

**OPTIMAL INVESTMENT STRATEGIES FOR BUS-BASED TRANSPORT UNDER  
LOW TO MEDIUM PASSENGER DEMAND CONDITIONS**

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A thesis submitted in partial fulfilment of the requirements for the degree of

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## THESIS SUMMARY

### OPTIMAL INVESTMENT STRATEGIES FOR BUS-BASED TRANSPORT UNDER LOW TO MEDIUM PASSENGER DEMAND CONDITIONS

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In South Africa, a number of BRT systems are currently either in the planning stage, detail design and construction stage or operational. Cities such as Cape Town, Tshwane, Johannesburg, Bloemfontein, Polokwane, Rustenburg, Nelson Mandela Bay and Durban are currently in some BRT development or operational stage. These systems are being implemented at much lower passenger demand than in the majority of developing nations (Hensher & Golob, 2008), (City of Cape Town, 2012), (Rea Vaya, 2009), (Botha et. al., 2013).

Planning authorities in South Africa are required by the National Land Transport Act (NLTA) to integrate all non-contracted services into a single public transport system (Republic of South Africa, 2009). Current availability of funding through the Public Transport Infrastructure and Systems grant (PTIS) and the Public Transport Operational Grant (PTOG), (Republic of South

Africa, 2012), has made it possible for municipalities to plan, implement and operate such systems.

No country possesses infinite funds to apply on the implementation and operation of public transport systems. It is therefore important that an analysis should be done on bus based infrastructure and operational alternatives. The incremental implementation of network wide BRT like features, has however been proven to have greater benefit-cost ratios (Lindblom, 1979), rather than implementing a full BRT on a single line (Eddington, 2006), (Niles & Jerram, 2010), (Hitge & van Dijk, 2012) and (Hidalgo, c.a. 2006).

When the decision is made to implement a bus based public transport system, the planning authority is faced with various questions. Two of the more critical questions faced are:

- What level of bus service should be implemented?
- What type of bus should be used?

The goal of this study therefore is, taking into consideration an incremental increase in passenger demand, to find the optimum size of bus to use in combination with the extent of public transport infrastructure to be implemented.

A model was created for this study in order to re-create a real life scheduled bus service for each of the different variables. One of the variables used in this study is the type of bus, with a single BRT bus, articulated bus and bi-articulated bus used in the model. Another variable used in this study is the type of service, with a traditional bus service, operating in mixed traffic (base case scenario), a London style bus lane service and a BRT service being used to populate the model. Other variables include the level of traffic congestion experienced in the mixed lane bus service and the passenger demand encountered on the public transport line.

Initially, the data obtained from the model shows, when compared to the same type of service, a bi-articulated bus always has the best benefit-cost ratio. This is followed by an articulated bus, with a single bus having the worst benefit-cost ratio. An increase in traffic only raises the benefit-cost values, and does not alter the general trend of the services or buses.

When comparing the combination of different types of buses and the different types of services, a London style bus lane, operating a bi-articulated bus has a similar  $B/C_1$  ratio (excluding capital costs) than the  $B/C_1$  ratio for an articulated bus operated on a BRT service. For a  $B/C_2$  analysis (including capital costs) a London style bus lane, operating a bi-articulated bus has a better  $B/C_2$  than for an articulated bus operated on a BRT service. Comparing the  $B/C_1$  and  $B/C_2$  ratios for buses operating on a BRT service, the  $B/C_1$  ratio for an articulated bus is very similar to the  $B/C_2$  ratio of a bi-articulated bus.

A hybrid model was also developed where the London style bus lane service also receives traffic signal priority, like with the initial BRT model.  $B/C_1$  ratios for the alternative London style services comes very close to the original BRT values.  $B/C_2$  ratios show better values for the hybrid London style bus lane service than for the original BRT service.

For traffic volumes that necessitate the use of a segregated bus lane, an optimal investment strategy was developed, taking into consideration passenger demand, service type and vehicle selection, both excluding and including capital expenditure.

The two services offering the highest  $B/C_1$  ratios for a peak hour passenger demand range between 500 and 800 passengers per hour, are for the hybrid services, operating with articulated or bi-articulated buses. From approximately 800 passengers per hour, the bi-articulated bus, operated on the hybrid service exceeds the  $B/C_1$  ratio of the articulated bus, also operating on the hybrid service. The hybrid service, operating a bi-articulated bus, has the greatest  $B/C_1$  ratio for a passenger demand of up to approximately 5 000 passengers per hour. For a passenger demand beyond 5 000 passengers per hour, the BRT service, operating a bi-articulated bus has the highest  $B/C_1$  ratio. This indicates that this service would be the most beneficial for a passenger demand exceeding 5 000 passengers per hour, when capital costs are excluded.

Should the infrastructure costs for the system be included ( $B/C_2$  ratio), the two services offering the highest  $B/C_2$  ratios are for the hybrid services, operating with articulated or bi-articulated buses. From approximately 800 passengers per hour, the bi-articulated bus, operated on the hybrid service exceeds the  $B/C_2$  ratio of the articulated bus, also operating on the hybrid service. The hybrid service, operating a bi-articulated bus, has the greatest  $B/C_2$

ratio for a passenger demand of up to approximately 12 000 passengers per hour. For a passenger demand beyond 12 000 passengers per hour, the BRT and hybrid services, both operating a bi-articulated bus has a very similar  $B/C_2$  ratio, indicating that any one of the two options could be equally beneficial.

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**LIST OF EQUATIONS**

$$C_b = \frac{C_o}{[L_f * F * N_{sb}]} \dots\dots\dots \text{Equation 2.1}$$

..... 24

$$\text{Capacity} = \frac{3600 * n * C_v}{h_{\min}} \dots\dots\dots \text{Equation 2.2}$$

..... 27

$$y = 2.294x^2 + 0.1431x + 1.0864 \dots\dots\dots \text{Equation 2.3}$$

..... 33

$$t = y * t_o \dots\dots\dots \text{Equation 2.4}$$

..... 33

$$h = \frac{60}{f} \dots\dots\dots \text{Equation 2.5}$$

..... 46

$$f = \frac{P_{\max}}{\alpha * n * C_v} \dots\dots\dots \text{Equation 2.6}$$

..... 46

$$T' = 2T_o + t_{t1} + t_{t2} \dots\dots\dots \text{Equation 2.7}$$

..... 47

$$N = \left[ \frac{T}{h} \right] \dots\dots\dots \text{Equation 2.8}$$

..... 47

$$T = N * h \dots\dots\dots \text{Equation 2.9}$$

..... 48

$$V_c = \frac{120 * L}{T} \dots\dots\dots \text{Equation 2.10}$$

..... 48

$$D_{PSn} = \text{MAX} (D_{PBn}, D_{PAN}) \dots\dots\dots \text{Equation 3.1}$$

..... 57

$$S_{RT} = \min \left[ S_R, \frac{61}{1 + e^{-1.00 + (1.185 \text{ Nts} / L)}} \right] \dots\dots\dots \text{Equation 3.2}$$

60

$$D_{TR} = D_{TS} + D_{TC} + D_{RE} \dots\dots\dots \text{Equation 3.3}$$

62

$$D_{TOTAL} = D_{TR} + D_{PSD} \dots\dots\dots \text{Equation 3.4}$$

63

$$S_2 = S_{RT} - \left[ \frac{60}{(D_{TR} + D_{PSD})} \right] \dots\dots\dots \text{Equation 3.5}$$

64

$$B/C_1 = \frac{\text{Monetised time savings}}{\text{Operational Costs}} \dots\dots\dots \text{Equation 3.6}$$

70

$$B/C_2 = \frac{\text{Monetised time savings}}{\text{Operational Costs} + \text{Capital Costs}} \dots\dots\dots \text{Equation 3.7}$$

75

## GLOSSARY OF TERMS

AFC	:	Automatic Fare Collection
BRT	:	Bus Rapid Transit
B/C	:	Benefit-cost ratio
CBD	:	Central Business District
IPTN	:	Integrated Public Transport Network
IPTS	:	Integrated Public Transport System
IRPTN	:	Integrated Rapid Public Transport Network
IRR	:	Internal Rate of return
ITS	:	Intelligent Transportation Systems
KM	:	Kilometres
NLTA	:	National Land Transport Act
NPV	:	Net Present Value
PAX/HR	:	Passengers per hour
PTOG	:	Public Transport Operating Grant
PTIS	:	Public Transport Infrastructure Grant
PWOC	:	Present Worth of Cost
TCRP	:	Transit Cooperative Research Programme
TOD	:	Transit Oriented Design
TRB	:	Transport Research Board
VA	:	Vehicle Actuated

## 1. INTRODUCTION

### 1.1 Background

Public transport forms an essential part of the functioning of any successful city. The very influential BRT Planning Guide (Wright & Hook, 2007) starts off its preface by saying that a fundamental part of human development is the ability to access jobs, education and public services. An efficient and cost-effective public transport system essentially connects people to daily life. For many cities, effective public transport has been forgone, leaving mobility needs exclusively in the hands of private vehicles and uncoordinated and unlicensed public transport operators. These cities have been largely unprepared for the consequences, including severe traffic congestion, air and noise pollution, accidents, and the loss of the sense of community. A high quality public transport system remains an indispensable element in creating a city where people and community come first. The BRT planning guide goes on by saying that to provide an effective and efficient public transport system should be treated as a fundamental objective for all cities as energy security dwindles and climate change is a reality.

Very strong evidence suggests that public transport is essential to the effective and efficient working of any city and serves as a catalyst for sustainable economic development. The manner in which public transport is planned and deployed can significantly affect the efficiency in which it operates. This study is aimed at improving clarity on the conditions under which greater efficiency can be achieved in public transport provision.

Focus is given on bus based public transport, as opposed to other forms of public transport. (Hensher & Golob, 2008), states that for developing countries there is a renewed interest in finding ways of providing efficient and effective public transport that does not come with a high price tag. As South Africa falls within the developing country category, it is of the utmost importance to work efficiently with the limited funds available for public transport. It is usually found that alternative public transport systems to bus based public transport modes are more expensive. Cost comparisons provided in the BRT Planning Guide (Wright & Hook, 2007) suggests that for the same expenditure required to construct seven kilometres of subway, 14 kilometres of elevated rail can be implemented, or 40 kilometres of light rail or 426 kilometres of Bus Rapid Transit. It is therefore likely that the majority of improved public transport services implemented in developing countries would be bus-based.



## 1.2 Problem statement

The 2020 vision of the South African National Public Transport Strategy (NDoT, 2007) provides a road map for a lasting legacy in terms of public transport by proposing that 85% of the 6 Metro cities' current 16 million inhabitants should be within 1km of a public transport service network line. This Strategy also states that by 2014 Phase 1 and 2 network implementation needs to be in place in the 6 metropolitan cities and at least Phase 1 implementation completed in the 6 smaller cities and rural districts.

According to the South African National Public Transport Strategy (NDoT, 2007), the general population travelling on public transport in South Africa are unhappy with the current public transport service quality. A response to address the low level of contentment is given in the strategy. Firstly, modal upgrading is proposed by stabilising the operating environment through short-term interventions. The second proposal is to implement high quality, integrated mass rapid public transport networks. Physical infrastructure proposed by the strategy includes (NDoT, 2007):

- Segregated busways or bus-only roadways, predominantly in the median of the roadway.
- Existence of publicly managed integrated “network” of routes and corridors.
- High quality publicly owned and managed stops, stations, terminals and depots.
- Enhanced stations that are convenient, comfortable, secure, and weather-protected.
- Stations provide level access between the platform and vehicle floor.
- Special stations and terminals to facilitate easy physical integration between trunk routes, feeder services, and other mass public transport systems (if applicable).
- Improvements to nearby public space.

South African public transport grant incentives (infrastructure implementation as well as operational) (Republic of South Africa, 2012), have proven to be a great catalyst for the majority of South African cities, even the smaller ones, who now can afford to pursue the implementation of a BRT type system. In most of these cases, these cities are leaping ahead with full blown BRT designs. These full BRT systems are being implemented at much lower passenger demand levels than what is typically associated with BRT in other developing countries.

Once completed, phase 1A of the MyCiti BRT service will have a capacity of 12 500 passengers per hour per direction, but will only have a peak passenger demand of 3 252 passengers per hour per direction (Grey & Behrens, 2013). This is a v/c ratio of 0.26. Nelson Mandela Bay Municipality initiated a BRT pilot service in 2010. The majority of the routes on this BRT service carried between 45 and 2 000 passengers per month (Botha, Pretorius & Ackerman, 2013). The Rea Vaya in Johannesburg reports to have an average daily passenger volume of between 344 and 1 582 on its 17 routes (Rea Vaya, 2009). Comparing these values to international norm, table 1.1 below shows peak loads in selected BRT corridors in different cities (Hidalgo & Carrigan, 2010)

**Table 1.1: International peak passenger volumes**

	<b>Bogota</b>	<b>Santiago</b>	<b>Curitiba</b>	<b>Mexico City</b>	<b>Beijing</b>	<b>Jakarta</b>
<b>Maximum pax/h/dir</b>	45 000	22 000	13 000	9 000	8 000	3 600

*Source: (Hidalgo & Carrigan, 2010)*

This raises the question of whether full BRT specification is the most appropriate design for most South African cities with its lower passenger demand volumes, or whether more limited intervention, at lower cost, and perhaps linked to an incrementally phased approach, might not be more appropriate and better use of resources. Other literature have raised questions about appropriate levels of BRT implementation. The Eddington Transport Study (Eddington, 2006), (Niles & Jerram, 2010) as well as the BRT Planning Guide (Wright & Hook, 2007) all recommend that a phased implementation approach normally holds greater benefit. Several analytical questions can then be raised like:

- What infrastructure and level of operations will be required for the starter services?
- When should the infrastructure be implemented and the operations of these services commence?
- Under what circumstances the subsequent phasing should be implemented.

When the decision is made to implement a bus based public transport system, the planning authority is then faced with two of the more critical questions:

1. What level of bus service should be implemented? (Mixed traffic service, BRT etc.)
2. What size of bus should be used?

### 1.3 Goals and objectives of the study

The overall purpose of this study is to improve planning and decision making around public transport upgrading, especially in low to medium demand cases, typical of South African cities.

Bus based public transport lines and services come in different forms and shapes. These services vary from a standard single bus (traditional South African bus services), travelling in mixed traffic, to a bi-articulated bus travelling on a comprehensive bus rapid transit system (e.g. Bogota’s TransMilenio). The study sets out to derive appropriate guidelines for choosing between these investment levels, taking passenger demand conditions and cost variables into account.

The figure below graphically illustrates the outline of this study:

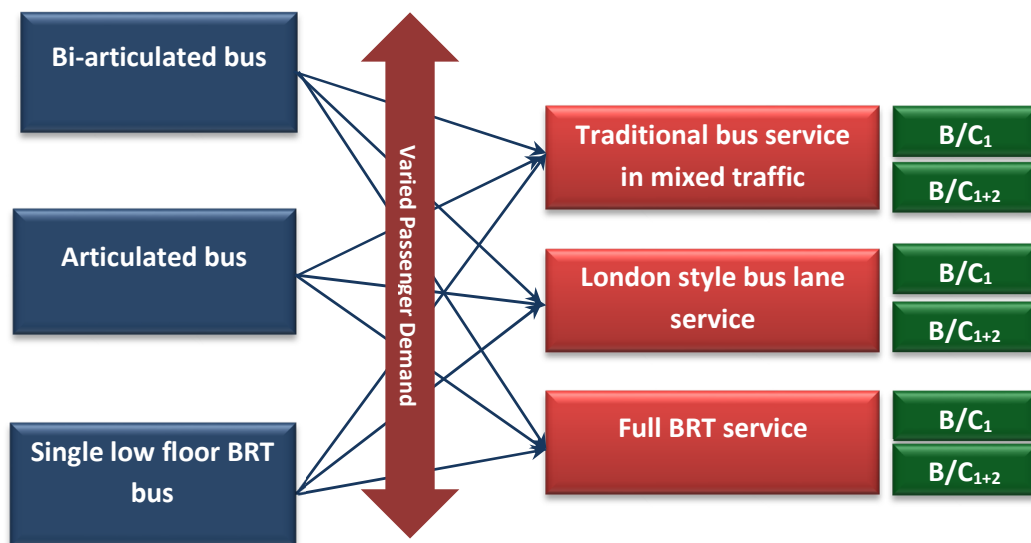


Figure 1.1: Study objectives outline

Figure 1.1 above shows a summarised outline of the model used in the study. Three types of buses, single low-floor BRT buses, articulated buses as well as bi-articulated buses were used in parallel, linking it to an incrementally increased passenger demand. This information in turn was then modelled on three different levels of infrastructure provision. The traditional

bus service represents a bus service operating in mixed traffic, with minimal infrastructure requirements. The London style bus lane service represents a kerb side bus lane, similar to what is currently operational in London. The full BRT service represents a segregated median lane bus lane. Figures 1.2, 1.3 and 1.4 below graphically shows these different types of infrastructure.

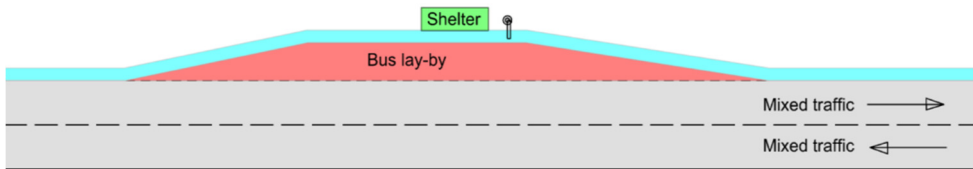


Figure 1.2: Type 1 bus service infrastructure (Traditional bus service)

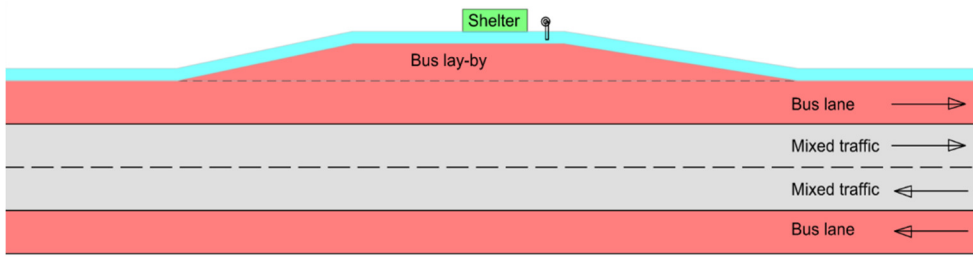


Figure 1.3: Type 2 bus service infrastructure (London bus lane service)

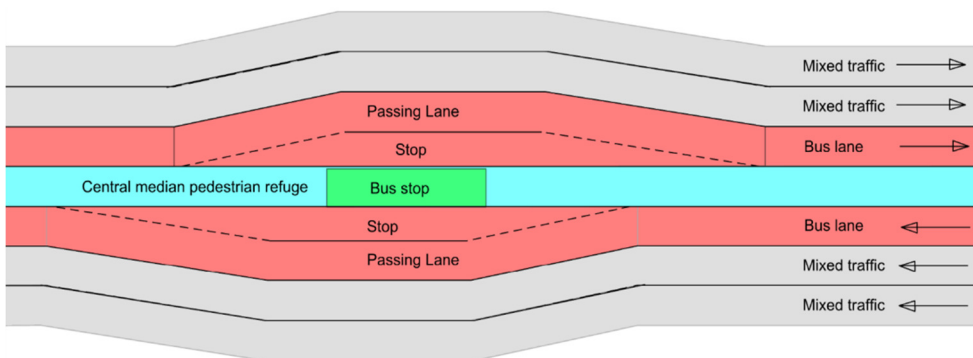


Figure 1.4: Type 3 bus service infrastructure (BRT service)

Two separate benefit-cost ratios were then calculated. The first of which takes into consideration the reduction in travel time, using the monetised value of time of the travelling public, with the costs associated to operating each of the systems. For the second

economic analysis, the benefit remained the same, with the capital expenditure (infrastructure costs) added to the operational costs.

Specific objectives of this study are:

1. To develop a model from which various scenarios and alternatives can be modelled. This model should, as far as possible, reflect the operational variables and costs of a real scheduled service.
2. To compare the different buses and services by means of an economic analysis, **excluding** infrastructure costs. In some cases, the expensive nature of infrastructure provision for BRT services, in relation to the other two modelled services, distorts the benefits derived from operations only. This study therefore will initially do an economic evaluation (benefit-cost), with the costs solely based on the operational costs, assuming the infrastructure has already been implemented by a separate entity.
3. To compare the different buses and services by means of an economic analysis, **including** infrastructure costs. As mentioned in objective two, to implement a BRT is more expensive than the other two operations modelled in this study. This objective will investigate the relation between the different types of buses and services, using a benefit-cost calculation, with the costs including operational as well as infrastructure costs.
4. To compare the two B/C ratios developed in the previous two objectives, and make recommendations.

The goal of the study is, taking into consideration various passenger demands, to find the optimum combination of the size of bus to use with the extent of public transport infrastructure to be provided.

