	43.2	28.8	14.4	0.27	0.31	0.38	0.94	1.04	1.39	2.08	4.17
134	115	96	38	64	48	32	16	0.45	0.52	0.63	1.56	0.94	1.25	1.88	3.75
67	58	48	19	64	48	32	16	0.89	1.04	1.25	3.13	0.94	1.25	1.88	3.75
45	38	32	13	57.6	43.2	28.8	14.4	1.34	1.56	1.88	4.69	1.04	1.39	2.08	4.17
45	38	32	13	57.6	43.2	28.8	14.4	1.34	1.56	1.88	4.69	1.04	1.39	2.08	4.17
67	58	48	19	51.2	38.4	25.6	12.8	0.89	1.04	1.25	3.13	1.17	1.56	2.34	4.69
67	58	48	19	51.2	38.4	25.6	12.8	0.89	1.04	1.25	3.13	1.17	1.56	2.34	4.69
67	58	48	19	51.2	38.4	25.6	12.8	0.89	1.04	1.25	3.13	1.17	1.56	2.34	4.69
67	58	48	19	57.6	43.2	28.8	14.4	0.89	1.04	1.25	3.13	1.04	1.39	2.08	4.17
134	115	96	38	64	48	32	16	0.45	0.52	0.63	1.56	0.94	1.25	1.88	3.75
224	192	160	64	48	48	32	32	0.27	0.31	0.38	0.94	1.25	1.25	1.88	1.88
179	154	128	51	57.6	43.2	28.8	14.4	0.33	0.39	0.47	1.17	1.04	1.39	2.08	4.17
90	77	64	26	51.2	38.4	25.6	12.8	0.67	0.78	0.94	2.34	1.17	1.56	2.34	4.69
22	19	16	6	44.8	33.6	22.4	11.2	2.68	3.13	3.75	9.38	1.34	1.79	2.68	5.36
22	19	16	6	32	24	16	8	2.68	3.13	3.75	9.38	1.88	2.50	3.75	7.50
22	19	16	6	6.4	4.8	3.2	1.6	2.68	3.13	3.75	9.38	9.38	12.50	18.75	37.50

APPENDIX E: PASSENGERS-ALIGHTING SPECIFICATION SPREADSHEET

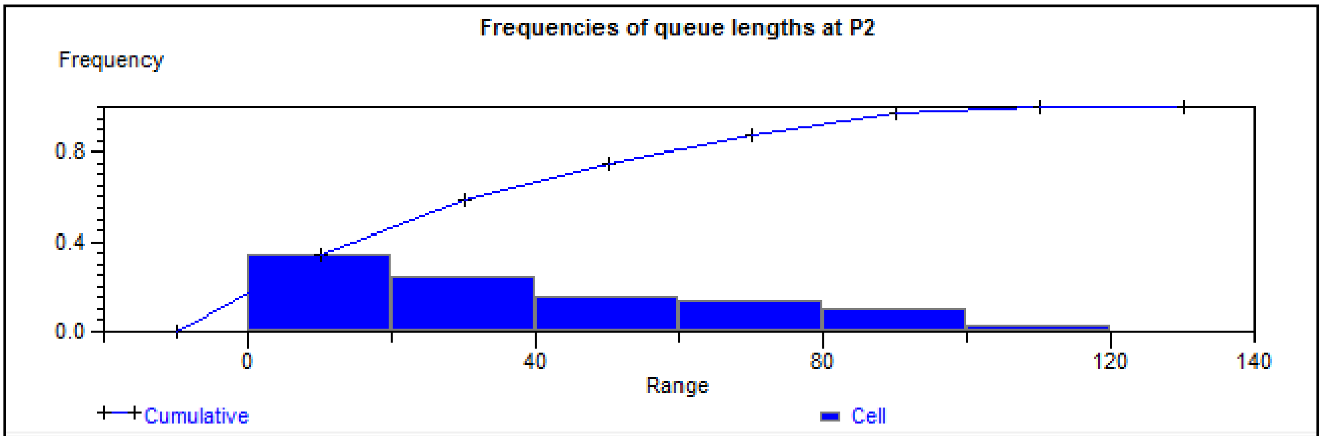
Specifying the number of passengers on an arriving bus and the number of alighting passengers							
Time	Load factor: % of bus capacity which is full	Bus capacity	Passengers on bus at P1	% of Passengers alighting the bus	Number of alighting passengers at P1	Passengers on bus P3	Number of alighting passengers P3
				TO1			
4-5am	5%	120	6	25%	2		
			6		2		
			6		2	6	2
5-6am	15%	120	18	25%	5	18	5
			18		5	18	5
			18		5	18	5
			18		5	18	5
6-7am	45%	120	54	25%	14	54	14
			54		14	54	14
			54		14	54	14
			54		14	54	14
			54		14	54	14
7-8am	50%	120	60	25%	15	60	15
			60		15	60	15
			60		15	60	15
			60		15	60	15
			60		15	60	15
8-9am	30%	120	36	25%	9	36	9
			36		9	36	9
			36		9	36	9
			36		9	36	9
			36		9	36	9
9-10am	15%	120	18	25%	5	18	5
			18		5	18	5
			18		5	18	5
10-11am	10%	120	12	25%	3	12	3
			12		3	12	3
			12		3	12	3
11-12pm	10%	120	12	25%	3	12	3
			12		3	12	3
			12		3	12	3
12-13pm	15%	120	18	25%	5	18	5
			18		5	18	5
			18		5	18	5
13-14pm	15%	120	18	25%	5	18	5
			18		5	18	5
			18		5	18	5
14-15pm	15%	120	18	25%	5	18	5
			18		5	18	5
			18		5	18	5
15-16pm	15%	120	18	25%	5	18	5
			18		5	18	5
			18		5	18	5
16-17pm	30%	120	36	25%	9	36	9
			36		9	36	9
			36		9	36	9
			36		9	36	9
17-18pm	50%	120	60	25%	15	60	15
			60		15	60	15
			60		15	60	15
			60		15	60	15
			60		15	60	15
			60		15	60	15
18-19pm	40%	120	48	25%	12	48	12
			48		12	48	12
			48		12	48	12
			48		12	48	12
			48		12	48	12
19-20pm	20%	120	24	25%	6	24	6
			24		6	24	6
			24		6	24	6
			24		6	24	6
20-21pm	5%	120	6	25%	2	6	2
			6		2	6	2
21-22pm	5%	120	6	25%	2	6	2
			6		2	6	2
22-23pm	5%	120	6	25%	2	6	2
			6		2	6	2
23pm						6	2

Time	Load factor: % of bus capacity which is full	Bus capacity	Passengers on bus at P2	% of Passengers alighting the bus	Number of alighting passengers at P2	Passengers on bus P4	Number of alighting passengers P4
			TO2				
4-5am	5%	40	2	25%	1		
			2		1	2	1
			2		1	2	1
5-6am	15%	40	6	25%	2	6	2
			6		2	6	2
			6		2	6	2
			6		2	6	2
6-7am	35%	40	14	25%	4	14	4
			14		4	14	4
			14		4	14	4
7-8am	45%	40	18	25%	5	18	5
			18		5	18	5
			18		5	18	5
8-9am	50%	40	20	25%	5	20	5
			20		5	20	5
			20		5	20	5
			20		5	20	5
9-10am	50%	40	20	25%	5	20	5
			20		5	20	5
			20		5	20	5
			20		5	20	5
10-11am	45%	40	18	25%	5	18	5
			18		5	18	5
			18		5	18	5
			18		5	18	5
11-12pm	45%	40	18	25%	5	18	5
			18		5	18	5
			18		5	18	5
			18		5	18	5
12-13pm	40%	40	16	25%	4	16	4
			16		4	16	4
			16		4	16	4
			16		4	16	4
13-14pm	40%	40	16	25%	4	16	4
			16		4	16	4
			16		4	16	4
			16		4	16	4
14-15pm	40%	40	16	25%	4	16	4
			16		4	16	4
			16		4	16	4
			16		4	16	4
15-16pm	45%	40	18	25%	5	18	5
			18		5	18	5
			18		5	18	5
			18		5	18	5
16-17pm	50%	40	20	25%	5	20	5
			20		5	20	5
			20		5	20	5
			20		5	20	5
17-18pm	50%	40	20	25%	5	20	5
			20		5	20	5
			20		5	20	5
			20		5	20	5
18-19pm	45%	40	18	25%	5	18	5
			18		5	18	5
			18		5	18	5
			18		5	18	5
19-20pm	40%	40	16	25%	4	16	4
			16		4	16	4
			16		4	16	4
			16		4	16	4
20-21pm	35%	40	14	25%	4	14	4
			14		4	14	4
			14		4	14	4
21-22pm	25%	40	10	25%	3	10	3
			10		3	10	3
22-23pm	5%	40	2	25%	1	2	1
			2		1	2	1
23pm			2		1	2	1