#### 1.4 Scope of the study

One of the more significant aspects investigated during the modelling of this study is the operational cost for bus based public transport lines. Line scheduling is a critical part of the operational cost calculation. The public transport line scheduling was done by means of the method described by Vuchic (Vuchic, 2005). This process requires the maximum volume of passengers along any section of the public transport line. Therefore, when referring to passenger demand in this study, it means the maximum volume of passengers along any section of the public transport line.

Passenger service delay refers to the delay incurred when allowing passengers to embark or disembark the bus. It should be noted that the additional delay created by wheelchair users and cyclists when using the bus services is not incorporated into this model.

The output generated for this study is from an excel based model, with no emphasis on primary data collection.

Due to the tremendous amount of possible variables to consider when developing a model such as the one developed for this study, the model only considers the effects of a single public transport line of 10 km within a CBD area. A weekday public transport service was modelled with Saturdays and Sundays excluded, it however includes peak and of-peak services. Network effects were ignored for this study.

In a US report (US GAO, 2005), a list of direct benefits and costs, associated with public transport projects are given. Table 1.2 below shows which of these are used in the economic evaluation of this study:

It was decided that two separate benefit-cost ratio's should be calculated for this study. The first is as the public transport operator would view the system, as this calculation only takes into consideration the costs associated with the operation of the system. The second benefit-cost calculation is how the implementing agency would assess the system. This calculation takes into account the operational as well as the implementing costs. The benefit for both of the calculations is a monetised time saving. It is noted that these two calculations

are not independent from each other, and that the second calculation ( $B/C_2$ ) would provide a more accurate result for the financial viability of a system.

**Table 1.2: Costs and Benefits used in this study**

Direct benefits	Used in this study	Costs	Used in this study
Monetised travel time savings	x	Project costs (Implementation)	x
Savings in user operating expenses	(x)	Costs for operating and maintaining the project	x
Reductions in accidents, injury, morbidity and mortality		Mitigation costs (e.g. noise reduction barriers )	
Reductions in vehicle operating costs		User costs	(x)
Reductions in emissions		Change in user fares	
Reductions in noise		Increase in transport support services	
Employment accessibility benefits			
Reduced parking costs			

Source: (US GAO, 2005)

(x): Indirect user benefits not analysed in this study.

Other indirect benefits that can be used in an economic analysis is (US GAO, 2005):

- Economic productivity, benefits and growth
- Changes in property values and employment
- Employment, output and income effects due to construction
- Higher density development, being more effective
- Joint development income
- Property tax income

Benefits for this study will solely be calculated from the monetisation of travel time savings, in comparison to a standard bus service base case scenario. Costs will be calculated from both the operational costs as well as the infrastructure (implementation costs).

Other assumptions of the model used in this study are described in chapter 3.

### **1.5 Methodology**

A phased approach was followed during the development of this study. The first phase consisted of a detailed literature review.

Phase two of the study entailed the development of the cost and benefit model. The aim of this model was to simulate, under various assumptions, what the benefit/cost ratios of different levels of capital and operational expenditure would be. Benefits used in these calculations consist of a monetised travel time saving.

Phase three of the study commenced with the application of the model to the various scenarios and variables. The variables include: the type of bus to be used, existing public transport demand along the route and the level of existing mixed traffic flow on the adjacent lane.

Having a set of variables, and the fact that two benefit-cost calculations were made for each scenario, hundreds of models were run. These variables were chosen as they are regarded to play an important role in the eventual economic analysis. The analysis of this data was undertaken during phase four of the study, in order to compare the output by means of passenger demand, type of bus, type of operation and level of infrastructure provision.

The representation, sensitivity analysis and conclusion on the findings of the information were done during the final phase of the study, phase five.

### **1.6 Organisation of the report**

The remainder of the report will be structured by the following chapters:



Chapter 2 will form part of the literature study which consists of various topics, namely: existing bus based systems, calculation of delay in public transport, public transport scheduling, calculation of operational and capital costs and the calculation of benefits.

Chapter 3 forms part of the experimental setup. This chapter will describe the process of developing the model from the research done during the previous chapter. The model is then calibrated and run through a series of sequences with changing variables to produce an extensive output of information.

Chapter 4 will describe the analysis and summary of the output information obtained during the running of the model.

Chapter 5 contains the conclusions and recommendations of the study.

A list of references follows chapter five at the end of the report.

## 2. LITERATURE STUDY

### 2.1 Introduction

In this chapter, the logic of the study is defined whilst reviewing existing literature on the various elements highlighted. The previous chapter already mentioned how highly the South African National Public Transport strategy (NDoT, 2007) regards public transport, and to what extent the remedial measures are proposed in order to create a better public transport experience for all, hence attracting/retaining ridership.

Bus based public transport systems are an everyday part of urban life. Bus services are described by Vuchic (Vuchic, 2005), as representing the most widely used public transport technology. Buses are operated in virtually every city where public transport services exist. Larger cities that operate a rail based public transport system also operate extensive bus networks. These bus services are usually on lines with lower passenger volumes or as feeders to rail lines. In other words, bus based public transport systems are relevant for the vast majority of cities, including South Africa.

Public Transport systems should be designed around the end user and not for other purposes. The BRT Planning Guide (Wright & Hook, 2007) mentions that should you design a system and ignore customer service issues, then failure is inevitable. If you however design a system with customer service issues in mind, then the system is almost assured of success. From a customer's perspective, small and simple measures that improve comfort, safety, and security are more important than sophisticated vehicle technologies or bus way designs. If one looks from the perspective of the traveling public, one of the most significant aspects of his/her journey would be how long the trip takes. Travel time reductions are therefore an important part of how the public would perceive and rate differences in alternative public transport services.

As an example of a cost comparison, one could ask the question, when shown the lower infrastructure expenditure of bus based public transport systems in relation to rail, how would the attractiveness of a bus based system fare when compared to rail? In other words, why BRT and not rail? An article published on the demand performance of BRT (Currie, 2005) concludes by saying: *"These findings suggest that BRT systems can be as effective in*

*attracting passengers as heavy and light rail. Since BRT has been shown to have significant cost advantages over rail, an overall cost effectiveness advantage may be claimed for BRT.”*

In light of the above, it seems that the high-end product of a bus based public transport system (BRT) rivals the effectiveness of rail in attracting passengers. Passenger volumes of up to 45 000 per hour has been successfully managed by the Bogota BRT (Wright & Hook, 2007). Figures 2.1 and 2.2 below shows an interesting development that happened over the last few years. It shows what the existing views of public transport capacity capabilities are versus what was traditionally thought possible.

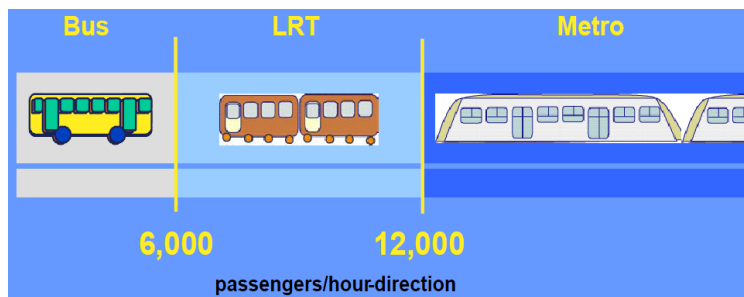


Figure 2.1: Traditional view of public transport capacity

Source: (Wright & Hook, 2007)

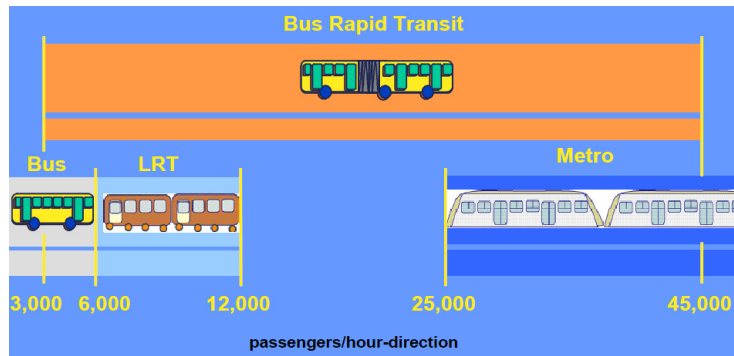


Figure 2.2: New view of public transport capacity

Source: (Wright & Hook, 2007)

It is evident from various writings that for passenger demands below 25 000, a bus based public transport system is much more effective than for rail. Passenger volumes below 45 000 can also be effectively accomplished with proper planning, implementation and

operation, as this has already been implemented. It was therefore decided to create a model which will probe a bit deeper into the various bus based public transport options.

Public transport line speed is one of the key items to calculate, in order to accurately determine what the operational cost of a public transport service would be. Public transport line speed is influenced by numerous events throughout the cycle length of the service. Traffic congestion, traffic signals, bus re-entry from a lay-by back into the mixed traffic lane and passenger service delay all play a role in slowing the bus down.

## **2.2 Incrementalism and phasing in public transport investment**

Limited funding for public transportation schemes is not something new, nor is it unique to South Africa. It is important to implement a cost effective and efficient public transport system, aligning the available budget with the ridership demand anticipated. One could ask the question: For the same amount of expenditure, is it better to implement a single full BRT public transport line or to implement BRT like features on a network level?

A Mineta Transportation Institute report (Niles & Jerram, 2010) suggests the latter could be a good alternative. The report states that instead of implementing a full BRT system on a line by line basis, a reasonable alternative would be to take the most cost effective BRT elements and implement them on a network wide level on multiple lines. This study concludes by saying that BRT is *“fundamentally incremental”*. In other words, the various different elements consisting of a BRT service can be used separately in order to fulfil the planning, implementation and operational requirements of the relevant authority. It provides a certain extent of flexibility in what, where, how and when it can be implemented.

When the TransMilenio was re-structured in 2006, a phased approach was followed (Hidalgo, c.a. 2006). This decision was made after the system has been operational for some time, which proves that the TransMilenio decision makers saw the value in the incremental approach.

Although the implementation of BRT internationally has been done for a few decades, South Africa has only quite recently made the decision to implement this public transport mode. It

cannot be said that the public transport challenges faced in South Africa are the same as the challenges overcome by our international counterparts. For example the minibus-taxi industry and the unique challenges faced during the negotiation and planning stages. Therefore uncertainty to a certain extent does exist when planning this type of public transport service, to this scale. With too many possible alternatives and too many possible consequences due to the level of uncertainty, it would only make sense to utilise an incremental approach, in order to minimise or even mitigate the risks involved (Lindblom, 1979).

It is interesting to note that the incremental development process of the Curitiba BRT system, which took three decades to develop, is not mentioned much (Hitge & van Dijk, 2012). It is common practice for implementing agencies to aim to implement a final Curitiba-like product as soon as possible. Cape Town for instance has taken the decision to implement a full world class standard BRT on the phase A1 corridor, without incremental upgrading (City of Cape Town, 2012).

The highly regarded Eddington Transport Study (Eddington, 2006) states that small incremental improvements tend to have greater cost-benefit ratios than large scale infrastructure projects. This study noted that to invest in a smaller number of items that will yield high returns, rather than a single large project is sensible.

Case studies conducted in North America (Niles & Jerram, 2010) also suggests that a reasonable alternative approach to a full BRT corridor implementation would be to upgrade multiple lines with selected high-value BRT like elements. The benefits achieved, like travel time reduction, will then be spread across the system and not solely on one line.

In the BRT Planning Guide (Wright & Hook, 2007) it is mentioned: *“A BRT project will likely encompass a multi-phase process since it would be unrealistic to build a complete network in a single, brief period. The size of the initial phase will depend upon many factors, but generally a project’s first phase should capture enough passengers to establish the new system on a sound financial basis.”*

The aim of this study is to take it one step further, and formalise three distinct types of operations (or stages) of bus based public transport systems for comparison.

### 2.3 Public transport costs and benefits

Previous work on public transport costs and benefits has been done by various authors. The Victoria Transport Policy Institute (Litman, 2014) produced a summary table for public transport benefits and costs. This table can be seen below as table 2.1:

**Table 2.1: Public transport benefits and costs.**

Category	Improved Transit Service	Increased Transit Travel	Reduced Automotive Travel	Transit-orientated Development
Indicators	Service Quality (speed, reliability, comfort, safety etc.)	Transit Ridership (passenger-miles or mode share)	Mode shifts or automobile travel reductions	Portion of development with TOD design features
Benefits	<ul style="list-style-type: none"> <li>Improved convenience and comfort for existing users.</li> <li>Equity benefits (since existing users tend to be disadvantaged).</li> <li>Option value (the value of having an option for possible future use).</li> <li>Improved operating efficiency (if service speed increases).</li> <li>Improved security (reduced crime risk).</li> </ul>	<ul style="list-style-type: none"> <li>Increased user security, as more users ride transit and wait at stops and stations.</li> <li>Mobility benefits to new users.</li> <li>Increased fare revenue.</li> <li>Increased public fitness and health (if transit travel stimulates more walking or cycling trips).</li> </ul>	<ul style="list-style-type: none"> <li>Reduced traffic congestion.</li> <li>Road and parking facility cost savings.</li> <li>Consumer savings.</li> <li>Reduced chauffeuring burdens.</li> <li>Increased traffic safety.</li> <li>Energy conservation.</li> <li>Air and noise pollution reductions.</li> </ul>	<ul style="list-style-type: none"> <li>Additional vehicle travel reductions (leverage effects).</li> <li>Improved accessibility, particularly for non-drivers.</li> <li>Reduced crime risk.</li> <li>More efficient development (reduced infrastructure costs).</li> <li>Farmland and habitat preservation.</li> </ul>
Costs	<ul style="list-style-type: none"> <li>Increased capital and operating costs, and therefore subsidies.</li> <li>Land and road space.</li> <li>Traffic congestion and accident risk imposed by transit vehicles.</li> </ul>	<ul style="list-style-type: none"> <li>Transit vehicle crowding.</li> </ul>	<ul style="list-style-type: none"> <li>Reduced automobile business activity.</li> </ul>	Various problems associated with more compact development.

Source: (Litman, 2014)

These benefits and costs can also be used for a benefit-cost ratio analysis.

The Transit Cooperative Research Programme (St. Jacques & Levinson, 1997) writes that Public transport capacity depends on the size and configuration of vehicles and how often they operate as it deals with the movement of both people and vehicles. These two aspects of public transport forms part of the more critical items when calculating the operational costs for a public transport line.

Total cost for providing a public transport service consists of capital as well as operational costs (Vuchic, 2005). In a paper presented at the South African Transport Conference (Del Mistro & Aucamp, 2000), only the capital and operational costs were derived for economic analysis. The following capital costs were included in their study when estimating the cost public transport services:

- The cost of the vehicle; including the cost of one or more refurbishments/overhauls during it's life or the analysis period.
- The cost of the way; which would include railways and roadways (more specifically high occupancy vehicle lanes (HOV) lanes).
- The cost of terminals, bus termini and minibus ranking facilities at the beginning and end of routes.
- The cost of stations and stops
- The cost of depots, where vehicles can be stored, maintained and/or overhauled.

Their operating costs included:

- The cost of energy or fuel
- The operating costs of the vehicles which include operating staff costs, management costs, offices rentals, insurance, overheads, licenses, marketing, vehicle maintenance, etc. These costs can be apportioned as either cost/vehicle-km or cost/vehicle/year or both.
- The annual operating, staff and maintenance costs of the railway and roadway.
- The annual operating, staff and maintenance costs of termini, ranks, stations and stops. (It is possible that income can be derived at these from rentals from shops and offices.)

- The annual operating cost of the depot. (In the study it was not possible to obtain separate values for this cost; and instead were included as part of the vehicle operating cost.)

## 2.4 Economic evaluation

Different types of economic evaluation can be used to assess the feasibility of a project. In an economic evaluation guideline document (Hromic et. al, 1995, p.2-1) the authors' state: *"Economic evaluation is the conceptual framework for the assessment of all gains (benefits) and losses (costs) on investment projects regardless of to whom they accrue within a country."* This report mentions three evaluation criteria on which the project viability can be assessed:

- Absolute advantage (Net present Value)
- Relative advantage (Benefit-cost ratio, or Internal rate of return)
- Minimum total cost (Present worth of cost)

For the present worth of cost method (PWOC), the project that has the least cost value, would be the superior project. The benefit-cost ratio (B/C) determines the ratio between the project costs and the benefits. The higher the ratio, the more advantageous the project will be. For the Net Present Value (NPV) method, the discounted costs of a project is subtracted from the discounted savings, when compared to an alternative. For the internal rate of return method (IRR) is the rate of return required for a zero NPV.

Reasoning behind the choice of a benefit-cost analysis for this study, is that it is a fairly simple calculation. It is a very effective way to compare different projects. The implications of only using a benefit-cost analysis, and none of the other methods mentioned above, is that only the benefits and costs used in the analysis are considered. Although the benefits and costs can be quite extensive, additional information is sometimes required. No additional economic guidelines are provided by the benefit-cost ratio. For example, the rate of return required for the project to have a net present value equal to zero.

A core part of the benefit-cost analysis is to be able to ascertain the benefits to be achieved when implementing a public transport service. In the BRT Planning guide (Wright & Hook, 2007) it is said that probably the best response to critics of public transport enterprises



would be the overall benefit that these projects would bring to a city and the quality of life of its inhabitants. In many cases, these benefits can be directly quantified to produce results in monetary terms.

An article published in the research results digest (Ang-Olson & Mahendra, 2011) mentions that when you wish to compare alternatives, you first need to standardize the categories of benefits and costs considered, including the methodology to be used to calculate them. Direct benefits to users of the transportation system include travel time savings, vehicle operating expenses, out-of-pocket expenses, and reduced crash costs. This article also writes that the most important aspect of a benefit-cost analysis for a BRT project would be the impact on vehicle delay and public transport ridership.

The article in the Research Results Digest, (Ang-Olson & Mahendra, 2011) also mentions that while the calculation of these impacts will differ for every project, it will be possible to evaluate hypothetical projects (such as traffic volume and public transport ridership) in order to illustrate how these parameters would influence the outcome.

Direct user benefits or dis-benefits are distinguished in the article between travel cost savings/increase and travel time changes.

- Travel cost savings/increase can be described as the change in travel costs. This refers to the vehicle operating and ownership costs and can be directly related to the distance travelled by each vehicle.
- Travel time changes would, for example, exist when a bus service operating in mixed traffic would be upgraded to a segregated BRT service. The reduction in travel time would then be the travel time of the new BRT service, compared to the original mixed traffic service.

A report presented to the U.S. Congressional Committee (US GAO, 2005) states that the largest benefit to be generally gained from transportation investments, would be the reduction in travel time resulting from the investment. Additional time becomes available for passengers to spend on other activities when travel time is reduced. The value of travel-time savings is an estimate of how much people would be willing to pay for reductions in travel time.

This report goes on to say that the purpose of a benefit-cost analysis is to determine the project alternative that would provide the greatest net benefit of the local area, region, or nation, by comparing the monetary value of benefits and costs of each alternative.

Guidelines, developed for the city of Cape Town (Hromic et. al., 1995) states that taxes and subsidies should be excluded from an economic analysis, since they cause transaction prices not to reflect opportunity costs based on the actual scarcity value of resources, but merely the transfer of funds between the public and private sector.

In a different guide book, developed by the Transit Cooperative Research Programme (TCRP, 2002, pp. 1-9) it is suggested to be wary of fringe benefits. It states: *“For example, transportation evaluation typically counts reductions in travel time as a benefit. But some evaluations go on to count as benefits the increase in property values and tax revenues that might primarily be the effects of such reductions in travel time, thereby double counting the benefit. In other words, to the extent that the benefits of travel time are capitalised into the increases in property values (as theory suggests they are, to a large extent), double counting occurs.”* Property value increases/decreases and tax revenue will not form part of the model in this study.

In the BRT planning guide (Wright & Hook, 2007) it mentions that factors such as time savings can be calculated in a fairly straight-forward manner. The monetisation of this time savings will enable a benefit-cost analysis to be conducted. Benefits to be focussed on in this study, will be the reduction in travel time, converted to a monetary value. These values can then be compared to the base case, which is the traditional bus service. Looking at the other end of the scale, the cost implications of the economic analysis will be done in two stages. Initially the operational cost will be solely used in the economic analysis to see how the operational expenditure alone would affect the alternatives. Then, capital expenditure will also be included to see what the effect would be once it is included.

## **2.5 Types of bus services**

When calculating the benefits and costs of a public transport service, the type of service obviously plays a significant role. A paper published in the Journal of Public Transportation

(Galicia et. al., 2009) developed three distinct phases for BRT implementation. All three of these phases have BRT like features, with the last phase representing a full BRT system, like Bogota's TransMilenio. The paper reviewed and summarised the infrastructure and operational features of BRT systems worldwide. Most of the BRT systems reviewed shared common but not all BRT features. The paper mentions that when a BRT is designed, the different features should be hand-picked that would comply with the demand requirements, budget availability, traffic and corridor characteristics. The three different phases of BRT implementation that were proposed in the paper were in increasing order of cost, engineering sophistication and implementation time frames. As the phasing increases, the response to ridership attraction and operating speed showed to be more positive.