APPENDIX F: STOCHASTIC MODEL 2 FREQUENCY RESULTS

Time and passenger frequency results for platform 2 and 4

Scenario 1: Platform 2

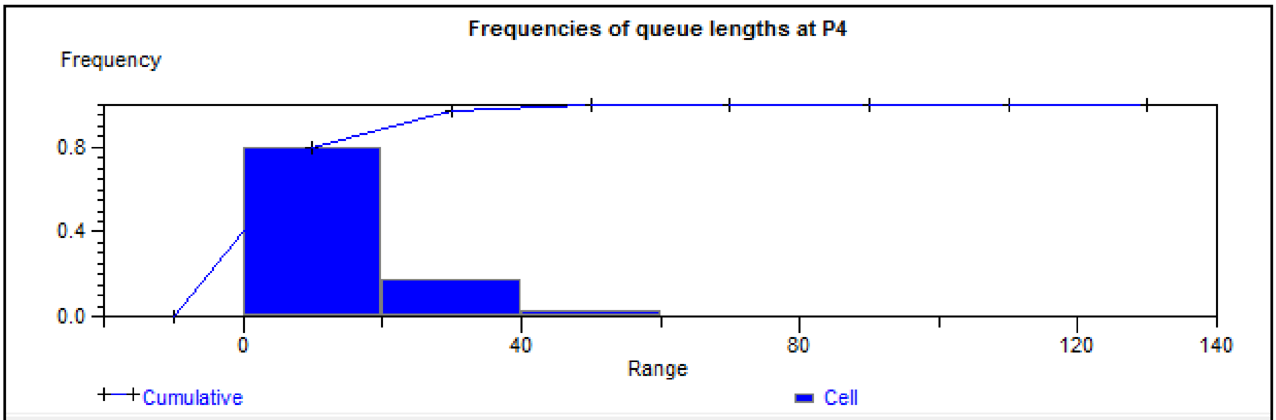


Histogram Summary
Frequencies of queue lengths at P2

Cell	Cell Limits From	Cell Limits To	Abs. Freq. (Time) Cell	Abs. Freq. (Time) Cumul.	Rel. Freq. Cell	Rel. Freq. Cumul.
1	-Infinity	0	0	0	0	0
2	0	20	6.576	6.576	0.3461	0.3461
3	20	40	4.628	11.2	0.2436	0.5897
4	40	60	2.985	14.19	0.1571	0.7468
5	60	80	2.488	16.68	0.131	0.8778
6	80	100	1.836	18.51	0.09662	0.9744
7	100	120	0.4859	19	0.02557	1
8	120	+Infinity	0	19	0	1

Queue length	Passenger frequency	Relative frequency	Upper limit	Cumulative frequency
0 < X ≤ 20	594	0.32	**X ≤ 20**	0.32
20 < X ≤ 40	533	0.29	**X ≤ 40**	0.61
40 < X ≤ 60	357	0.19	**X ≤ 60**	0.8
60 < X ≤ 80	218	0.12	**X ≤ 80**	0.92
80 < X ≤ 100	113	0.06	**X ≤ 100**	0.98
100 < X ≤ 120	37	0.02	**X ≤ 120**	1
X >120	0	0		1

Scenario 1: Platform 4

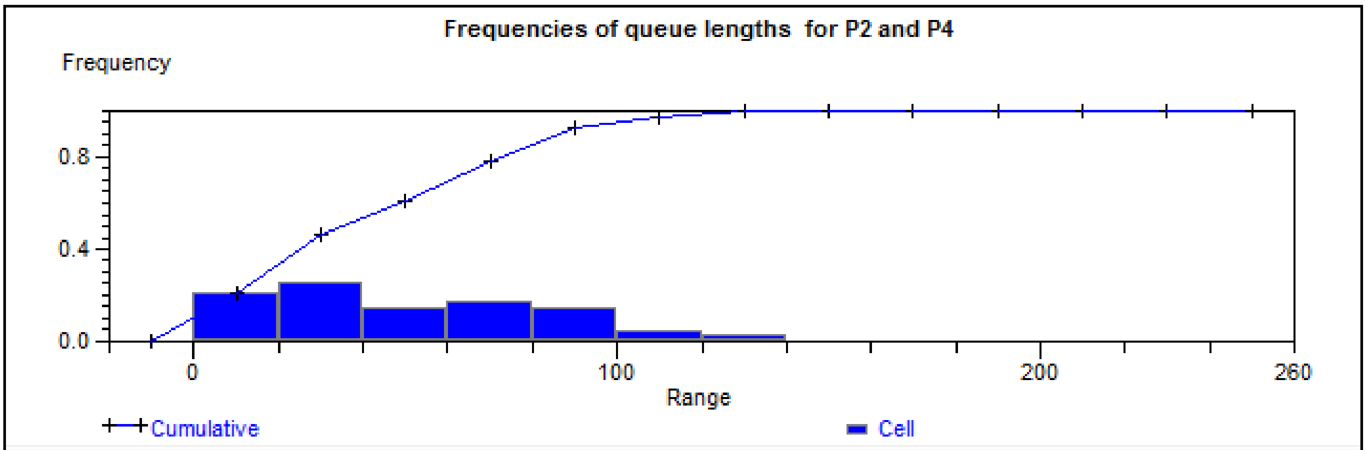


Histogram Summary
Frequencies of queue lengths at P4

	Cell Limits		Abs. Freq. (Time)		Rel. Freq.	
Cell	From	To	Cell	Cumul.	Cell	Cumul.
1	-Infinity	0	0	0	0	0
2	0	20	15.19	15.19	0.7995	0.7995
3	20	40	3.35	18.54	0.1763	0.9758
4	40	60	0.4605	19	0.02424	1
5	60	80	0	19	0	1
6	80	100	0	19	0	1
7	100	120	0	19	0	1
8	120	+Infinity	0	19	0	1

Queue length	Passenger frequency	Relative frequency	Upper limit	Cumulative frequency
0 < X ≤ 20	1025	0.78	**X ≤ 20**	0.78
20 < X ≤ 40	245	0.19	**X ≤ 40**	0.97
40 < X ≤ 60	38	0.03	**X ≤ 60**	1
60 < X ≤ 80	0	0	**X ≤ 80**	1
80 < X ≤ 100	0	0	**X ≤ 100**	1
100 < X ≤ 120	0	0	**X ≤ 120**	1
X >120	0	0		1