A similar rationale was followed during the development of the model in this study. Instead of having three phases of a BRT line, three distinct options were chosen for comparison. As South Africa only recently started planning and implementing BRT schemes, the majority of bus based systems still consists of the more traditional high floor buses operating in mixed traffic. The first of these public transport service options would resemble such a traditional bus service, with one exception, low floor buses would be used due to the South African universal accessibility requirements (NDoT, 2007). It would therefore be very beneficial to use this scenario as a base case in order to see what the benefits would be, should one upgrade from this type of mixed traffic service to a more advanced bus based public transport service.

The second type of bus based public transport service to be modelled in this study, is the "London-style" bus lane service. This service would imitate the existing services currently being operated in London by means of a kerb-side dedicated bus lane. Bus lanes are very common, as many cities have similar types of bus lane infrastructure. Some of these cities include Los Angeles, New York, Paris, San Francisco, Seoul and Sydney (Agrawal et. al., 2013).

The BRT Planning Guide mentions that the bus network in London serves about 5.4 million passenger trips every day. This is even more than the underground train based system. London is also one of the few cities where bus based trips has risen over the last few years. London's success can be connected with the following broad goals of service quality (Wright & Hook, 2007):

- 1. Frequency ('turn up and go' service with waiting times of 12 minutes or less);
- 2. Reliability (enforce bus lanes);
- 3. Comprehensiveness; and
- 4. Simplicity. To accomplish these goals, London has implemented many BRT-type features within a conventional bus service.

In other words, if operated well enough, this type of service has great potential in not only keeping existing passenger numbers, but attracting new passengers. The final type of service to be modelled would be a full BRT service, running in an exclusive lane, demarcated by physical infrastructure. These options can be summarised as shown in table 2.2 below, based on a similar table layout as the above paper (Galicia et. al., 2009). Bus Rapid Transit (BRT), is defined as a flexible, rubber-tired form of rapid transit that combines stations, vehicles, services, running ways and information technologies into an integrated system with strong identity (Levinson et. al., 2003).

**Table 2.2: Alternative elements for each type of service**

<b>Guide way and lane infrastructure features</b>	<b>Type 1</b>	<b>Type 2</b>	<b>Type 3</b>
Mixed traffic flow	x		
Dedicated guide way		x	x
Kerb-lane	x	x	
Median lane with barrier			x
<b>Station infrastructure features</b>			
Enhanced shelters with seats and lighting		x	x
Air conditioning in shelters			x
Level platforms			x
Pedestrian crosswalk with signals		x	x
<b>ITS features</b>			
Traffic signal priority			x
Real-time information systems (stations)		x	x
Real time information system (on board)		x	x
<b>Fare collection</b>			
Cash	x		
Ticketing or smart card		x	
Pre-boarding ticketing			x

Items shown in table 2.2 are described in more detail in the sub-sections below.

### 2.5.1 Guide ways and lane infrastructure features

A type 1 service refers to the traditional bus service, operating in mixed traffic. Type 2 refers to the bus lane service, operating on the kerb side of the travelled way, with a type 3 service referring to a full BRT service.

Mixed traffic flow means that the bus would have to negotiate all the traffic related delays that normal vehicles would encounter, within the same traffic lanes. A dedicated guide way is where a public transport vehicle has an exclusive lane to travel in. It is not necessarily demarcated with physical infrastructure like kerbing. A kerb lane refers to a dedicated guide way that runs on the outside lane, (kerb side) of the roadway. These lanes are usually demarcated by means of road markings. The median lane with barrier refers to a dedicated BRT lane, physically separated from mixed traffic by means of kerbing. Figures 1.2, 1.3 and 1.4 shows the schematic layout of each of the three options' lane configurations:

### 2.5.2 Station infrastructure

Enhanced shelters signifies an upgraded shelter that is more than just a roofed structure. It would have comfortable seating, advertising space and appropriate lighting. Pedestrian cross walks refers to the priority that passengers enjoy when embarking / disembarking at the stations. Push button activated traffic signals would allow passengers to safely cross the road.

### 2.5.3 ITS features

Traffic signal priority refers to the priority that public transport vehicles would enjoy when approaching a signalised intersection. Active signal priority refers to when a certain traffic signal stage is activated once a bus is detected, by whatever means (Wright & Hook, 2007).

Real time information systems refers to the traveller information at bus stops. This information typically shows the awaiting passengers when the next bus will arrive. Real time information within the bus typically informs the passengers of various information, like the specific bus route he or she is on and where the next stop will be.

#### 2.5.4 Fare collection

The fare collection for all three services are proposed to be different. Traditional bus services, operating in mixed traffic is proposed to work with cash, payable on board the bus. Ticketing or smart card payment refers to a system where you still need to verify proof of payment to the dedicated person on the bus, either by means of swiping the smart card, or presenting the ticket. For the full BRT service, a pre-payment method is proposed whereby passengers will pay a fare to get into the station. When in the station, they can just board the bus without any additional payment delay.

#### 2.6 Vehicle selection

In the Bus Rapid Transit planning guide (Wright & Hook, 2007), it mentions that many vehicle sizes are available for bus based public transport operations. Reduced operation costs, especially driver labour costs are the main advantages of having larger vehicles in the fleet. However, the largest bus is not always the best option. This is why one should delve deeper into the major factors playing a role in operational costs.

In the Nelson Mandela Bay Integrated Public Transport System (IPTS) operational plan (KPMG, 2013) the following types of buses are shown to be currently available for public transport operations. Large variations of these types of buses are available, table 2.3 below shows the typical buses available in South Africa.

**Table 2.3: Types of buses available**

Type of bus	Capacity (passengers)
Bi-articulated bus	160
Articulated Bus	127
BRT Bus (low floor)	70
Regular Bus (high floor)	69
Midibus	35
Minibus	21

Source: (KPMG, 2013)

One needs to transport a certain passenger volume over a certain peak period, usually a peak hour. In order to be able to do this, either the number of buses to be used, or the size of the bus should be determined. Optimum vehicle size is calculated in the BRT planning guide (Wright & Hook, 2007) by means of the following calculation:

$$C_b = \frac{C_o}{[L_f * F * N_{sb}]}$$

Equation 2.1

Where:

$C_b$ = Vehicle capacity	pas/h
$C_o$ = Corridor capacity	pphpd
$L_f$ = Load factor	$L_f$
$F$ = Service frequency	veh/h
$N_{sb}$ = Number of stopping bays	$N_{sb}$

The BRT planning guide (Wright & Hook, 2007) shows an example for calculating the optimal vehicle size. If the potential vehicle frequency is one minute and the potential load factor is 0.85, and the demand analysis shows a corridor capacity of 15 000 passengers per hour per direction and two bays per stop are assumed, the calculation would read.

$$C_b = \frac{15\,000 \text{ pphpd}}{[0.85 * 60 \text{ veh/hr} * 2]}$$

This equals 147 passengers per bus, therefore a 160 capacity bi-articulated bus would be appropriate to use for this example.

## 2.7 Public transport line costs

Total cost for providing a public transport service consists of capital as well as operational costs (Vuchic, 2005). The following section describes these costs in more detail.

### 2.7.1 Operational Costs

An article published in the research results digest (Ang-Olson & Mahendra, 2011) defines operational costs as recurring costs in relation to the administration of public transport infrastructure and services, maintenance and operations of the service. It is important to keep these costs inflation-related and calculated to current values as it is typically historically calculated. The article further defines operational costs to be the costs associated with the cost of fuel, oil, maintenance, insurance and depreciation of the vehicle from wear.

Vehicle purchasing costs could be debated to be either placed with the capital costs or with the operational costs. In the BRT Planning Guide (Wright & Hook, 2007) it is mentioned that the purchasing of the vehicle itself usually is considered an operational expense, with the cost of the vehicle to be amortised through the useful life of the vehicle. This is typically 10 to 12 years. This model will therefore treat the purchase of vehicles as an operational expense, rather than a capital cost.

A general list of operating expenses for public transport is given by the BRT Planning Guide (Wright & Hook, 2007), as shown in table 2.4 below:

**Table 2.4: Operating cost categories for public transport**

Category	Elements
Re-payment of Capital	<ul style="list-style-type: none"> <li>• Vehicle depreciation</li> <li>• Cost of Capital</li> </ul>
Fixed Operating Costs	<ul style="list-style-type: none"> <li>• Driver / conductor salaries</li> <li>• Fare collection salaries</li> <li>• Information staff salaries</li> <li>• Security staff salaries</li> <li>• Mechanic salaries</li> <li>• Salaries of administrative personnel and supervisors</li> <li>• Other administrative expenses</li> <li>• Insurance</li> </ul>
Variable Operating Costs	<ul style="list-style-type: none"> <li>• Fuel</li> <li>• Spare parts</li> <li>• Lubricants and other items</li> <li>• Maintenance</li> </ul>

Source: (Wright & Hook, 2007)



### 2.7.2 Capital Costs

Typical costs encountered on a BRT project, which will be the high end option for this study, is summarised by the BRT Planning guide (Wright & Hook, 2007) to include bus ways, stations, transfer stations, terminals, depots, pedestrian infrastructure, bicycle and taxi integration facilities, control centre, and property acquisition.

In the research results digest (Ang-Olson & Mahendra, 2011, p. 5) capital costs are defined as to “include the one-time costs to the transit or funding agency of acquiring right-of-way, constructing the BRT corridor and stations, procuring vehicles, and installing supporting systems such as fare collection, security, and passenger information systems.”

In the BRT planning guide (Wright & Hook, 2007) capital costs are defined as the costs related to any infrastructure expenditure as well as any costs associated with land or property acquisition. An initial analysis of these costs can help focus the possible design work on financially realistic options. The guide goes on to say that cities should be encouraged to experiment with a range of possibilities with respect to both design options and the amount of financial resources likely to be available.

In a comparative assessment of various BRT systems world-wide (Henser & Golob, 2008), the variation of total infrastructure expenditure (US\$m/km) seems to be quite large. Figure 2.3 below shows these various infrastructure costs.

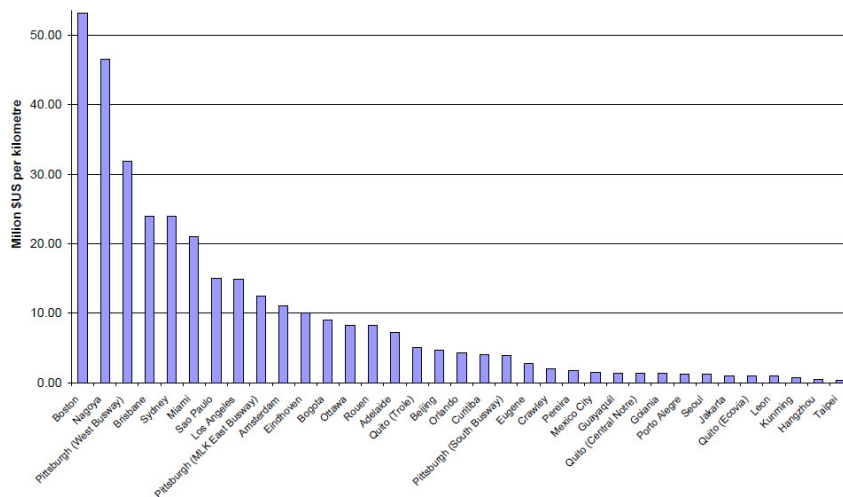


Figure 2.3: Total infrastructure cost per kilometre for BRT systems

Source: (Hensher & Golob, 2008)

## 2.8 Capacity

The Transit Capacity and Quality of Service Manual (TRB, 2003) explains that public transport capacity is focussed on how many people can be served rather than how many vehicles can be run in the given time. In other words, the focus is on person capacity, rather than vehicle capacity. The number of vehicles that can be served in a given time is however often an initial step in determining how many passengers can be served.

The model being developed for this study will use the different types of vehicle capacities to see what the effect on various passenger demands will be. The difference between public transport line capacity and vehicle capacity is described below:

### 2.8.1 Public transport line capacity

Public transport line capacity is defined (Vuchic, 1981) to be the maximum number of units that can be transported on a line past a fixed point during one hour under a given set of conditions.

The TCRP report (St. Jacques & Levinson, 1997) mentions reasons why the capacity information of a bus lane is important. These are:

1. the ability of a bus lane in a central area to accommodate the number of buses and passengers that want to use it;
2. the need to estimate the number of berths required to serve a specified bus or passenger flow along an arterial street or in a terminal, and
3. the ability to estimate how bus speeds will decline as bus volumes approach capacity.

Corridor capacity can be calculated with the following calculation (Vuchic, 1981):

$$\text{Capacity} = \frac{3600 * n * C_v}{h_{\min}} \quad \text{Equation 2.2}$$

Where:

C = Capacity sps/hour

$n$ = number of vehicles per transit unit	Veh/TU
$C_v$ = number of spaces per vehicle	sps/veh
$h_{\min}$ = minimum headway	s/TU

Equation 2.2 calculates what the capacity of the number of passenger spaces would be on a certain section of the public transport route. By dividing the number of spaces available on a bus, and how many units there are on the bus (two for articulated buses etc.) by the minimum headway (seconds per vehicle) you will get the maximum number of passenger spaces that can traverse this section in an hour.

### 2.8.2 Vehicle capacity

Optimal vehicle capacity is dependent on a few factors. (Vuchic, 1981) states that the optimal vehicle capacity depends mostly on the trade-off between frequency of service (higher with smaller vehicles) and cost of system operation (lower with larger vehicles). In order to develop a model which takes into consideration various alternatives, three types of buses, with different capacities, will be utilised in the model. Section 3.3.2 expands on these options.

The chosen vehicle size (capacity) will have a direct influence on the number of vehicles required to run the service (Wright & Hook, 2007). This guide also notes that when purchasing larger vehicles, less vehicles will be required. When purchasing smaller vehicles, more vehicles will be required, but the frequency will be higher than that of the larger vehicles, having shorter waiting periods for passengers. Buses will not always be completely full. This needs to be taken into consideration by means of a load factor.

Load factor, in essence, is an indication as to what extent the planner would anticipate the buses to be utilised by the public. It is described in the BRT guide (Wright & Hook, 2007) being a percentage of the total vehicle capacity being occupied. For example, if a vehicle has a maximum capacity of 160 passengers and an average use of 128 passengers, then the load factor is 80 percent. A load factor value of 0.8 will be adopted for the modelling process, meaning that the operations for this public transport line will be designed not to be overcrowded.

## 2.9 Public transport delay and operating speed

Various public transport speeds can be calculated for a service. It is obvious that average bus based public transport speed rarely, if ever, reach the posted speeds for the length of the line. In the TCRP report (St. Jacques & Levinson, 1997) it says bus speed along arterials are influenced by the number of stops along the line, how long the bus stops at each of these stops, interference with traffic and traffic signals. Different speeds are relevant to this study, these are shown in table 2.5 below (Vuchic, 2005):

**Table 2.5: Public transport speeds (vehicle-on-line speeds)**

Category	Speed designation
Vehicle-on-line speeds	Running
	Operating (commercial)
	Cycle

Source: (Vuchic, 2005)

Running speed can be defined as the average speed achieved of a bus from leaving the station or stop, to arriving at the next. Operating speed, or commercial speed, is the speed in which the travelling public is interested in. It can be described as the average speed at which a bus travels along a public transport route. This includes for all delays and terminal, stop times. Cycle speed on the other hand is the speed in which the operator would be interested in as it is used to calculate how many public transport vehicles are required to operate the service. The cycle speed can be described as the average speed of the bus when completing a round trip of the public transport route.

In the Transit Cooperative Research Program report (St. Jacques & Levinson, 1997, pp. 4), the importance of bus speed is underlined by saying: *“Bus travel times and speeds are important to the transit passenger, transit operator, traffic engineer, and transport planner. The transit passenger wants a quick and dependable trip. The transit operator (or service planner) measures and analyses bus speeds to set, monitor, and refine schedules, estimate vehicle requirements, and plan new routes and services. The traffic engineer uses bus speeds to assess the impact of traffic controls or bus priority treatments, and the transport planner uses speed to quantify congestion and provide inputs into the transit demand and modelling*

process.” It is therefore clear that the model to be developed in this study, should take into consideration the speed variations of the various public transport options.

Final operating speed of a public transport line is dependent on certain factors. One of the factors affecting the final operating speed of public transport services is the delay experienced on the line. A New Jersey DoT report (McKnight, et. al., 2003) states that traffic congestion, the number of bus stops, the number of passengers boarding and alighting and the number of signalised intersections influence bus speed and travel time. The report mentions that factors, other than that mentioned above, were found to have less of an impact on bus speed. These factors are explored in more detail below.

Operating speed is the average speed at which the public transport service completed the length of the public transport line, taking into account the various delays encountered during the negotiation of the line. One must however be mindful that the general public transport user is more concerned with how long his or her trip takes, rather than how fast the vehicle is travelling. It is therefore evident that this study should consider the impact of travel time when considering various options.

If one compares commercial speed, taken from different systems (Hensher & Golob, 2008), it would appear that the average commercial speed for the majority of these systems would be in the vicinity of 20km/h, as can be seen in figure 2.4 below.

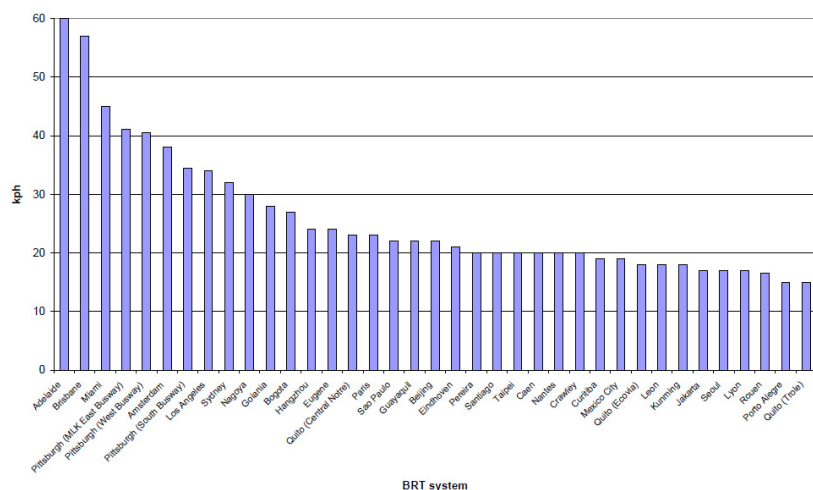


Figure 2.4: Average all day commercial speed

Source: (Hensher & Golob, 2008)

### 2.9.1 Traffic Congestion

A National Cooperative Highway Research Program report (Lomax et. al., 1997) describes that congestion to the traveller is immobility. When a bus is travelling in mixed traffic and it experiences traffic congestion, the travel time of the bus will inevitably be extended. In the TCRP Report 26 (St. Jacques & Levinson, 1997), they mention that the interaction of general traffic and buses is a complex phenomenon that is not clearly understood.

In another report, done by the New Jersey Department of Transport, (McKnight, et. al., 2003, pp. 1) their summary states: *“As traffic volumes or congestion increase, traffic speeds decrease, as established in traffic engineering formulas and curves that show speed as a function of the traffic volume to capacity ratio. This results in additional time being required to travel a fixed distance.”* The report goes on to say that as the time required to provide a service is extended due to traffic congestion, substantial operational and monetary penalties are incurred by the operating company. It is therefore evident that the model should include the influence of traffic congestion on public transport operations.

In a report done for the New Jersey Department of Transport (McKnight et. al., 2003), traffic related delay values were produced from original values derived by St. Jacques (St. Jacques & Levinson, 1997). Table 2.6 below shows the new values:

**Table 2.6: Estimated Traffic Delay (minutes per mile)**

Component	CBD	City	Suburbs
Traffic Signals	1.2	0.6	0.5
Right turns	0.8	-	-
<i>Traffic Congestion</i>	<i>1.0</i>	<i>0.3</i>	<i>0.2</i>
Total for mixed flow bus operation	3.0	0.9	0.7
Normal flow bus lane	2.0	0.6	0.5
Contra-flow of dual bus lanes	1.2	0.6	0.5

Source: (St. Jacques & Levinson, 1997) and (McKnight et. al., 2003)

These figures, shown in table 2.6 above, were derived from surveys done on various bus routes in New Jersey, by means of on-board surveys, car-following surveys and automatic

passenger counters. These counters automatically recorded the number of passengers embarking and disembarking, and the exact location thereof.

The “traffic signals” line in table 2.6 represents the delay experienced by the bus, due to traffic signals. The data shows a delay of 1.2 minutes per mile for a CBD service, which translates to 42 seconds per kilometre. Further research is however required to investigate the average delay experienced by traffic signals in a South African context. Although traffic congestion is also shown in table 2.6, a more sensitive analysis should be sought, taking into consideration the range of traffic congestion as well as previous work done on the influence of traffic congestion under South African conditions.

As traffic congestion will be one of the variables in the model, a different method should be followed to obtain values that are sensitive to the increase in traffic. Travel time functions for various saturation levels fortunately do exist. In a study done on the calibration, for South African conditions, of these curves, values were derived from the original Davidson curves (Van der Merwe et. al., ca. 1990). The curve shown in figure 2.5 below represents urban one-way streets.