Scenario 1: Platform 2 and 4 combined

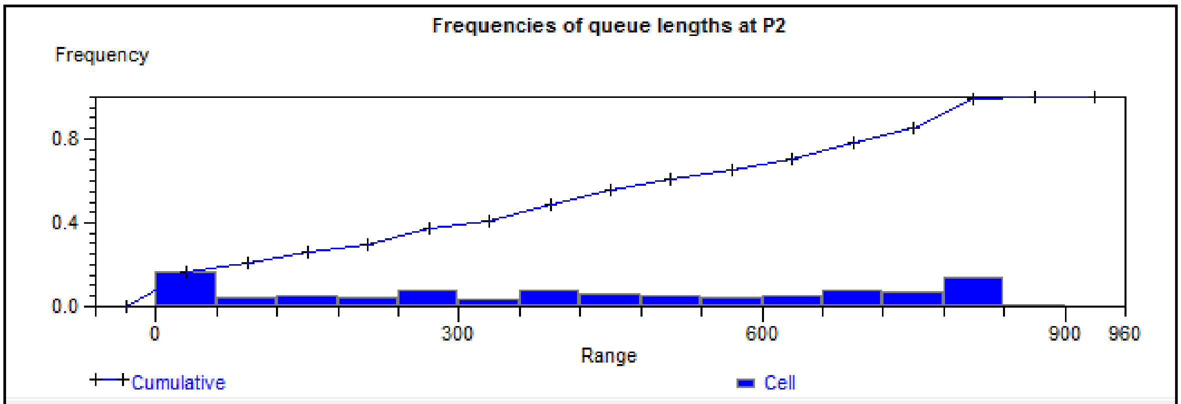


Histogram Summary
Frequencies of queue lengths for P2 and P4

	Cell Limits		Abs. Freq. (Time)		Rel. Freq.	
Cell	From	To	Cell	Cumul.	Cell	Cumul.
1	-Infinity	0	0	0	0	0
2	0	20	3.921	3.921	0.2064	0.2064
3	20	40	4.908	8.829	0.2583	0.4647
4	40	60	2.698	11.53	0.142	0.6067
5	60	80	3.309	14.84	0.1742	0.7808
6	80	100	2.759	17.59	0.1452	0.926
7	100	120	0.896	18.49	0.04716	0.9732
8	120	140	0.4532	18.94	0.02385	0.9971
9	140	160	0.05596	19	0.002945	1
10	160	180	0	19	0	1
11	180	200	0	19	0	1
12	200	220	0	19	0	1
13	220	240	0	19	0	1
14	240	+Infinity	0	19	0	1

Queue length	Passenger frequency	Relative frequency	Upper limit	Cumulative frequency
0 < X ≤ 20	483	0.15	X ≤ 20	0.15
20 < X ≤ 40	930	0.3	X ≤ 40	0.45
40 < X ≤ 60	552	0.18	X ≤ 60	0.62
60 < X ≤ 80	589	0.19	X ≤ 80	0.81
80 < X ≤ 100	411	0.13	X ≤ 100	0.94
100 < X ≤ 120	125	0.04	X ≤ 120	0.98
120 < X ≤ 140	53	0.02	X ≤ 140	1
140 < X ≤ 160	7	0	X ≤ 160	1
160 < X ≤ 180	0	0	X ≤ 180	1
180 < X ≤ 200	0	0	X ≤ 200	1
200 < X ≤ 220	0	0	X ≤ 220	1
220 < X ≤ 240	0	0	X ≤ 240	1
X > 240	0	0		1