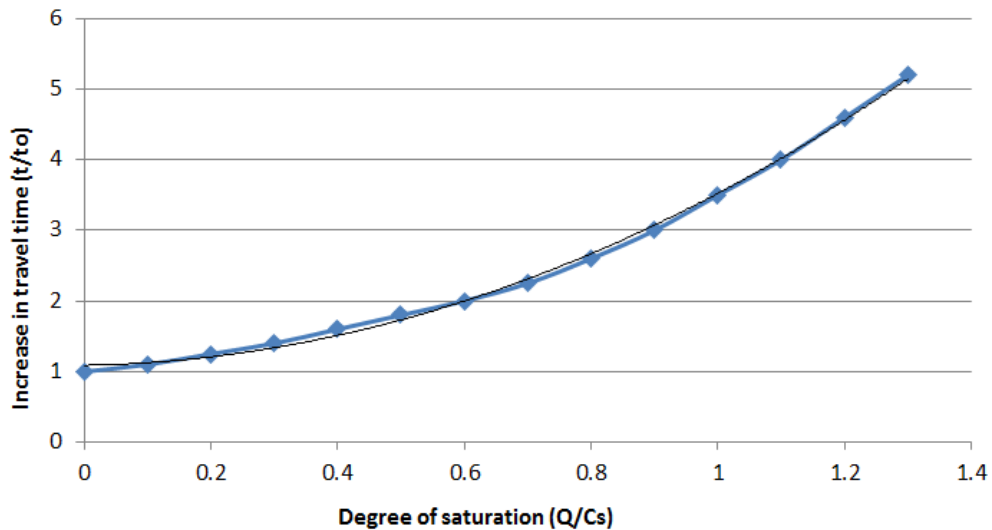


Figure 2.5: Calibrated Davidson curve for urban two-way streets

Source: (van der Merwe et. al., ca. 1990)

If one derives a formula from the graph above, it would read:

$$y = 2.294x^2 + 0.1431x + 1.0864$$

Equation 2.3

Where:

Y = the increase in travel time      t/to

X = the degree of saturation      Q/Cs

Then, the new travel time can be obtained by substituting the answer from the above equation with y for the following equation:

$$t = y * t_0$$

Equation 2.4

Where:

t = new travel time      min/km

Y = the increase in travel time      factor

t<sub>0</sub> = original travel rate      min/km

This equation will be used in the modelling exercise to obtain the increase in travel time for various degrees of saturation. Traffic congestion, however, will only have an influence on the bus service operated in mixed traffic. The model will therefore reflect this.

### 2.9.2 Traffic Signals

As with traffic congestion, traffic signals encountered on a public transport route results in delays experienced by the travelling public. Normally the effect that a traffic signal has on an intersection is measured by the green time ratio (g/C). This is the average green time divided by the cycle time. In a TCRP report (St. Jacques & Levinson, 1997), average delays due to the effect of traffic signals were developed. An average delay was calculated for a bus service operating in a CBD, on which this



model will be based. The traffic signal delay was calculated to be 1.2 minutes per mile. That translates to 0.7 minutes per kilometre, or 42 seconds per kilometre.

It is assumed in this model that traffic signal priority will initially only be given for the BRT type of service. The delay experienced due to traffic signals on the public transport route will therefore only influence the operational speed of the Type 1: traditional bus service, as well as Type 2: London style bus lane service.

In a report done for the proposed BRT service for the Nelson Mandela Bay Municipality (Botha et. al., 2012), a micro-simulation was done to simulate the functioning of a segregated BRT lane, enjoying a very high level of traffic signal priority. The rationale behind this can be seen in figure 2.6 below:

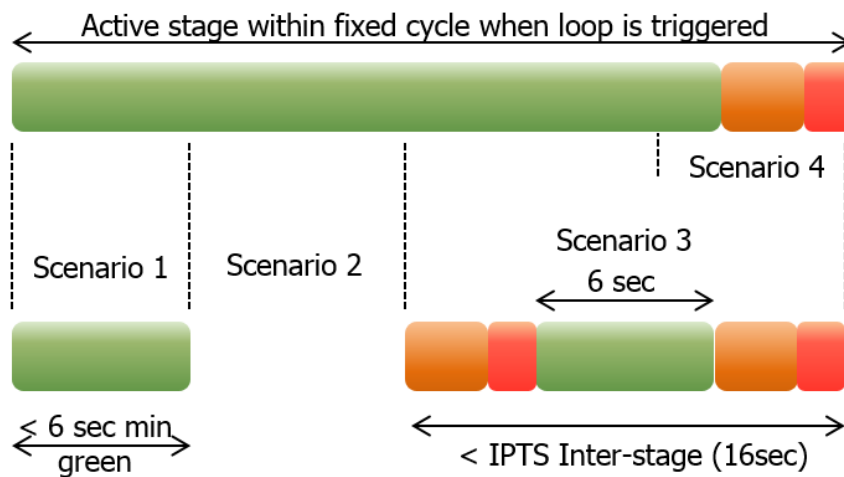


Figure 2.6: BRT Vehicle Actuated Scenarios

Source: (Botha et. al., 2012)

Seeing that stages vary in length, and that the time of arrival of a BRT bus cannot be pre-empted to the second, all possible scenarios should be programmed for within the cycle stage. The diagram above shows the four possible scenarios that can be encountered by a BRT bus. Vehicle detection loops, set a distance away from the signalised intersection will be triggered by the bus. This can be done during any active traffic signal stage. The following scenarios can be encountered when deciding how the bus should be allowed priority.

**Scenario one** refers to when a BRT bus triggers the VA loop during the green time of a certain stage where the minimum green of six seconds for that stage is not yet achieved. The action for this query is simply to continue with the existing stage green time until the minimum green is achieved, then implement the BRT inter-stage. This action however is still dependant on scenario three not to be activated.

If **Scenario three** is achieved, whereby the time left in the stage is less than 16 seconds, the BRT priority inter-stage cannot be implemented without impeding the offset settings for synchronisation of mixed traffic. When scenario three is activated the appropriate action is to continue with the current stage, until the time it was supposed to end. On completion of this stage the BRT priority inter-stage will then be implemented after the inter-green, on condition of the remaining scenarios above of course.

**Scenario four** refers to when the BRT priority inter-stage is implemented and completed, a certain length of time remains within the length of the original active stage. This time however, is shorter than the minimum allowable green to be allocated to the interrupted stage. In other words, the interrupted stage cannot be continued after the BRT inter-stage is completed. This surplus time is then allocated to the following stage.

The last achievable scenario, **scenario two**, would be when the minimum green time was allocated to the active stage, and enough green time is left for the BRT priority inter-stage. The additional green time is returned to the original stage upon completion of the BRT priority inter-stage, on condition that the minimum green time can be achieved, if this minimum green time cannot be achieved, scenario four will apply.

The only stage where a BRT inter-stage will wait to be implemented is where scenario three is activated, but the following stage is a short turning stage, usually equal to the minimum allowable green time. The BRT priority inter-stage will then be postponed until this short phase is completed. This delay is so minimal, as the

detection loops are typically placed at between 100 and 150m from the signalised intersection. By the time the bus arrives at the intersection, all or most of the “delay” time would have passed that the model will treat the delay at bus prioritised traffic signals as zero.

This programming logic ensures that the maximum green time is also allocated to the mixed traffic lanes, with only the exact green time that is required to be allocated to the BRT buses. If a BRT bus will traverse a certain intersection every 5 minutes, which is a very frequent headway, only six seconds green time is taken away from a 300 second cycle time.

### **2.9.3 Re-entry delay**

Re-entry delay refers to the delay experienced when a bus has completed the loading and off-loading of passengers in a lay-by bus stop and wishes to re-enter the mixed traffic lane in order to continue with its service. In the Transit Capacity and Quality of Service Manual (TRB, 2003), clearance time is described as when a bus stops in a lay-by, it is the time required for the bus to obtain a substantial gap in the traffic, large enough to be able to re-join the mixed traffic lane. This delay is dependent on the level of congestion, and will increase as traffic volumes increase.

A table showing average bus re-entry delays for various adjacent lane traffic volumes was developed by the TRB. These values were calculated using the Highway Capacity Manual (HCM) un-signalised intersection methodology. Assuming a 7 second critical gap and random vehicle arrivals. Table 2.7 below shows these values:

The values shown in table 2.7 below will therefore be used in the model to calculate the delay experienced by a bus wanting to re-enter the mixed traffic lane after loading or off-loading passengers at a bus lay-by. It should however be noted that this delay will only be applicable to the Type 1 service, (traditional bus service) operating in mixed traffic.

Table 2.7: Average bus re-entry delay

Adjacent Lane Mixed Traffic Volume (veh/h)	Average Re-entry Delay (seconds)
100	1
200	2
300	3
400	4
500	5
600	6
700	8
800	10
900	12
1000	15

Source: (TRB, 2003)

#### 2.9.4 Passenger service delay

Passenger service delay refers to the delay experienced when a bus is waiting for passengers to board or climb off the bus at the bus stop. The Transit Capacity and Quality of Service Manual (TRB, 2003), mentions that the door that has the highest volume of passengers passing through, is the deciding factor of how long it will take for passengers to be served. The proportion of alighting and boarding passengers through this door also plays a significant role in determining the delay experienced by passengers. Alighting passengers will just disembark the bus, but embarking passengers will have to negotiate the fare payment system.

Passenger service delay is very dependent on the fare payment method also. Fare payment is described to be a major influence on the time required to serve each boarding passenger (TRB, 2003). Some fare payment systems only allow for cash payment on the bus, whilst other systems requires payment before boarding the bus. Some systems also allow for a smart card, which proves to serve passengers quicker than cash payment, but slower than pre-boarding payment.

It is therefore very important to have an accurate estimation of how long it takes to service passengers for the various payment methods, as this will be a critical part of the model. Fortunately, the Transit Capacity and Quality of Service Manual (TRB, 2003) shows typical passenger service times for different payment methods. Three different methods are proposed in this manual for the estimation of dwelling time:

- Method 1: Field measurements
- Method 2: Default values
- Method 3: Calculation

When evaluating an existing public transport route, then field measurements from the existing bus route is the preferred method. Should you plan a new service, with no existing service currently operational on this route, default values can be used for boarding and alighting. This method should only be used when reliable possible passenger volumes are not available. Should these values be available, as for this study, the manual then suggests to use the calculation method. Table 2.8 below is an extract from this document, showing the values to be used for calculating the delay experienced due to boarding and alighting of passengers:

**Table 2.8: Passenger service times**

<b>Passenger Service Time (s/p)</b>		
<b>Situation</b>	<b>Observed Range</b>	<b>Suggested Default</b>
<b>BOARDING</b>		
Pre-payment	2.25 – 2.75	2.5
Single ticket or token	3.4 – 3.6	3.5
Exact change	3.6 – 4.3	4.0
Swipe or dip card	4.2	4.2
Smart card	3.0 – 3.7	3.5
<b>ALIGHTING</b>		
Front door	2.6 – 3.7	3.3
Rear door	1.4 – 2.7	2.1

Source: (TRB, 2003)

An additional 0.5 seconds per passenger is suggested to be added if standees are present, which we will assume will be. The manual also suggests that 0.5 seconds per passenger should be subtracted should a low floor bus be used. Seeing that the new South African regulations (South African Department of Transport, 2007) require low floor buses for universal access, this study will assume that only low floor buses will be used. Additional assumptions made for this study includes that passengers can only embark at the front door and disembark through the rear door. Boarding for all three types of buses is restricted to the front door only. Single buses therefore has one front door for boarding and one rear door for alighting. The articulated bus has two rear doors for alighting, whilst the bi-articulated bus has three rear doors for alighting.

This model will be built on the maximum passenger demand along any section of the public transport line (Vuchic, 2005) due to the fact that public transport line scheduling forms such an important part of the model. From this information alone, one cannot see how many passengers will board and how many will disembark the bus at each of the bus stops. As boarding and alighting has different delay times, it would be beneficial to estimate these figures.

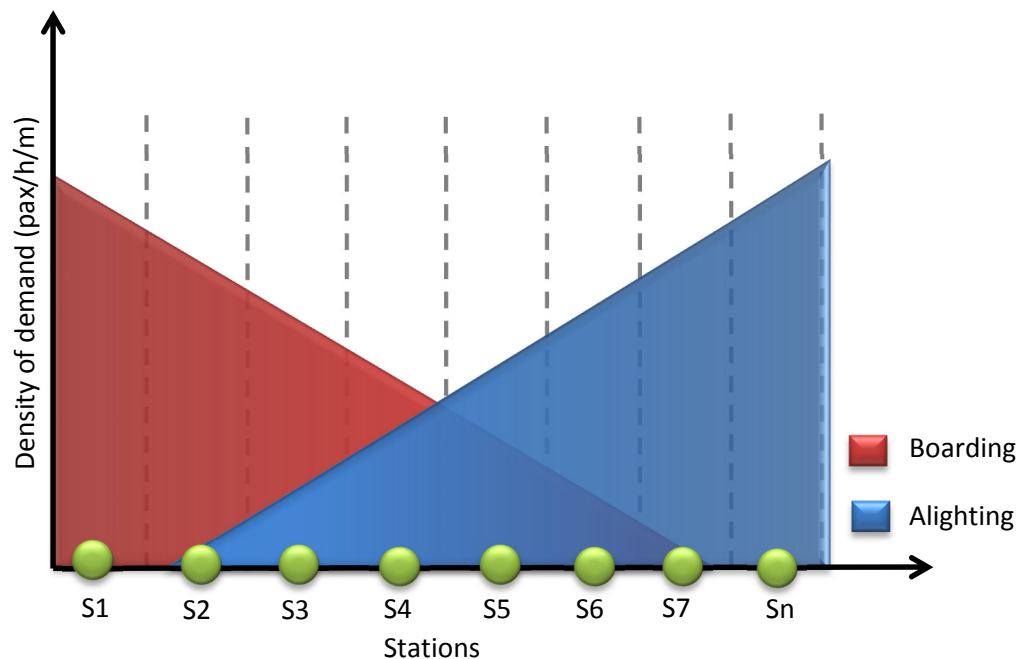


Figure 2.7: Demand distribution along the corridor

Source: (Lindau et. al., 2011)

In a paper done on the impact of design elements on the capacity and speed of BRT (Lindau et. al, 2011) a logical demand distribution was developed for a theoretical route. This is typical of a radial route with a strong origin and destination layout. Figure 2.7 above depicts the demand distribution throughout the length of this route.

### **2.10 Bus stop placing and layout**

In the service planning guidelines of the TCRP report (St. Jacques & Levinson, 1997), they write that the speed of a bus service is dependent on factors such as the number of bus stops along the route, how long the bus stops at each stop and if the bus can pass another bus, stationary at a bus stop.

The Transit Capacity and Quality of Service Manual (TRB, 2003) mentions that the less stops there are on a route, the greater the number of passengers will be that would like to embark/disembark at each stop. A balance should therefore be reached between having too few stops, having long passenger waiting times and long walking distances, and too many stops which will reduce the travel time due to the excess acceleration and deceleration plus the possibility of additional waiting time to get back into mixed traffic.

Looking at bus stop spacing, (Wright & Hook, 2007) writes that distance of approximately 500m between stations tend to be the current standard for BRT services. The Tshwane BRT has an average station spacing of between 800 and 1 000 m (Tshwane BRT, 2009) with the MyCity having a station spacing of approximately 800m (City of Cape Town, 2012).

In a comparison of various BRT systems around the world (Hensher & Golob, 2008) the average distance between bus stops seems to be in the region of 500 to 600m. Figure 2.8 below shows the different spacing of bus stops for various systems.

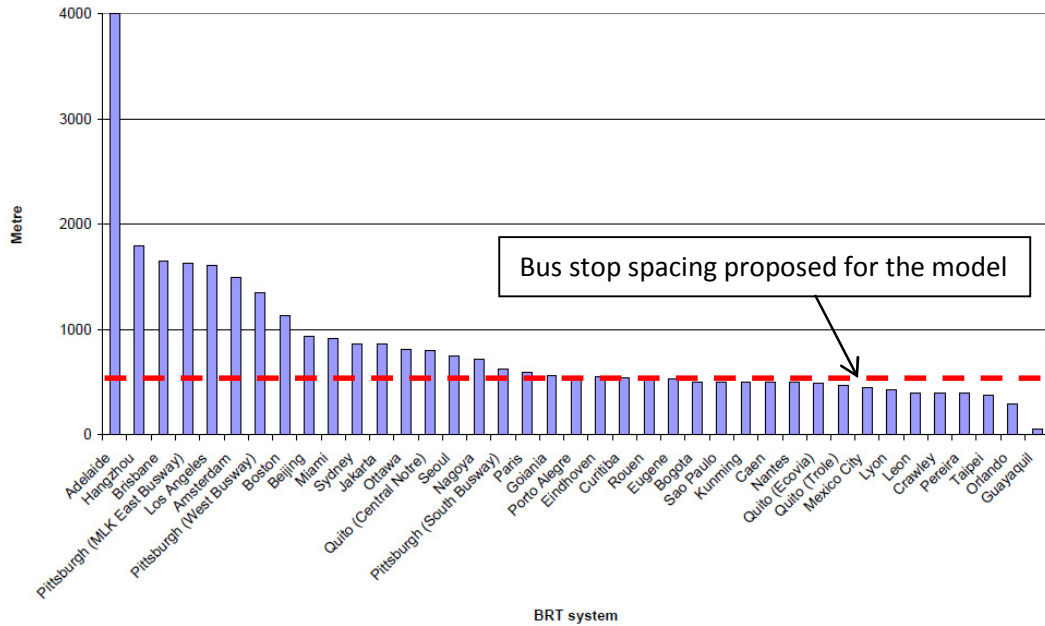


Figure 2.8: Average distance between stations

Source: (Hensher & Golob, 2008)

Looking at figure 2.8 above, a distance of 500 m between stops makes sense and will therefore be used for modelling purposes.

### 2.11 Public transport passenger demand

Passenger demand is an essential part of financial planning. One cannot estimate what the operational requirements would be without proper information on the number of passengers that would use the service. The public transport line then runs the risk of being over or under designed, either costing the authority unnecessary capital, or costing the travelling public in extended travel times.

The BRT planning guide (Wright & Hook, 2007) states that customer needs should be regarded as the most important aspect of designing a system. Demand estimates therefore forms the critical part for designing the system, the planning of operations and assessing the economic viability of the whole system. Understanding how the extent of passenger demand along each corridor will enable planners to tailor the system design according to the needs of the travelling public. Peak ridership tends to vary quite considerably between different



systems. Figure 2.9 below (Hensher & Golob, 2008) supports this as the range varies from less than 1 000 to 45 000 passengers per hour per direction.

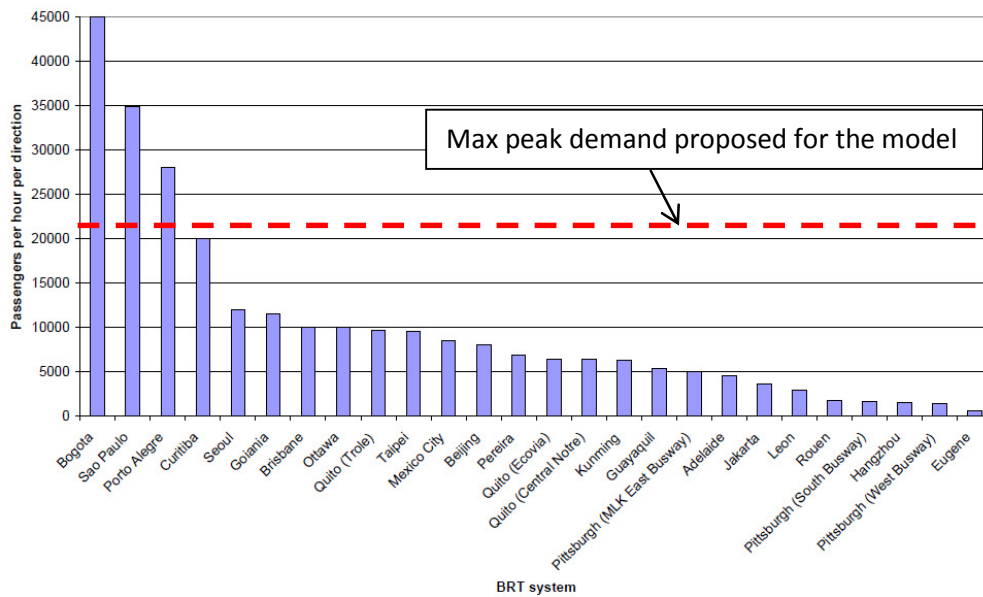


Figure 2.9: Peak ridership

Source: (Hensher & Golob, 2008)

An incremental increase of the passenger demand on the model, to be developed for this study, will be done for each of the various options. A distance of 500m separates bus stops in this model, thus for a line 10km long, a total of 20 stops will be required. The model will try and represent as many existing systems as possible, therefore a maximum peak hour demand of just over 20 000 peak passengers per hour per direction will be modelled.

Should the quality of the public transport service increase, the demand could inevitably increase. Should the fare of the specific route increase, the demand could become lower. The elasticity possibilities for a public transport service were not considered in this study, nor were any fares.

### 2.12 Public transport line scheduling

The method for public transport line scheduling, used for this study, is based on the method developed by Vuchic (Vuchic, 1981) and (Vuchic, 2005). The following public transport

operations and scheduling definitions and symbols were sourced from the two sources above:

**Headway (h)**

Headway is the duration of time between two public transport vehicles. Public transport passengers are interested with having short waiting times, hence short headways. It is however cheaper to operate a smaller number of large vehicles than a greater number of small vehicles.

The figure below shows a comparison of all the average headways for various systems around the world. Headways less than one minute seem to be very rare. The minimum peak headway proposed for the model will therefore be one minute, as shown in figure 2.10 below.

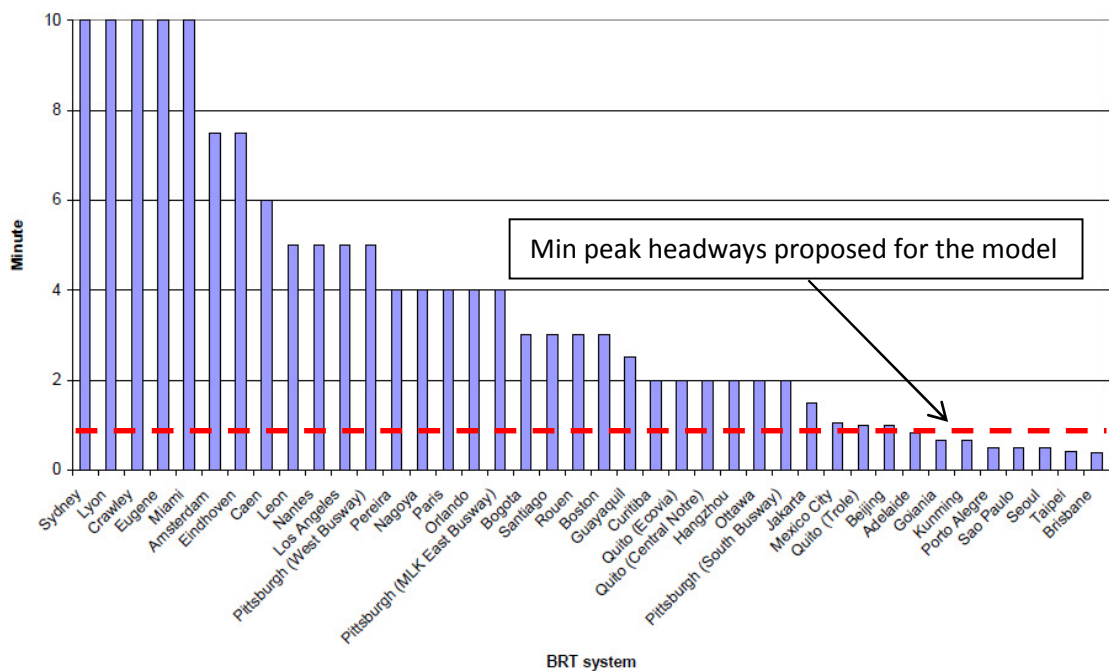


Figure 2.10: Average peak headways

Source: (Hensher & Golob, 2008)

**Policy headway (h<sub>p</sub>)**

In order to ensure that the end user of the public transport system does not wait too long for a public transport unit to pass, due to operational cost limitations, a policy headway

should be implemented for the public transport system. This will ensure that the amount of time that passengers would wait for a public transport unit to pass would have a set maximum. Due to the different demand patterns for peak and off-peak movements, two different policy headways are usually given.

South African policy headways for peak hours are currently envisaged to be around 10 minutes with off-peak headways being 10 to 30 minutes (South African department of Transport, 2007). The minimum headways used during the modelling of the various scenarios were 15 minutes for peak, and 30 minutes for off-peak periods.

### **Frequency of service (f)**

Frequency of service is the number of public transport trips that passes a specific point on the public transport line in a single hour (or any given time period). Short headways therefore means a high frequency and longer headways means lower frequencies.

The BRT Planning Guide (Wright & Hook, 2007) reports that peak frequencies of 60 seconds to 90 seconds are quite common on BRT systems. However, general average frequency per stopping bay tends to be around one minute.

### **Vehicle Capacity ( $C_v$ )**

Vehicle capacity is the number of passenger spaces that is available on the vehicle. It is calculated by adding the number of seats plus the standing and wheelchair capacity.

### **Maximum line capacity ( $C_{MAX}$ )**

Public transport capacity is measured in passengers and not vehicles. The maximum capacity of a line is therefore the maximum number of passengers per hour a line can carry with minimum operationally feasible headways.

### **Operating time ( $T_o$ )**

The scheduled time interval between departure of a vehicle from one terminal (end-of-line stop or station) and its arrival at another terminal on a route is called the operating time. Operating time  $T_o$  is usually expressed in minutes.

**Operating speed ( $V_o$ )**

Operating speed is the average speed of a public transport vehicle, including stopping time at stations or stops and expected delays due to traffic. It is computed as the one-way line length ( $L$ ) in miles divided by the operating time in minutes. For the purpose of the model, kilometres will be used instead of miles.

**Terminal Time ( $t_t$ )**

Terminal time is the time a public transport vehicle spends at a terminal or end-of-line stop. This time excludes the time required for boarding and alighting passengers. The purpose of terminal time is to allow time for the vehicle to turn or change of driver's cabin, resting of the driver and adjustment allowance in the schedule. This is to be able to maintain uniform headway, or to recover delays incurred in travel.

**Cycle Time ( $T$ )**

Cycle time is the total time taken for a public transport vehicle to complete a total round trip. i.e., the time interval between two consecutive times the same vehicle passes a fixed point travelling in the same direction.

**Commercial Speed ( $V_c$ )**

Commercial speed is the average speed of a public transport vehicle when completing a round trip. Commercial speed is the most important type of speed for the operator since it directly determines (along with headway) the required fleet size and cost of operation. This information will form a fundamental part of the model.

**Fleet Size ( $N_f$ )**

Fleet size is the total number of vehicles which a public transport operator owns. The fleet size consists of the vehicles required for regular peak hour service on all lines ( $N$ ), vehicles in reserve ( $N_r$ ), plus vehicles which are in maintenance and repair ( $N_m$ ).

**Load Factor ( $\alpha$ )**

The number of passengers in a vehicle compared to the public transport vehicle capacity is referred to the load factor. A higher value of  $\alpha$  means that a vehicle is crowded and that it is

more likely that some vehicles will not have sufficient capacity to collect all waiting passengers.

### Transit unit (TU)

A transit unit is a single unit, and could be made up of a number of vehicles, e.g. an articulated bus consists of one TU, but two vehicles (**n**).

### Maximum volume of passengers ( $P_{max}$ )

The maximum volume of passengers on any section along the line is measured in passengers per hour.

Using the descriptions above, the following public transport line scheduling equations are shown (Vuchic, 2005):

Based on the passenger volume, frequency and headways are calculated:

$$h = \frac{60}{f}$$

Equation 2.5

Where:

h = headway (minutes)

f = frequency (TU/hour)

Equation 2.5 is fairly straight forward. One divides the frequency by the available 60 minutes in one hour to get the number of vehicles that will pass a certain point in one hour. In order to obtain the frequency, one should refer to equation 2.6 below.

$$f = \frac{P_{max}}{\alpha * n * C_v}$$

Equation 2.6

Where:

f = frequency (transit units/hour)

n = number of vehicles per transit unit (veh/transit unit)

$\alpha$  = desired maximum utilization coefficient (passengers /space)  
 $C_v$  = vehicle capacity (spaces/transit unit)  
 $P_{\max}$  = maximum volume of passengers along any section along the line (persons/hour)

In order to obtain the frequency, which will in turn allow you to calculate the headway, you need to know what the maximum volume of passengers along any section of the public transport line is. The  $P_{\max}$  value is then divided by the proportional vehicle capacity. In other words, how many seats you have on a vehicle, is it a single articulated or bi-articulated bus, and how full the bus will be, e.g. 90%.

The headway should be rounded down and devisable into 60, for ease of scheduling as well as to ensure that the schedule repeats itself over the next hour. The smallest number between  $h$  and  $h_p$  is adopted. A first estimate of cycle time  $T'$  is computed as:

$$T' = 2T_o + t_{t1} + t_{t2}$$

Equation 2.7

Where:

$T'$  = first estimated cycle time (minutes)  
 $T_o$  = operating time (minutes)  
 $t_{t1}, t_{t2}$  = terminal times (minutes)

The number of transit units (TU's) operating for the computed schedule is computed as:

$$N = \left[ \frac{T}{h} \right]$$

Equation 2.8

Where:

$N$  = number of transit units (TU)  
 $T'$  = first estimated cycle time (minutes)

h = headway (minutes)

Note that N should be rounded up to the next integer value. Final cycle time is then calculated as:

$$T = N * h \quad \text{Equation 2.9}$$

Where:

T = cycle time (minutes)

N = number of transit units (TU)

h = headway (minutes)

Cycle speed is then calculated as follows:

$$V_c = \frac{120 * L}{T} \quad \text{Equation 2.10}$$

Where:

V<sub>c</sub> = cycle speed (km/hour)

L = length of the public transport line (km)

T = cycle time (minutes)

These calculations (Vuchic, 2005) will form the backbone of the public transport scheduling model. The model will replicate a realistic peak and off-peak service in order to calculate the required operational costs.

### 3. EXPERIMENTAL SETUP

#### 3.1 Introduction

A cost model was developed in this study to compare different types of buses, operating in different types of services, with different levels of infrastructure expenditure. In order to be able to obtain data with a reasonable level of accuracy, an actual scheduled service should be developed for each scenario. These scheduled services should be run in peak as well as off-peak times, to be able to obtain a realistic operational cost for the service. This operational cost, including the capital cost forms part of the cost section of the benefit-cost analysis. The benefits to be gained forms part of the monetised travel time savings, when comparing a base case traditional bus service, operating in mixed traffic, with the remaining two options. Travel time is influenced by traffic signals, traffic congestion, passenger service delay, terminal time etc. The following factors should therefore form part of the core model:

- Assumptions
- Peak and off-peak traffic flow
- Peak and off peak passenger demand
- Modelling variables
- Delay
- Line scheduling
- Travel time savings
- Monetised benefits
- Operational costs
- Capital costs
- Economic evaluations
- Sensitivity analysis

For each type of public transport service, with different levels of infrastructure provision, the variables used in the model include: the type of bus, current level of congestion and public transport demand. An incremental approach was followed where all the variables remained as they are, but the passenger demand was incrementally increased, with the output being recorded for each increment. This process was followed until all the variable combinations were run in the model.



A sensitivity analysis was also undertaken in order to see how sensitive this model was to changes in the variables.

### 3.2 Measures of effectiveness

This study investigated various alternative bus configurations as well as infrastructure implementation costs. The benefits used in the model comprised of monetised time savings, using the traditional bus service as a base case. Costs for the B/C ratio consists of the following:

- Model 1: Operational cost recovery, with only the operational costs used as a cost for the B/C ratio. In this study it is referred to the B/C<sub>1</sub> ratio.
- Model 2: Full cost recovery, a combination of the operational and capital cost. In this study it is referred to the B/C<sub>2</sub> ratio.

A benefit/cost ratio was therefore used in this study in order for these alternatives to be evaluated and compared.

### 3.3 Modelling

#### 3.3.1 Assumptions

During the development of the model, the model evolved from a basic service to a fully scheduled peak and off-peak service. Variables included implementation costs, operational costs and passenger demand. As this is a theoretical model, various assumptions were made during the development of the model. For example, in order to be able to compare each model run with the other, one has to standardise on certain assumptions. Bus stop spacing for example could influence the capital costs. It was therefore decided to obtain and standardise these assumptions in order to have an accurate and workable model to derive the relevant output from. Table 3.1 below summarises these assumptions:

The diesel price is based on values obtained from the Automobile Association of South Africa in May 2013 (AA, 2013). Basic salaries, as shown in table 3.1 below was discussed with local human resource agents, whilst renting prices were discussed with local real estate agents.

The price for a mid-range personal computer was obtained from local information technology personnel. For office space, the increase in office space required for the BRT service would be for the ITS control centre capabilities as well as the normal bus operating personnel and activities.

**Table 3.1: List of general assumptions used in the model development**

General Assumptions	Value	Unit
Locality of the model	CBD	N/A
Length of public transport line	10	km
Current diesel price per litre	11.46	Rand
Motorised running speed (posted speed)	60	km/h
Terminal time to be spent at start terminal A	5	minutes
Terminal time to be spent at end terminal B	5	minutes
Desired maximum utilization coefficient	0.8	prs/space
Average number of bus stops per kilometre	2	No.
Basic salary of a bus driver	8 000	Rand/month
Basic salary of maintenance personnel	8 000	Rand/month
Basic salary of a security guard	8 000	Rand/month
Basic salary of operating personnel	8 000	Rand/month
Basic salary of management	18 000	Rand/month
Basic salary of admin personnel	12 000	Rand/month
Price for renting office space	120	Rand/m <sup>2</sup> /month
Price for renting depot space	40	Rand/m <sup>2</sup> /month
Price for a computer	10 000	Rand
Office space required for a traditional bus service	200	m <sup>2</sup>
Office space required for a London style bus service	350	m <sup>2</sup>
Office space required for a BRT service	600	m <sup>2</sup>
Inflation	6	%

During the economic analysis, certain population specific assumptions were made. Table 3.2 below lists these assumptions.

**Table 3.2: List of population assumptions used in the model development**

Population Assumptions	Value	Unit
Proportion of low income workers (<R4k/month)	45	%
Proportion of medium income workers (R4k-20k/month)	50	%
Proportion of high income workers (>R20k/month)	5	%
Value of time of working traveller (low income)	9.5	Rand/hour
Value of time of working traveller (medium income)	44.2	Rand/hour
Value of time of working traveller (high income)	118.4	Rand/hour
Value of time of non-working traveller (low income)	2.14	Rand/hour
Value of time of non-working traveller (medium income)	10.08	Rand/hour
Value of time of non-working traveller (high income)	27.0	Rand/hour
Peak passengers: Proportion of working passengers	97	%
Peak passengers: Proportion of non-working passengers	3	%
Off-peak passengers: Proportion of working passengers	70	%
Off-peak passengers: Proportion of non-working passengers	30	%

### 3.3.2 Vehicle selection

The literature study expanded on the types of buses that are available for public transport projects. Currently, the articulated bus has become a standard for BRT operations worldwide (Wright & Hook, 2007). As the base case of this study will be a traditional service, operated in mixed traffic, it would make sense to model single buses also, as they are mostly used for these type of services. Another possible bus to use is the bi-articulated bus, currently being operated on only a few BRT systems, of which the Curitiba system is one of them. These three types of buses, a single bus, articulated bus and a bi-articulated bus would therefore represent the majority of trunk systems currently being operated.

The vehicles that will therefore be used for modelling purposes of this study will include:

- Bi-articulated bus
- Articulated bus
- BRT single bus (low floor)



Figure 3.1: Types of buses to be used

Source: (Wright & Hook, 2007)

### 3.3.3 Relationship between peak and off-peak

In order to calculate reasonable operational costs for the economic analysis, a scheduled service should be modelled to reflect a real scheduled service as closely as possible. To do this, peak and off-peak services should be evaluated separately as their operational requirements differ due to demand differences as well as traffic conditions. The problem posed now is that peak passenger demand could vary from zero to 45 000 (Bogota BRT). Traffic saturation levels could also vary between zero to just over one. To reduce the number of evaluations to a reasonable number, a number of composite scenarios, deemed typical of the range of operational and demand conditions in actual services, are defined.

#### Passenger demand

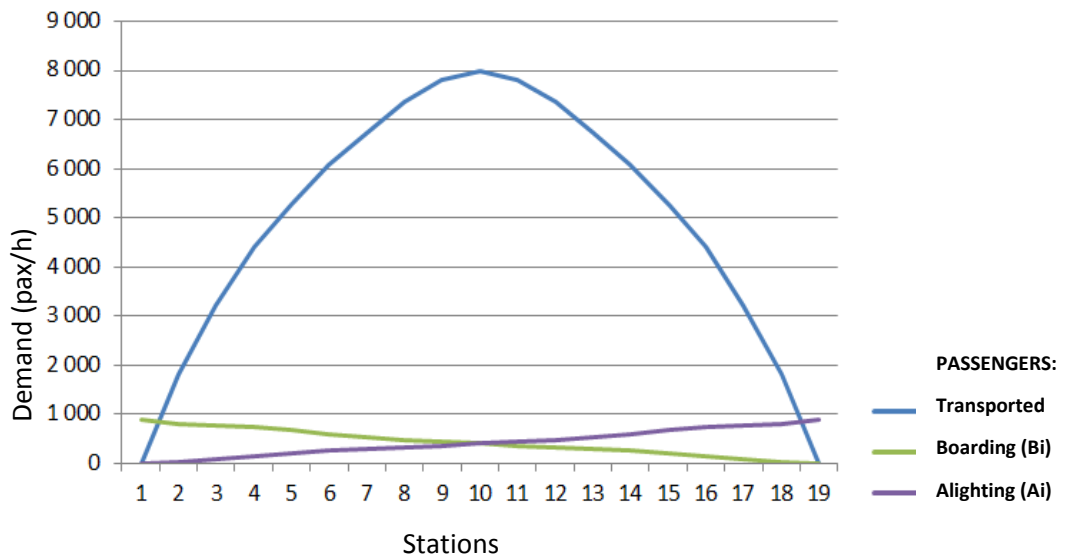
Nicolai & Weiss, (2008) suggested that the peak passenger demand comprise of approximately 14% of the daily passenger demand on the public transport route. In order for the simplification of the modelling process to be achieved, the model will be developed to take into account that the peak hour passenger demand will consist of 14% of the daily passenger demand. This rational will be used for all the alternative types of services modelled.

Table 3.3 below shows this distribution for a 14 hour day of operation, should the peak hour passenger demand be 5 000 passengers per hour.

**Table 3.3: Passenger demand assumptions**

Period	Time from	Time to	Duration (Hours)	% of pax	pax/hour
Off-peak	06:00	07:00	01:00	6%	2 143
AM Peak	07:00	08:00	01:00	14%	5000
Off-peak	08:00	16:30	08:30	51%	2 143
PM Peak	16:30	17:30	01:00	14%	5000
Off-peak	17:30	20:00	02:30	15%	2 143

In this theoretical 10 km long model, with bus stop spacing at 500m, a passenger demand of 8 000 would produce a loading diagram as shown in figure 3.2 below. From this information, one can estimate what the distribution of boarding and alighting would be for a specific demand. Based on the figure above, for a 10 km length of public transport line, with bus stop spacing 500m apart, the following loading graph could be derived, as shown in figure 3.2 below:



**Figure 3.2: Example loading diagram (for a passenger demand of 8 000)**

Source (Lindau et al, 2011)

Only the passenger demand in the above diagram would vary during the running of the model as the length of line, as well as the number of stations, would stay constant. The extent (turning point) of this loading diagram is related to the maximum passenger demand along any section of the public transport line ( $P_{max}$ ). Figure 3.3

below shows the incremental difference between 1 000 passengers per hour to 10 000.

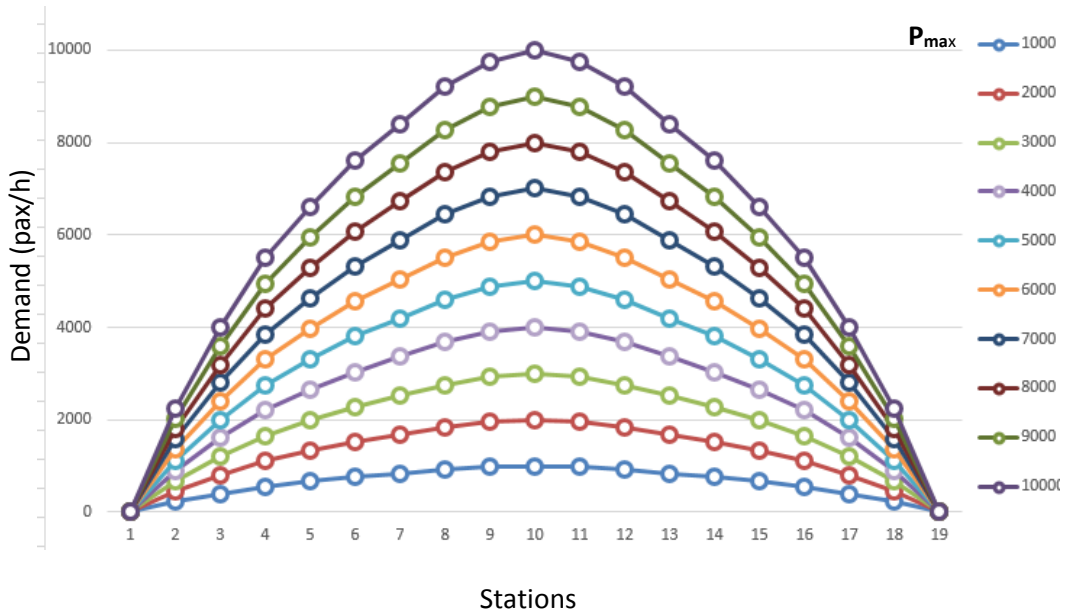


Figure 3.3: Loading diagrams for a passenger demands ranging from 1 000 to 10 000 passengers per hour

Delay experienced by the three types of buses would be distributed according to the above diagram. A single bus has space for 70 passengers, with an articulated bus 127 and a bi-articulated bus 160 spaces. Table 3.4 below shows the boarding and alighting figures used in the model for the three bus types:

Table 3.4: Bus passenger distribution (boarding,  $B_i$  and alighting,  $A_i$ ) for different bus types

Station	( $B_i$ ) Bi-articulated Boarding	( $A_i$ ) Bi-articulated Alighting	( $B_i$ ) Articulated Boarding	( $A_i$ ) Articulated Alighting	( $B_i$ ) Single Boarding	( $A_i$ ) Single Alighting
1	18	0	14	0	8	0
2	16	1	13	0	7	0
3	15	2	12	1	7	1
4	15	3	12	2	6	1
5	14	4	11	3	6	2
6	12	5	10	4	5	2
7	11	6	9	5	5	3
8	10	6	8	5	4	3
9	9	7	7	6	4	3
10	8	8	6	6	4	4

11	7	9	6	7	3	4
12	6	10	5	8	3	4
13	6	11	5	9	3	5
14	5	12	4	10	2	5
15	4	14	3	11	2	6
16	3	15	2	12	1	6
17	2	15	1	12	1	7
18	1	16	0	13	0	7
19	0	18	0	14	0	8
<b>Total</b>	<b>160</b>	<b>160</b>	<b>127</b>	<b>127</b>	<b>70</b>	<b>70</b>

The data shown in figures 3.2 and 3.3 will not allow you to schedule the service for modelling purposes. One requires the boarding ( $B_i$ ) as well as the alighting ( $A_i$ ) of each individual bus. From table 3.4 above, for a 10km public transport route with 500m bus stop spacing, the following linear trend lines can be derived for each of the three bus types' boarding ( $B_i$ ) and alighting ( $A_i$ ). These linear trend lines can now be used to determine, for a variable passenger demand, how many passengers will board and alight the vehicle at each stop. From these values, the passenger service delay can be calculated, as seen in table 2.8.