Scenario 2: Platform 2

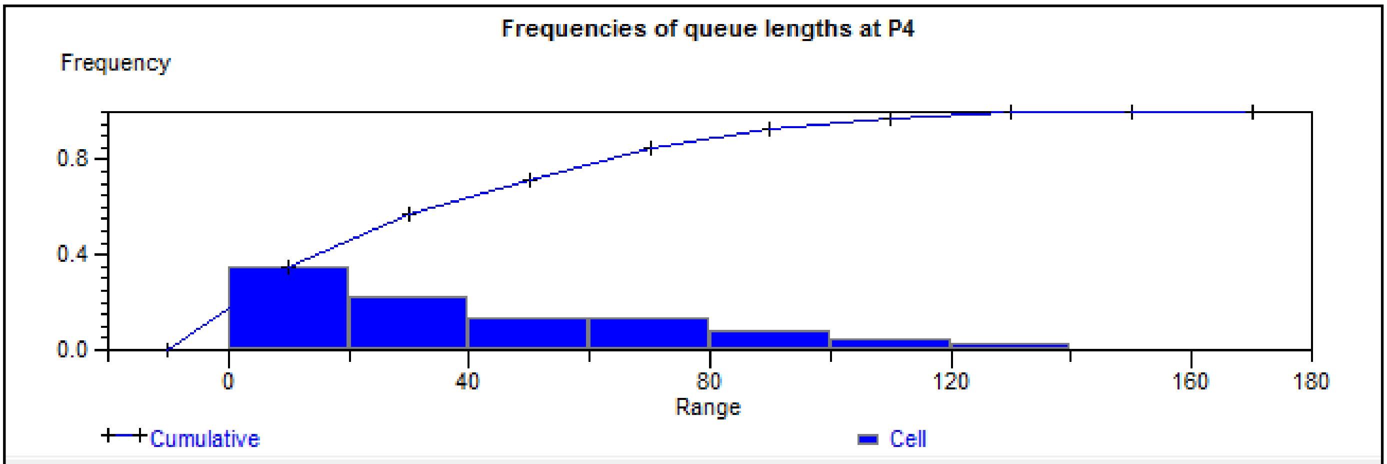


Histogram Summary
Frequencies of queue lengths at P2

	Cell Limits		Abs. Freq. (Time)		Rel. Freq.	
Cell	From	To	Cell	Cumul.	Cell	Cumul.
1	-Infinity	0	0	0	0	0
2	0	60	3.153	3.153	0.166	0.166
3	60	120	0.7893	3.943	0.04154	0.2075
4	120	180	0.9881	4.931	0.052	0.2595
5	180	240	0.7516	5.682	0.03956	0.2991
6	240	300	1.472	7.155	0.07749	0.3766
7	300	360	0.6507	7.805	0.03425	0.4108
8	360	420	1.494	9.3	0.07865	0.4895
9	420	480	1.228	10.53	0.06461	0.5541
10	480	540	1.006	11.53	0.05297	0.607
11	540	600	0.896	12.43	0.04716	0.6542
12	600	660	0.9644	13.39	0.05076	0.705
13	660	720	1.482	14.88	0.07801	0.783
14	720	780	1.364	16.24	0.07181	0.8548
15	780	840	2.632	18.87	0.1386	0.9933
16	840	900	0.1265	19	0.006657	1
17	900	+Infinity	0	19	0	1

Queue length	Passenger frequency	Relative frequency	Upper limit	Cumulative frequency
0 < X ≤ 60	248	0.09	X ≤ 60	0.09
60 < X ≤ 120	137	0.05	X ≤ 120	0.14
120 < X ≤ 180	196	0.07	X ≤ 180	0.21
180 < X ≤ 240	146	0.05	X ≤ 240	0.26
240 < X ≤ 300	266	0.1	X ≤ 300	0.36
300 < X ≤ 360	113	0.04	X ≤ 360	0.4
360 < X ≤ 420	243	0.09	X ≤ 420	0.49
420 < X ≤ 480	197	0.07	X ≤ 480	0.56
480 < X ≤ 540	163	0.06	X ≤ 540	0.62
540 < X ≤ 600	168	0.06	X ≤ 600	0.68
600 < X ≤ 660	175	0.06	X ≤ 660	0.75
660 < X ≤ 720	255	0.09	X ≤ 720	0.84
720 < X ≤ 780	215	0.08	X ≤ 780	0.92
780 < X ≤ 840	213	0.08	X ≤ 840	1
840 < X ≤ 900	12	0	X ≤ 900	1
X > 900	0	0		1

Scenario 2: Platform 4



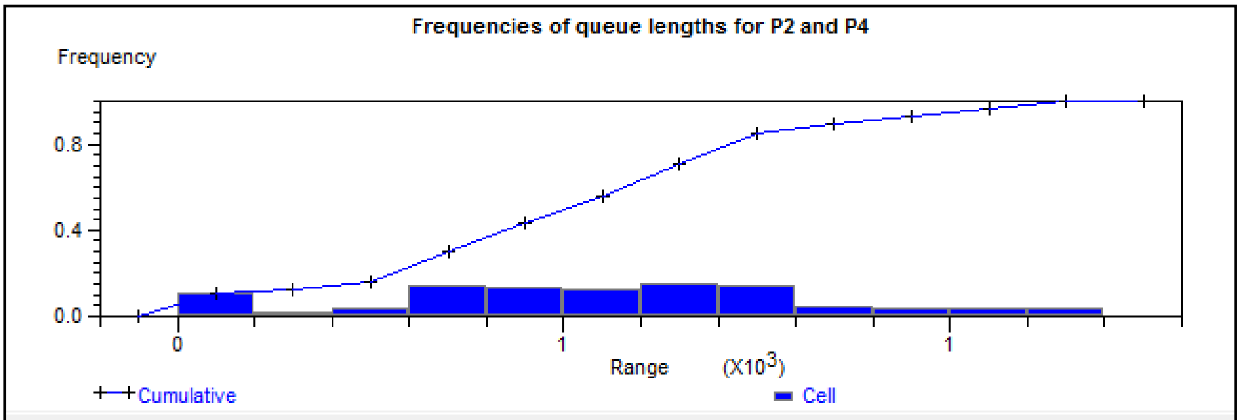
Histogram Summary

Frequencies of queue lengths at P4

	Cell Limits		Abs. Freq. (Time)		Rel. Freq.	
Cell	From	To	Cell	Cumul.	Cell	Cumul.
1	-Infinity	0	0	0	0	0
2	0	20	6.579	6.579	0.3463	0.3463
3	20	40	4.301	10.88	0.2264	0.5726
4	40	60	2.617	13.5	0.1377	0.7103
5	60	80	2.582	16.08	0.1359	0.8462
6	80	100	1.534	17.61	0.08076	0.927
7	100	120	0.8434	18.46	0.04439	0.9714
8	120	140	0.5322	18.99	0.02801	0.9994
9	140	160	0.01213	19	0.0006383	1
10	160	+Infinity	0	19	0	1

Queue length	Passenger frequency	Relative frequency	Upper limit	Cumulative frequency
0 < X ≤ 20	448	0.23	**X ≤ 20**	0.23
20 < X ≤ 40	466	0.24	**X ≤ 40**	0.48
40 < X ≤ 60	318	0.17	**X ≤ 60**	0.64
60 < X ≤ 80	320	0.17	**X ≤ 80**	0.81
80 < X ≤ 100	182	0.1	**X ≤ 100**	0.91
100 < X ≤ 120	110	0.06	**X ≤ 120**	0.97
120 < X ≤ 140	67	0.03	**X ≤ 140**	1.00
140 < X ≤ 160	0	0	**X ≤ 160**	1
X > 160	0	0		1

Scenario 2: Platform 2 and 4 combined



Histogram Summary
Frequencies of queue lengths for P2 and P4

Cell	Cell Limits From	To	Abs. Freq. (Time) Cell	Cumul.	Rel. Freq. Cell	Cumul.
1	-Infinity	0	0	0	0	0
2	0	100	2.05	2.05	0.1079	0.1079
3	100	200	0.2604	2.31	0.01371	0.1216
4	200	300	0.6863	2.996	0.03612	0.1577
5	300	400	2.759	5.755	0.1452	0.3029
6	400	500	2.516	8.271	0.1324	0.4353
7	500	600	2.272	10.54	0.1196	0.5549
8	600	700	2.925	13.47	0.154	0.7089
9	700	800	2.629	16.1	0.1384	0.8473
10	800	900	0.9193	17.02	0.04838	0.8956
11	900	1000	0.6546	17.67	0.03445	0.9301
12	1000	1100	0.7288	18.4	0.03836	0.9685
13	1100	1200	0.5964	19	0.03139	0.9998
14	1200	+Infinity	0.002891	19	0.0001522	1

Queue length	Passenger frequency	Relative frequency	Upper limit	Cumulative frequency
$0 < X \leq 100$	469	0.1	$X \leq 100$	0.1
$100 < X \leq 200$	175	0.04	$X \leq 200$	0.14
$200 < X \leq 300$	339	0.07	$X \leq 300$	0.21
$300 < X \leq 400$	783	0.17	$X \leq 400$	0.38
$400 < X \leq 500$	832	0.18	$X \leq 500$	0.56
$500 < X \leq 600$	368	0.08	$X \leq 600$	0.64
$600 < X \leq 700$	432	0.09	$X \leq 700$	0.73
$700 < X \leq 800$	882	0.19	$X \leq 800$	0.92
$800 < X \leq 900$	368	0.08	$X \leq 900$	1
$900 < X \leq 1000$	0	0	$X \leq 1000$	1
$1000 < X \leq 1100$	0	0	$X \leq 1100$	1
$1100 < X \leq 1200$	0	0	$X \leq 1200$	1
$X > 1200$	0	0		1