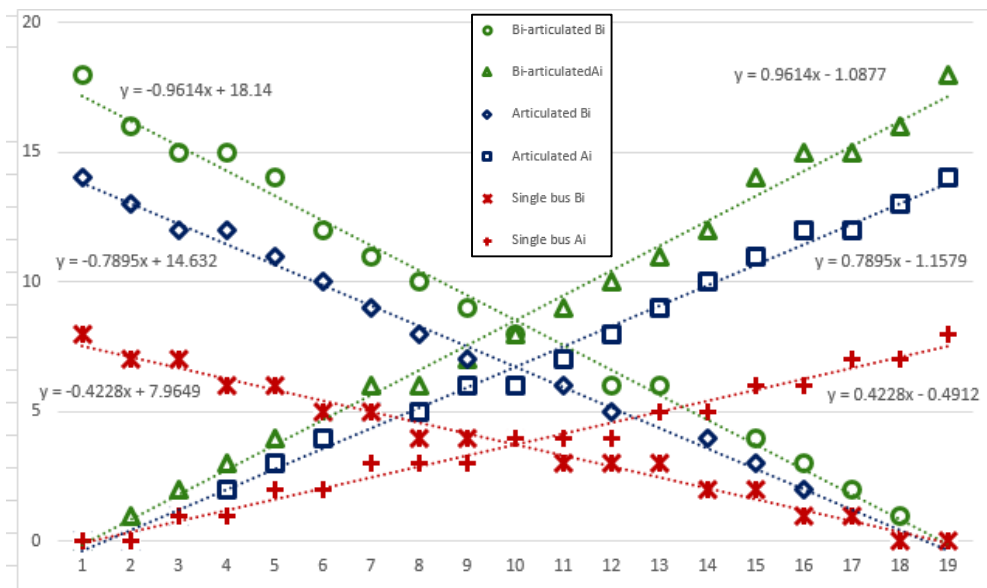


Figure 3.4: Linear alighting and boarding trend lines for three bus types

Values obtained from Table 2.8: Passenger service times (p.38), are then multiplied with the values in table 3.4: Bus passenger distribution. Passenger service delay, for example at stop n, would then be calculated as follows:

Passenger Service delay at stop n:

$$D_{PSn} = \text{MAX} (D_{PBn}, D_{PAN}) \quad \text{Equation 3.1}$$

Where:

$D_{PSn}$ = delay at stop n	seconds
$D_{PBn}$ = delay due to passengers boarding at stop nr	seconds
$D_{PAN}$ = delay due to passengers alighting at stop n	seconds

The maximum value between the alighting and boarding delay is used. If for example the boarding delay at stop n would be 40 seconds, and the alighting delay 10 seconds, it would be apparent to use the 40 seconds, as this would be the prevalent delay at the stop.

### Traffic

It is common practice in traffic engineering to assume that the sum of the morning and afternoon peak hour volumes consists of approximately 30% of the daily traffic on the same section of road (Jordaan & van As, 1988). This was reflected in the development of the model with a traffic distribution as shown in table 3.5 below. The table represents a scenario where the AM peak traffic is 1 000 vehicles per hour for the mixed traffic lane adjacent to the bus lay-by stop. It should be noted that the influence of mixed traffic congestion will only influence the base case traditional bus service as this is the only service operating in mixed traffic.

**Table 3.5: Peak hour traffic assumptions**

Period	Time from	Time to	Duration (Hours)	% of veh/h	veh/hour
Off-peak	06:00	07:00	01:00	6%	400
AM Peak	07:00	08:00	01:00	15%	1000
Off-peak	08:00	16:30	08:30	50%	392
PM Peak	16:30	17:30	01:00	15%	1000
Off-peak	17:30	20:00	02:30	14%	373



### 3.3.4 Modelling process

The image below clearly shows the process of the modelling exercise:



Figure 3.5: Modelling process

In order for reputable data to be obtained for the calculation and comparison of the final benefit-cost ratios, a model should be created in which a realistic scheduled service is modelled. This model should include peak and off-peak operations, delay due to traffic signals, passengers boarding and alighting and traffic congestion, changed into travel time (savings). The model developed in this study is excel based. This model compares different types of buses, operating in different types of services with different levels of infrastructure expenditure. The steps followed during the modelling process are described in more detail below:

### **Step1: Model Assumptions**

As an initial step, to start the model off, one should make a decision on what parameters will be assumed and which will be calculated. The experimental setup chapter of this study summarises the assumptions made during the development of the model.

### **Step 2: Public Transport Vehicle Running Speed**

Firstly, one should have an idea of what the general public transport running speed on the specific public transport line segment is, without delays and stopping. Running time for a public transport vehicle, the bus in this case, depends on two components (TRB, 2010):

- What is the time taken to run a segment without being delayed by traffic congestion, traffic signals and public transport stops?
- What is the delay due to the above mentioned elements?

The procedure for calculating the first component, the public transport running speed, is described in the Highway Capacity Manual 2010 (TRB, 2010). According to the HCM 2010, determining the public transport vehicle running time refers to the time required to travel the segment without experiencing any delays or stopping. The following equation is sourced from the HCM 2010 for calculating the public transport vehicle running speed:

$$S_{Rt} = \min \left[ S_R, \frac{61}{1 + e^{-1.00 + (1.185 N_{ts} / L)}} \right]$$

Equation 3.2

Where:

$S_{Rt}$ = public transport vehicle running speed	mi/h
$L$ = segment length	ft
$N_{ts}$ = number of public transport stops on the segment	stops
$S_R$ = motorised vehicle running speed (3600L)*(5280t <sub>R</sub> )	mi/h
$t_R$ = segment running time	seconds

Equation 3.2 above is derived from tables developed by the TCRP (St. Jacques & Levinson, 2007).  $S_R$  takes into account motorised vehicle running speed, whilst the right hand side of the equation takes into account acceleration and deceleration for bus stops, but not the delay at the stop itself. The lesser value of the two is chosen as this will be used to calculate the speed after all delays are incurred.

When converted to km/h, equation 3.2 above provides a running speed for the public transport line segment. This speed however is not subject to any stops or delays, as it is merely a starting point for the model from where the delaying factors will be calculated.

### Step 3: Variables

Three variables will be used in the modelling process to represent various conditions and treatments. These variables include:

- Type of bus
- Current level of traffic
- Public Transport demand

These variables all need to be varied individually for all eight steps. The following increments will be used for each of these variables, shown in table 3.6 below:

Table 3.6: Incremental increase for variables

Variable	Incremental increase proposed
Type of bus	Single BRT bus, Articulated bus and Bi-articulated bus
Current traffic	Increments of 100 veh/h/lane
Public Transport demand	Increments of 500 passengers per hour

#### Step 4: Bus Service Type

Three parallel processes are now set into motion within the model, dependant on the infrastructure requirements of each of the three types of services. These service types are described in chapter 2.5 (Types of bus services). To summarise, the following three services will be modelled:

- Traditional bus service, operated in mixed traffic
- London style bus lanes operated in a kerb-side bus lane
- Full BRT service, operated in an exclusive median way.

#### Step 5: Traffic Related Delay

Delay encountered by public transport services, due to traffic related effects, is calculated during this process. Chapter 2.9 (Public transport delay and operating speed) describes these traffic related delays in more detail. The different types of bus services to be modelled in this study are proposed to encounter the different delays shown in table 3.7 below:

Table 3.7: Applicability of traffic related delays

Type of traffic-related delay	Traditional service in mixed traffic	London style bus lane service	BRT service
Traffic congestion	x		
Traffic signals	x	x	
Re-entry delay	x		

Traffic related delay can therefore be calculated as shown in figure 3.6 below as well as equation 3.3.

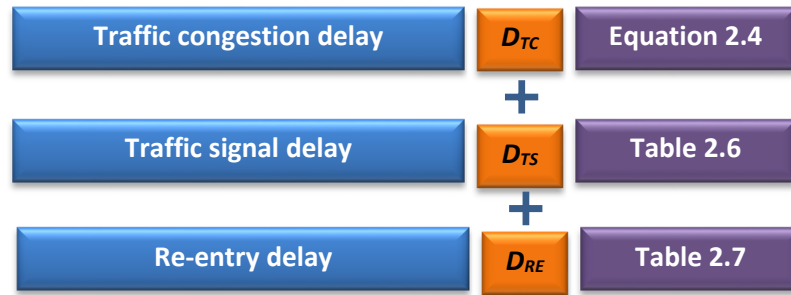


Figure 3.6: Traffic related delay

In order to obtain the total traffic related delay, the following calculation applies:

$$D_{TR} = D_{TS} + D_{TC} + D_{RE} \quad \text{Equation 3.3}$$

Where:

- $D_{TR}$  = Traffic related delay min/km
- $D_{TS}$  = Traffic signal delay min/km
- $D_{TC}$  = Traffic congestion delay min/km
- $D_{RE}$  = Re-entry delay min/km

The model also automatically calculates the capital expenditure required for passing lanes at stops. Hence, no additional delays are expected from buses waiting for another bus to finish loading / off-loading passengers. The bus can just pass the stationary bus, if required.

### Step 6: Passenger Service Delay

An additional delay encountered by public transport services, other than traffic related delay, is that of servicing passengers. Chapter 2.9 Public transport delay and operating speed) describes the delay experienced by public transport vehicles when loading and off-loading passengers. In order to align the information presented by the

Transport Research Board (TRB, 2003) with the model being developed in this study, the following passenger service delay values will be used, as shown in table 3.8 below:

**Table 3.8: Passenger service times to be used in the model**

Type of service	Situation	Passenger service delay (s/p)
<b>BOARDING</b>		
Type 1: Traditional bus service	Single ticket or token	4.0
Type 2: London type bus lanes	Smart card	3.5
Type 3: BRT	Pre-payment	2.5
<b>ALIGHTING</b>		
All services	Rear door	2.1

Following steps 5 and 6, an updated public transport speed can be calculated. The delays calculated, for traffic related as well as passenger servicing, can now be deducted from the public transport vehicle running speed obtained in step 2. The equation for calculating the total delay experienced by the public transport vehicle is shown in equation 3.4 below:

$$D_{TOTAL} = D_{TR} + D_{PSD} \quad \text{Equation 3.4}$$

Where:

$D_{TOTAL}$  = Total delay min/km

$D_{TR}$  = Traffic related delay min/km

$D_{PSD}$  = Passenger service delay min/km

In summary, the process of calculating the updated speed ( $S_2$ ) can be seen in figure 3.7 below. Note that the line scheduling has not been done at this stage.

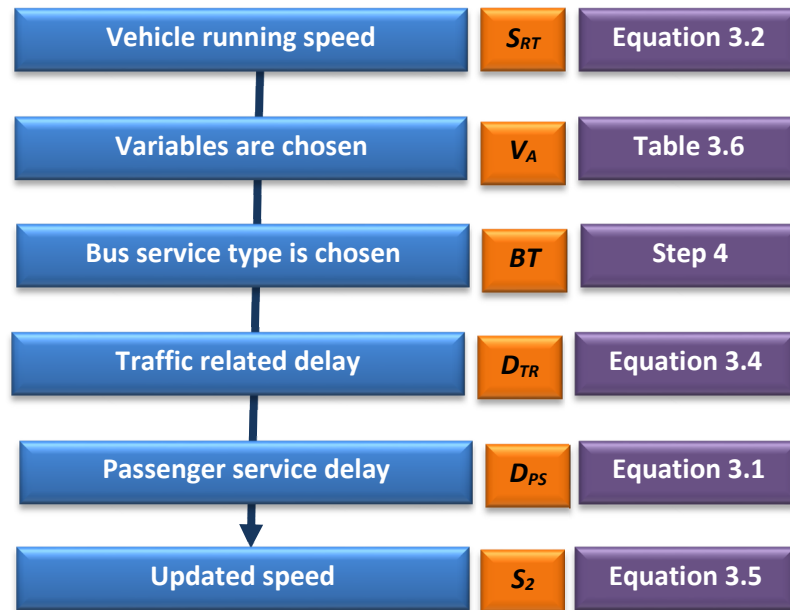


Figure 3.7: Process to calculate the updated speed ( $S_2$ )

Updated speed ( $S_2$ ) can therefore be calculated as shown in equation 3.5 below:

$$S_2 = S_{RT} \cdot \left[ \frac{60}{(D_{TR} + D_{PSD})} \right] \quad \text{Equation 3.5}$$

Where:

- $S_2$  = Updated speed km/h
- $S_{RT}$  = Public transport running speed km/h
- $D_{TR}$  = Traffic related delay min/km
- $D_{PSD}$  = Passenger service delay min/km

### Step 7: Line Scheduling

Once the updated speed is calculated in step 6, a service schedule can be developed. For this schedule to be calculated, a one-way travel time ( $T_o$ ) along the public transport line is required (see equation 2.5). It is for this reason that the initial steps

were taken in order for an accurate speed to be developed for each of the services to obtain a realistic travel time for the section.

The servicing schedule is based on the method described by Vuchic (1981). Chapter 2.12 Public transport line scheduling) shows the procedure for creating these schedules. A summary of this procedure can be depicted as shown in figure 3.8 below:

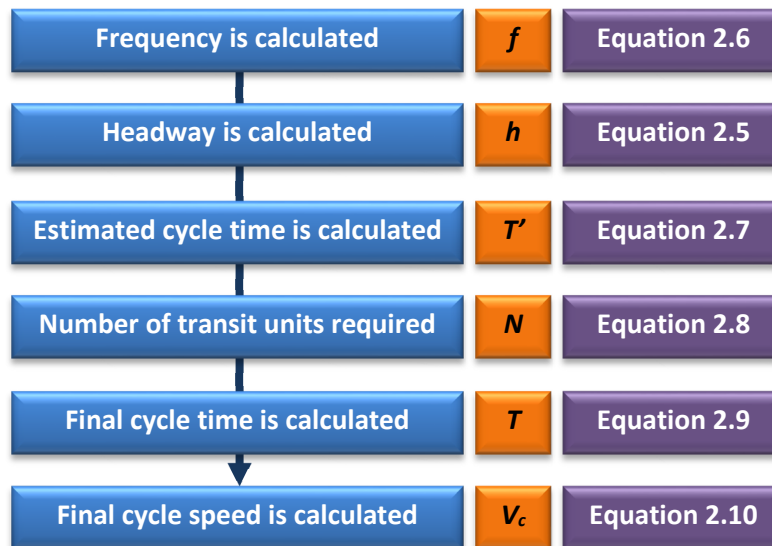


Figure 3.8: Public transport line scheduling process

In order to proceed to the subsequent steps of the modelling process, namely the economic evaluation, one must convert the information obtained thus far into benefits. As the sole benefit of the economic analysis in this study will be time saving, the final cycle speed of each type of service should be compared to one another. As the traditional mixed lane bus service will be used as a base against which the remaining two services are compared, the final cycle speed (km/h) for the base case scenario will be subtracted from the London style bus lane and BRT service type. The difference in public transport speed will then be used in the next step, step 8.

#### Step 8: Travel time savings

As soon as the final average public transport line speed is calculated from the previous step, the travel time savings can be calculated for the BRT and London style bus lane services. Travel speed for all three services is now converted to cycle time.



Comparison of the cycle time for the base case traditional bus services, with that of BRT and London style bus lane services, will provide the travel time gain or loss. This value is then multiplied by the passenger demand for the route. The values obtained in this step will be used in the economic evaluation step of the model.

### Step 9: Operational Cost

Once again, two parallel models were created for the calculation of operational requirements for both peak and off-peak services. Certain items for off-peak operations such as the number of buses etc. would obviously not be required additional to the peak services. The reasoning behind the parallel models stems from the idea to have a model which replicates, as close as possible, a realistic scheduled service. Operational expenditure was divided into three groups namely: operational running costs, fixed operational costs and overhead costs.

#### a) Running Costs

Figures obtained for the Nelson Mandela Bay Integrated Transport System (KPMG, 2013) suggest the following operational running costs for the three bus types used in this study:

Table 3.9: Operational bus running costs

Bus Type	Fuel (R/km)	Tyres (R/km)	Lubrication (R/km)	Maintenance (R/km)	Total Running cost (R/km)
Single	5.16	0.69	0.2	1.45	<b>7.50</b>
Articulated	8.02	1.15	0.2	2.00	<b>11.37</b>
Bi-articulated	11.46	1.38	0.2	2.25	<b>15.29</b>

Source: (KPMG, 2013)

The costs shown in table 3.9 above are typical for South African conditions, however variations of these values might apply.

#### b) Fixed operational Costs

Fixed operational costs differs from running costs in that it is a fixed amount every month. These costs will typically consist of the following items:

- Bus instalments
- Branding expenses
- Bus driver salaries
- Maintenance personnel salaries
- Other personnel salaries
- Depot rent
- Office rent

For bus instalments, a monthly expenditure of approximately 2% of the total vehicle cost will be used in the model. The following instalment figures will therefore be applied to the model, as shown in table 3.10 below:

**Table 3.10: Bus purchase and monthly instalment figures**

Type of bus	Purchase price (Rand)	Monthly instalment (Rand)
Single BRT bus	2 400 000	48 000
Articulated bus	3 500 000	70 000
Bi-articulated bus	4 500 000	90 000

Source: (KPMG, 2013)

Figures obtained for the Nelson Mandela Bay Integrated Transport System (KPMG, 2013) suggest that branding costs for a single BRT bus would be in the region of R30 000, with an articulated bus R40 000. It was estimated that the branding cost for a bi-articulated bus would then be R50 000. An additional assumption was made that this branding will be done twice in the 12 year life cycle of the bus.

Bus drivers salaries are directly linked to the number of buses required in the peak hours of operation. As these peak periods only lasts for a few hours of the day, additional drivers would be on stand-by, already on the payroll, ready for when drivers reach their maximum working hours or take leave.

An assumption was made, after discussions with industry personnel, that for every ten buses, one maintenance person would be required to service the buses. For additional staff, an assumption was made that for a BRT service 2 people will be employed for each stop in order to service the AFC ticketing and station, with an additional five people to work in the control centre. Only two additional people are proposed for the remaining two types of bus services.

Depot rent in the model is based on the type of vehicle to be used by the service, as this has an influence on the size requirements of the depot itself. An assumption was made that a single BRT bus requires approximately 90m<sup>2</sup> for a depot, with an articulated bus requiring 120m<sup>2</sup> and a bi-articulated bus 150m<sup>2</sup>. This is based on previous experience with turning radii and access roads required for each size bus. The assumed rental rate for these properties was then applied to these various requirements. Office space requirements was assumed to be approximately 200m<sup>2</sup> for the traditional bus service, 350m<sup>2</sup> for the London style bus lane service and 600m<sup>2</sup> for the BRT service.

#### c) Overhead Costs

Overhead expenditure is the last of the three operational cost elements. In this model, the following overhead costs were included as part of the operational expenditure:

- Telephone and internet usage
- Maintenance equipment
- Water and electricity bills
- Public relations expenses
- Security contract
- Computer equipment
- Salaries of management and admin staff
- Advertising
- Service vehicle instalments

All three operational elements were added up to the twelve year life cycle of the study, inflated by six percent per annum, to get to a total operating cost. This cost will be used in the following step of the model where the benefit-cost ratio will be calculated.

### Step 10: Economic Evaluation 1 (B/C<sub>1</sub>)

During this step of the model, an economic evaluation will be performed on the time saved by using either the London style bus service or the BRT service, compared to the base case traditional mixed lane bus service. These values will be monetised for the purpose of the benefit-cost ratio calculation. Costs will be derived from the preceding step 9, which calculated the operation costs for the three different services.

This study will follow the methodology used by a report done by SMEC South Africa (Naude, 2013) for monetising the time savings experienced in public transport services. Based on the population assumptions referred to earlier in this report (table 3.2), the values shown in table 3.11 below will be used:

Table 3.11: Proportional split of working and non-working travellers

Working/ non-working	Income Group	Income group split	Value of work / hour (Rand)	Proportional value (Rand)
<b>Workers</b>	Low	0.45	9.50	4.28
	Medium	0.50	44.20	22.10
	High	0.05	118.40	5.92
Value of time for working passengers			Value	32.30
<b>Non-workers</b>	Low	0.45	2.17	0.98
	Medium	0.50	10.08	5.04
	High	0.05	27.00	1.35
Value of time for non-working passengers			Value	7.37

Source: (Naude, 2013)

The split between working and non-working passengers, and peak and off-peak passengers can be seen in table 3.12 below.

**Table 3.12: Distribution of working and non-working passengers**

Peak hour	Split	Weighted value
working passengers	0.97	R 31.33
non-working passengers	0.03	R 0.22
TOTAL VALUE OF PEAK HOUR PASSENGER		R 31.55

Off-peak	Split	Weighted value
working passengers	0.7	R 22.61
non-working passengers	0.3	R 2.21
TOTAL VALUE OF TIME FOR OFF-PEAK HOUR PASSENGER		R 24.82

Source: (Naude, 2013)

A rand value of R31.55/hour for peak passengers and R24.82/hour for off-peak passengers will therefore be used to monetise the time savings experienced by passengers of the London style bus lane and BRT services, compared to the base case traditional bus service operating in mixed traffic. The following calculation will apply for the calculation of the first benefit-cost ratio:

$$B/C_1 = \frac{\text{Monetised time savings}}{\text{Operational Costs}}$$

**Equation 3.6**

### Step 11: Capital Costs

Capital Costs initially proves to be the more costly expenditure item on public transport projects. For the sake of this study, capital cost items were divided into two groups namely: linear cost items and network based items. Linear costs would typically be a capital cost that would be implemented on a public transport route, and be exclusively used for that route. This would include: bus ways, traffic signal prioritisation, NMT walkways, bus stops etc. Network based infrastructure refers to the implementation of public transport infrastructure that would be used to manage

various public transport routes together. This would include a control centre, bus depots, the fare control software etc.

The linear cost items shown in table 3.13 below will be included in the capital cost section:

**Table 3.13: Linear capital expenditure items**

Item	Traditional service	London style bus lane	BRT service
Bus ways		x	x
Lane separators		x	x
Landscaping			x
Bus stop/station	x	x	x
Passing lanes and lay-bys	x	x	x
ITS: real time information		x	x
Signalised pedestrian crossings		x	x
Pedestrian walkways	x	x	x
Bicycle integration			x
Minibus-taxi integration			x
Traffic signal prioritisation			x

It should be noted that no grade separated infrastructure, for BRT vehicles or pedestrians are proposed, due to the application of sophisticated traffic signal priority for BRT vehicles. Bus ways will not be implemented for traditional services, whilst the lane for London style bus services will only get a colouration treatment for the roadway. This service is based on what Transport for London implemented throughout the majority of streets in London, whereby existing traffic lanes were used for the implementation of bus lanes (Hodges, 2007). BRT services will receive a completely new lane. Axle loads were not taken into consideration in this study.

London style bus lanes are to be separated by means of road markings and BRT lanes with separator blocks. Landscaping is solely proposed for the BRT service with approximately one tree to be planted every 50m with general plantings included.

Bus stops for the traditional service will consist of a bus lay-by with a standard bus shelter. Stops for the London style bus lane service will also consist of a bus lay-by, but will have a more upmarket bus shelter with ITS real time information. BRT services will have a concrete platform to ensure ease of disembarking of passengers, with a small structure approximately 30m<sup>2</sup> per stop. The BRT stations will have two ITS real time displays. It should be noted that stops are placed 500m apart in the model, hence two stops per kilometre will be included in the linear rate.

The cost of implementing these stops are linked to the number of bays to be provided at each location, based on the passenger demand. Estimated maximum capacities of linear bus stops are shown in the Transit Capacity and Quality of Service Manual (TRB, 2003) to be as shown in table 3.14 below:

**Table 3.14: Bus stop capacities**

Dwell time (sec)	Number of On-Line Linear Loading Areas											
	1				2				3			
	(g/C) 0.25	(g/C) 0.5	(g/C) 0.75	(g/C) 1.0	(g/C) 0.25	(g/C) 0.5	(g/C) 0.75	(g/C) 1.0	(g/C) 0.25	(g/C) 0.5	(g/C) 0.75	(g/C) 1.0
30	37	48	56	69	66	84	102	120	93	118	144	169
45	29	38	45	55	53	66	80	93	74	93	113	131
60	22	27	33	38	39	48	57	66	56	68	81	93

Source: (TRB, 2003)

A ten second clearance time, 25% failure rate, 60% coefficient of variation of dwell times, and random bus arrivals are taken into account with the above figures (TRB, 2003). These figures are based on experience at the Port Authority of New York and New Jersey.

The “g” in table 3.14 above refers to the effective green time allocated to a certain movement, whilst the “C” refers to the cycle time. A g/C ratio of 0.5 would indicate that 50% of the cycle time is allocated to the movement’s effective green time.

For a traditional bus service, operating a cash on board system, the longest passenger delay on a bi-articulated bus would be just over 60 seconds. This means that for a maximum average dwell time of around 60 seconds, one stopping bay has the capacity to serve between 22 and 33 buses per hour, for the range g/C between 0.25 and 0.75. For the same bi-articulated bus, operating pre-boarding tickets will have a maximum dwell time of 45 seconds. One stopping bay has the capacity to serve between 29 and 45 buses per hour, also for the range g/C between 0.25 and 0.75. The worst case, e.g. a g/C ratio of 0.25 was assumed for all the service types except a BRT service. BRT services on the other hand will enjoy signal prioritisation which will effectively provide a g/C ratio of 1.0. The priority signalisation, as described in section 2.8.2 (Traffic signals), effectively allows the bus to traverse the intersection without any notable delay.

ITS real time information refers to the visual, and sometimes audible information presented at the bus stops. It shows the passengers waiting at the bus stop when the next bus is expected, and possibly some additional route information. The ITS information presented on each bus should be considered with the cost of the buses. The reason behind this is that the number of buses required will vary as the passenger demand and delay time varies.

Signalised pedestrian crossings refers to the implementation of push button activated pedestrian crossings where passengers can request signal green time to enable them to cross the road. Pedestrian walkways refers to the surface area provided to pedestrians, physically separated from vehicular traffic by means of a barrier kerb, normally constructed adjacent to the roadway.

Bicycle and taxi integration suggests that the design of the public transport facility will take into account the operations of taxis and bicycles by means of integration. In other



words, adequate space will be provided for taxis to pick-up and drop off passengers, and bicycle storage facilities will be provided.

Traffic signal prioritisation, as described in chapter 2.9.2 (Traffic Signals), refers to the method of how public transport can receive priority over normal mixed traffic.

Costs for these items were broken down into linear costs (Rand/km) for modelling purposes. This provides scope for future modelling exercises to be done on alternate lengths of public transport line segments. This model is however based on a 10km length of public transport line in one direction. Linear capital costs used in the model can be seen in table 3.15 below:

**Table 3.15: Linear rates for capital expenditure items**

Item	Traditional service (R/km)	London style bus lane (R/km)	BRT service (R/km)
Bus ways	-	450 000	4 200 000
Lane separators	-	8 000	50 000
Landscaping	-	-	90 000
Bus stop/station	120 000*	180 000*	420 000*
Passing lanes and lay-by	264 000*	264 000*	1 440 000*
ITS: real time information	-	136 000	272 000
Pedestrian crossings	-	180 000	180 000
Pedestrian walkways	100 000	100 000	400 000
Bicycle integration	-	-	115 000
Minibus-taxi integration	-	-	500 000
Traffic signal prioritisation	-	-	3 600 000
<b>TOTAL LINEAR RATE (R/km)</b>	<b>120 000</b>	<b>1 318 000</b>	<b>7 847 000</b>

\*Based on a single platform stop

Source: (Botha et. al., 2014)

Non-linear capital expenses would include the following, as shown in table 3.16 below:

**Table 3.16: Additional Capital Costs**

Item	Traditional service	London style bus lane	BRT service
Control centre			x
Fare system software			x

Some public transport infrastructure has the potential to source income to such an extent that the implementation costs can be fully recovered, or even be profitable. Due to this commercial possibility, the cost of implementing transfer stations and park and ride facilities is therefore not considered in this model. It would not make sense to cost infrastructure that would pay for itself within the analysis period. It is also assumed that the depot will be rented and not purchased; the cost of renting this space is included in the operational cost section. A purchase price for the fare system software was estimated to be in the vicinity of R3 million with the control centre estimated to cost R9 million (Botha et. al., 2014).

**Step 12: Economic Evaluation 2 (B/C<sub>2</sub>)**

A repeat of step 10 will be followed with one exception, the capital expenditure will now be added to the operational costs for the calculation of the benefit-cost ratio. Benefits to be used in the calculation will still remain the monetised travel time savings experienced by the BRT and London style bus lane services compared to the traditional mixed lane bus service. The following equation will apply for the calculation of the second benefit-cost ratio:

$$B/C_2 = \frac{\text{Monetised time savings}}{\text{Operational Costs} + \text{Capital Costs}} \tag{Equation 3.7}$$

**3.4 Hybrid solutions**

During the process of running the model, four main variables were compared to one another. A parallel process was run in the model where any input was analysed for all three

types of services. These services consists of a traditional bus service, operated in mixed traffic, a London style bus service operated on a bus lane and a BRT service, operated on an exclusive segregated lane.

Other variables include passenger demand, type of bus to be used as well as the traffic saturation level on the adjacent mixed lane. These items are described in detail in the previous chapters.

As travel time reduction is one of the largest benefits of public transport investment, it would make sense to find ways of reducing travel time at the lowest possible level of investment. In other words, is there something that will be cheaper than building new bus lanes whilst still having the benefits of the reduction in travel time, as with the BRT scenario?

Each day, approximately 8 000 buses carry about 6 million passengers in the greater London (Hodges, 2007). London also has one of the most extensive bus lane and traffic signal priority networks in the world. Since the inception of the London Bus Initiative, where these secluded lanes and signal prioritisation was driven, the patronage has increased by approximately 40% since 1999.

If one looks at the various transport infrastructure options, the question comes to mind: How would the London style bus lane service fare with traffic signal priority? The original model was initially developed to solely take into account traffic signal priority for the BRT scenario. The hybrid scenario will therefore take into consideration what the impact of bus priority traffic signalisation would be. The only amendment to the model would therefore be the inclusion of signal priority as the remaining conditions for the London style option will remain the same as with the original model.

#### 4. RESULTS AND ANALYSIS

In the preceding chapters, the reasoning and approach of the modelling process was described. In order to obtain relevant information for analysis, a model was created which simulated a scheduled service as closely as possible. This chapter will report on the data output and analysis of the modelling process.

##### 4.1 Speed

Average speed of the mixed lane service (base case) is subject to different types of delay, which the other two services are not. One of these types of delay is the delay experienced due to traffic encountered. As the number of vehicles encountered in mixed traffic increase, the average peak hour speed for buses operating in mixed traffic should decrease. The effect that an increase in traffic has on the model can be seen in figure 4.1 below.

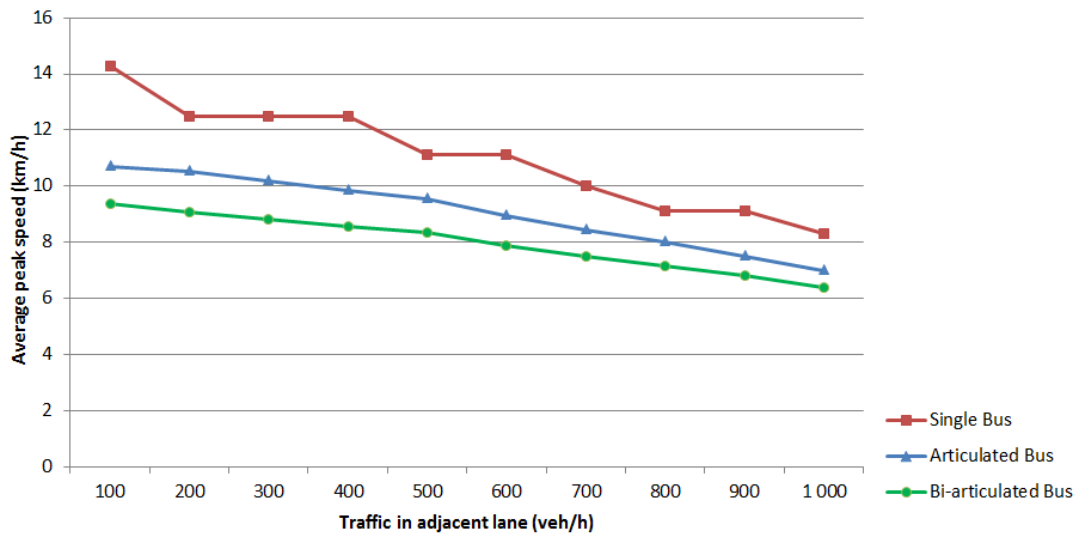


Figure 4.1: Average peak hour speed for mixed lane bus services

Data obtained during the modelling of the various scenarios, including London type bus lane services as well as BRT services, show that average peak hour speed fluctuate between 6km/h and 30km/h. These results, presented in figure 4.2 below, shows the different average peak hour speed for single buses, articulated buses as well as bi-articulated buses. These buses were all modelled utilising the three types of services

namely: traditional bus service in mixed traffic, London style bus lane service as well as a BRT service.

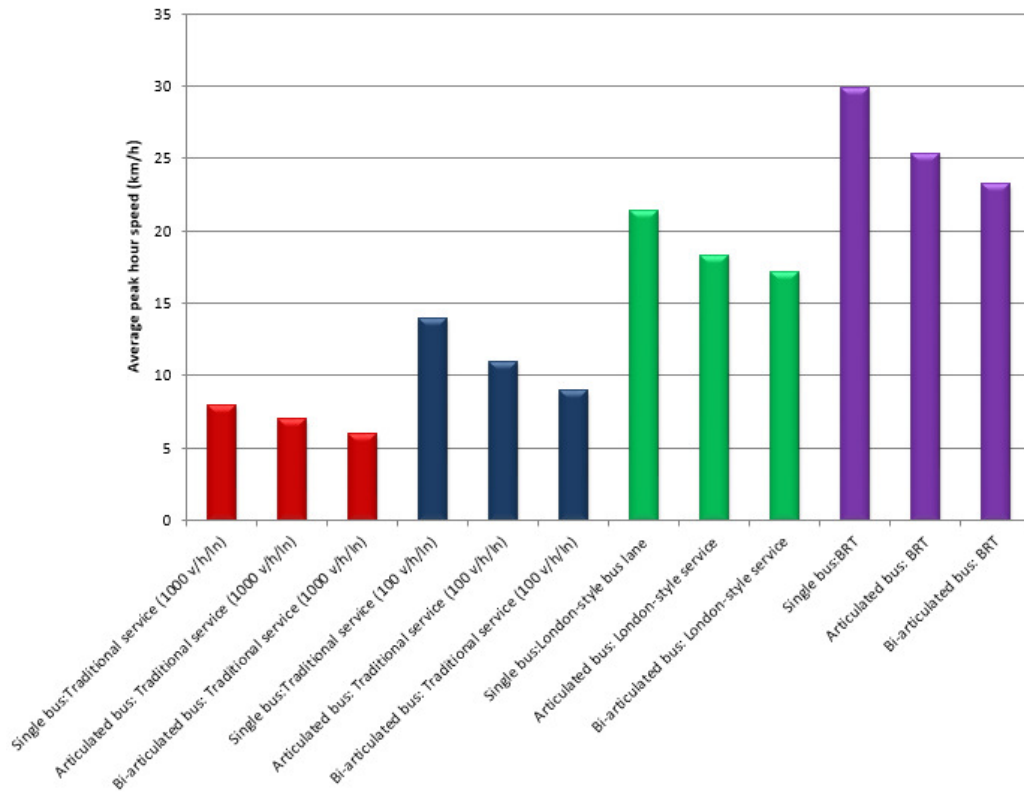


Figure 4.2: Average peak hour speed for the model

Results obtained from the model, on the average peak hour speed for BRT services, compare favourably with what existing services experience (Hensher & Golob, 2008). Superimposed on figure 4.3 below are the average speed produced by the model for the three types of buses operating on BRT infrastructure.

As a single bus has less capacity than an articulated and bi-articulated bus, the passenger service delay experienced by the single bus will be less, hence the higher commercial speed for single buses.

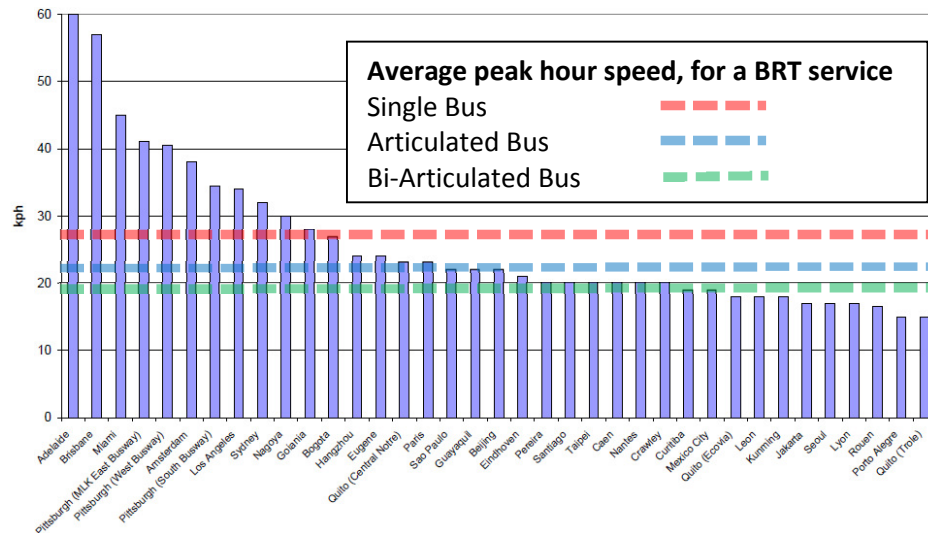


Figure 4.3: Average all day commercial speed for BRT systems

Source: (Hensher & Golob, 2008)

#### 4.2 Sources of delay

As mentioned previously, delay incurred by the public transport vehicle, which will reduce the average speed at which the bus travels, is influenced by traffic signals, traffic congestion, re-entry delay at lay-bys and passenger service delay at bus stops. Table 4.1 below shows the value of delay, measured in seconds/route/bus.

Table 4.1: Delay calculated for a single bus

	Traditional service			London style service			BRT service		
	Traffic congestion level (veh/h)			Traffic congestion level (veh/h)			Traffic congestion level (veh/h)		
	100	500	1 000	100	500	1 000	100	500	1 000
Traffic signal delay	420	420	420	420	420	420	-	-	-
Congestion delay	80	471	1 626	-	-	-	-	-	-
Re-entry delay	20	100	300	-	-	-	-	-	-
Passenger service delay	339	339	339	308	308	308	248	248	248

### 4.3 Headways

Headways estimated for the various models can be seen in figure 4.4 below. The end of each line represents the demand where headways fall below 1 minute. As only a hand full of systems around the world operate at peak headways of less than one minute, this model will treat a one minute headway as the maximum.

The extent of this model therefore is up to 3 000 peak hour passengers for a single bus, 12 000 for an articulated bus and 23 000 for a bi-articulated bus. These values depict when the headways become less than one minute. An extensive number of buses are then required to be able to transport the increased volume of passengers. This becomes less cost effective due to the increased number of buses required. Comparing these values to South Africa, section 1.2 clearly shows that the current South African BRT corridors still have some way to go in densification etc. to reach these figures.

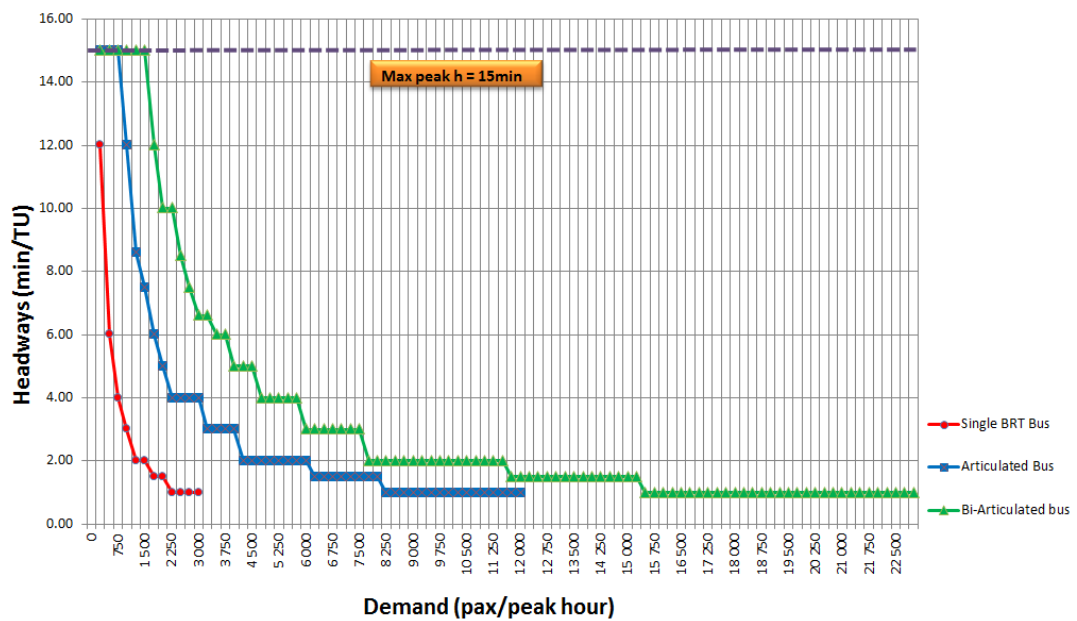


Figure 4.4: Headways

The steps seen in each of the curves represents where additional buses are required to be able to transport the increased volume of passengers. As the number of buses required increase, the headway automatically decrease.

#### 4.4 Number of buses

As passenger demand increases, the number of buses required to serve these passengers within a certain minimum headway, also increases. For a scenario where single buses are used for the operation of the three types of services (traditional bus service operating in mixed traffic, London style bus lane service and BRT service), the increase in the number of buses required, when peak passenger demand increases, is presented in figure 4.5 below:

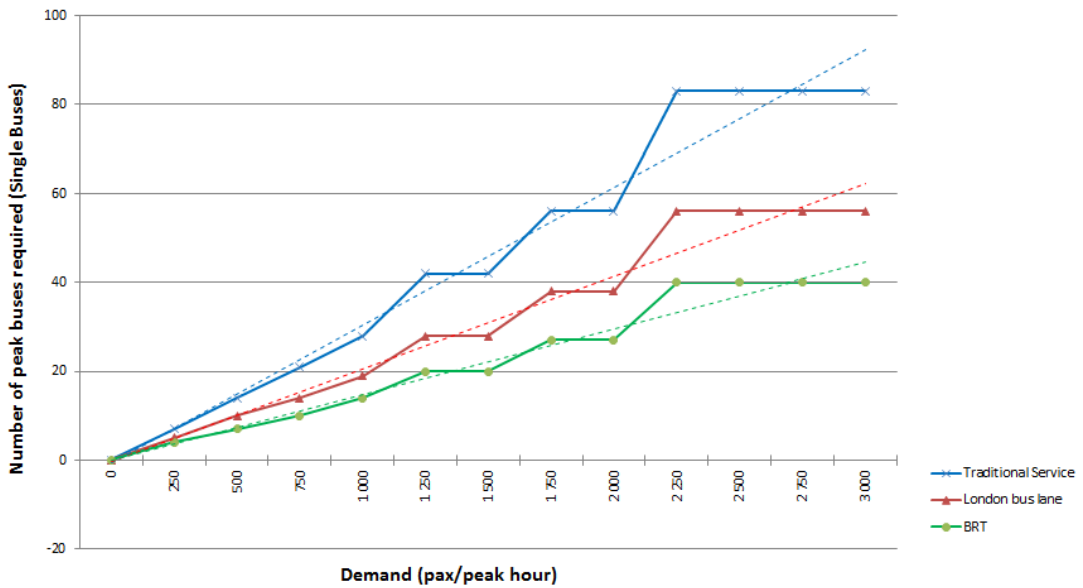


Figure 4.5: Number of single buses required

As can be seen in figure 4.5 above, a passenger demand of approximately 3 000 passengers per hour can be serviced with headways between one and 15 minutes in the peak. In order to serve 3 000 passengers per hour, a total number of 83 buses are required for a traditional service, operating in mixed traffic with a flow of 100 vehicles per hour. A London style bus lane service requires approximately 56 buses and a BRT service requires 40 single buses to be able to transport the 3 000 passengers in the peak hour. The dotted lines represents the linear trend line for each of the scenarios.

For a scenario where only articulated buses are used for the operation of the three types of services, the increase in the number of passengers that can be moved in a peak hour rises to approximately 12 000 passengers per hour. A traditional bus service requires



approximately 111 articulated buses to move the 12 000 passengers in an hour, whilst a London style bus lane service requires 65 and a BRT service only requires 47 articulated buses. Figure 4.6 below shows the increase in the number of articulated buses required as the peak hour passenger demand increases.

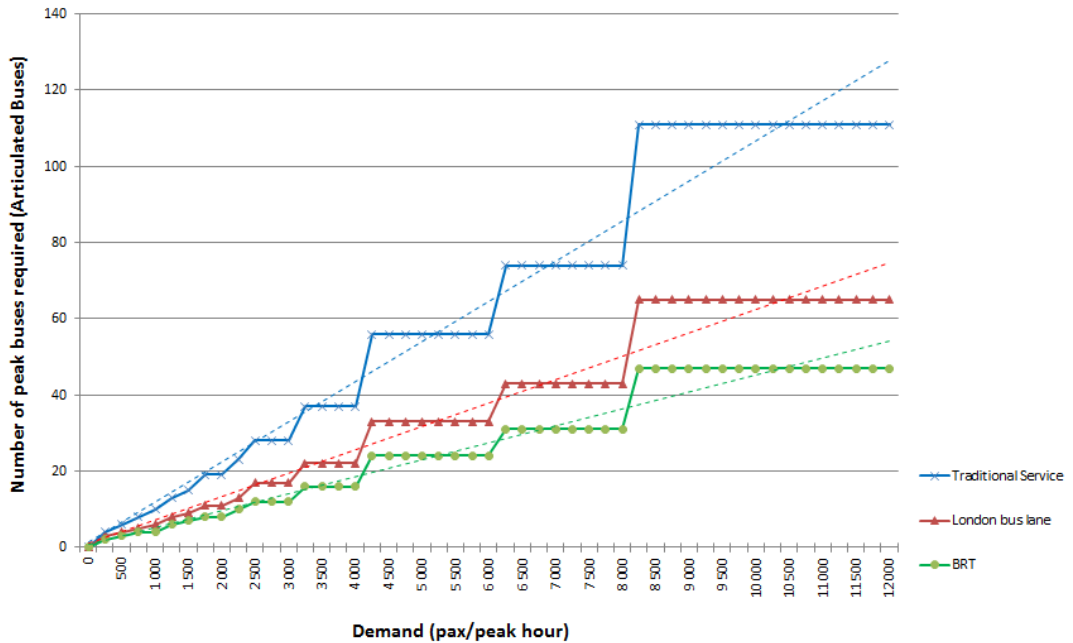


Figure 4.6: Number of articulated buses required

Bi-articulated buses, modelled for operating with peak headways between 15 and one minute on the three types of services, can move a maximum of 23 000 peak passengers in an hour. In order to move this amount of passengers in an hour, a traditional mixed lane service, operating in mixed traffic flow of 100 vehicles per hour, requires 127 bi-articulated buses. A London style bus lane service requires 69 buses and a BRT service requires 51 bi-articulated buses in order to transport the same amount of peak hour passengers in the peak hour.

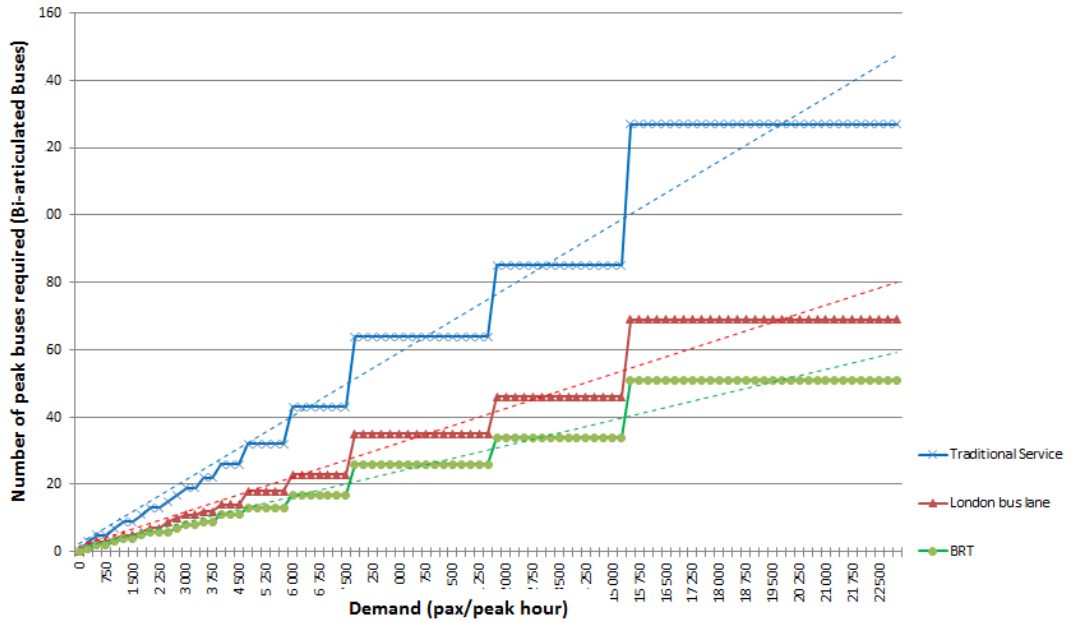


Figure 4.7: Number of bi-articulated buses required

Buses operating in mixed traffic are subject to the delays incurred due to the level of traffic experienced. As cycle speed reduces due to the increase in traffic, the number of buses required likewise increases. Figure 4.8 below shows such an increase for a single bus, operating in mixed traffic, in various levels of congestion.

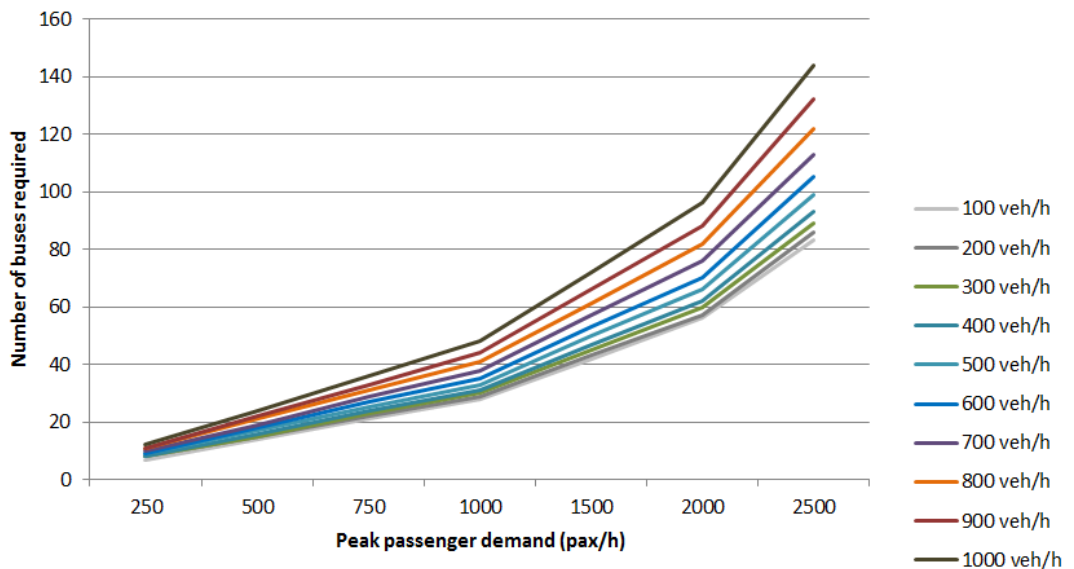


Figure 4.8: Number of single BRT buses required for various levels of traffic congestion

Articulated as well as bi-articulated buses, operating in mixed traffic, shows similar increases in the number of vehicles required as traffic volumes increase. The increase in the number of buses is due to an increase in traffic (Nicolai & Weiss, 2008)

#### 4.5 Benefit-Cost Ratio<sub>1</sub>

Two types of benefit-cost analysis were done for this study. Costs used in these calculations were calculated in two ways namely, operational costs only, and operational costs plus capital expenditure (infrastructure costs). Benefits used in both of these benefit-cost calculations were that of monetised time savings due to the increase in cycle speed, compared to the base case scenario of a service operating in mixed traffic. For ease of reference, the benefit-cost ratio that only takes into account operational costs will be referred to as B/C<sub>1</sub>, whilst the benefit-cost ratio that considers both operational cost and capital costs will be referred to as B/C<sub>2</sub>.

Single buses modelled for the three types of services shows B/C<sub>1</sub> ratios as presented in figure 4.9 below. These graphs represent a base value for a service operated in mixed traffic, with a mixed traffic flow of 100 vehicles per hour.

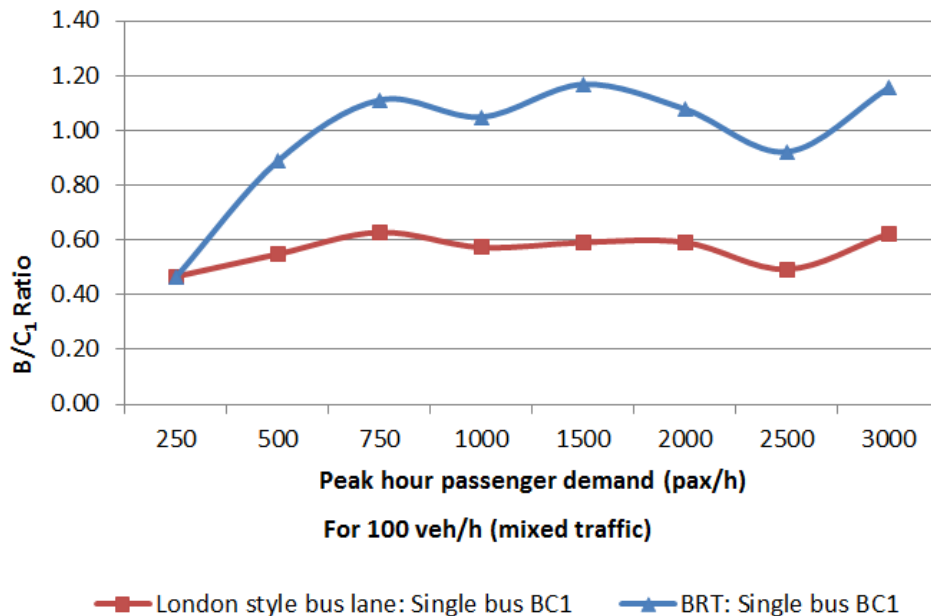


Figure 4.9: B/C<sub>1</sub> Ratio (excl. capital cost) for single buses – 100 veh/h mixed traffic

From the information gathered from the model, it can be concluded that the  $B/C_1$  ratio for a BRT service, operating with a single bus, is better than for a London style bus lane service also operating a single bus. For mixed traffic flow of 100 vehicles per hour per lane, the  $B/C_1$  ratio for a BRT service averages 0.98, meaning that the benefits almost equals the costs. The  $B/C_1$  ratio for a London style bus lane service on the other hand only averages 0.56 for the range of 250 to 3 000 peak passengers per hour.

The model shows that the travel time savings are higher for a BRT service than for a London style bus lane service. In other words, the cycle speed of the BRT service is higher than for a London style service. Also, the operational costs for the BRT service is lower than for a London style service. Due to the lower cycle speed of the London style bus lane service, the number of buses must be increased to be able to move the required volume of passengers, thus increasing the operational costs. As the benefits of the  $B/C_1$  ratio is the monetisation of travel time savings and the costs obtained from the operational costs only, the BRT option shows a far better benefit-cost ratio than for a London style bus lane service.

Upward fluctuations in the graph indicate where additional benefits are gained due to the increase in passenger volumes with no additional buses required to transport them. Downward fluctuations indicate where additional buses are indeed required in order to transport the increased passenger demand.

Should the flow of traffic in the mixed lane increase, the effect on both the London style bus lane service and the BRT service can be seen in figure 4.10 below. These graphs represent the  $B/C_1$  values for the same two services, compared to the base case scenario of a bus service operating in mixed lane traffic, for increases in mixed lane traffic flow of 500 vehicles per hour per lane and 1 000 vehicles per hour per lane respectively.

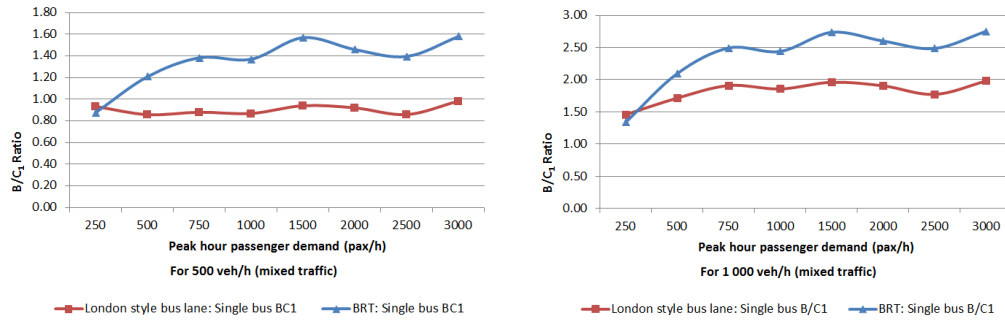


Figure 4.10: B/C<sub>1</sub> Ratio (excl. capital cost) for single buses – increased mixed traffic

From the data obtained from the model, it is clear that when traffic flow increases for the service operated in mixed traffic, the B/C<sub>1</sub> ratios increase for both the London style bus lane service and the BRT service. The average B/C<sub>1</sub> ratio for a single bus operating on a London style bus lane service, compared to a mixed lane service with 500 vehicles per hour, is now 0.9. Comparing these values to a mixed lane service operating in traffic flow of 1 000 vehicles per hour per lane, the average B/C<sub>1</sub> ratio increases even more to 1.82. This is considerably higher than the average B/C<sub>1</sub> ratio of 0.56 for the same service compared to a mixed traffic service with a traffic flow of only 100 vehicles per hour.

The increase in the benefit-cost ratios of the BRT service, as well as the London style bus lane service, compared to the base case traditional bus service operating in mixed traffic, is due to the increase in delay experienced by the traditional service through increased levels of traffic congestion. The lower cycle speed of the base case will in turn reduce the benefits due to a reduction in travel time savings and an increase in operational costs due to additional buses required to operate same passenger demand volumes at a lower speed.

For a BRT service compared to a mixed lane service operating in a traffic flow of 500 vehicles per hour per lane, the average B/C<sub>1</sub> ratio increases from 0.98 to 1.35. When comparing this service to a mixed lane service operating in a traffic flow of 1 000 vehicles per hour per lane, the average B/C<sub>1</sub> ratio increases to 2.37.

A similar trend was observed were the benefit-cost ratio for a BRT service remains better than for a London style bus lane service, for the articulated as well as the bi-articulated

buses. A summary of the results can be seen in table 4.2 below. This table summarises the average  $B/C_1$  ratio, for the range beyond the feasible benefit-cost ratio of one.

**Table 4.2: Average  $B/C_1$  comparison (for the feasible range)**

Type of service	Mixed traffic	Mixed traffic	Mixed traffic
	flow: 100 veh/h/ln	flow: 500 veh/h/ln	flow: 1 000 veh/h/ln
Single bus: London style bus lane service	N/A	N/A	1.80
Single bus: BRT service	1.07	1.40	2.29
Articulated bus: London style bus lane service	2.29	2.98	5.18
Articulated bus: BRT service	3.62	4.48	6.99
Bi-articulated bus: London style bus lane service	4.07	4.97	7.81
Bi-articulated bus: BRT service	6.09	6.93	10.04

For a benefit-cost ratio to be deemed feasible, the ratio should exceed one. In other words, the benefits should be greater than the cost.

From the data obtained during the modelling of the  $B/C_1$  ratio, the majority of the services, operating in different levels of traffic congestion, exceeded the  $B/C_1$  ratio of one. Table 4.3 below shows where each of these services exceeds a  $B/C_1$  ratio of one.

**Table 4.3: Approximate passenger demand where the B/C<sub>1</sub> ratio exceeds one**

Type of bus and level of service	Mixed traffic flow (veh/h/ln)	Passenger demand at which B/C <sub>1</sub> ratio exceeds 1 (pax/h)
Single bus, London style bus lane service	100	Does not exceed 1
	500	Does not exceed 1
	1 000	< 250
Single bus, BRT service	100	≈ 625
	500	≈ 300
	1 000	≈ 250
Articulated bus, London style bus lane service	100	≈ 600
	500	≈ 375
	1 000	≈ 360
Articulated bus, BRT service	100	≈ 375
	500	≈ 250
	1 000	≈ 250
Bi-articulated bus, London style bus lane service	100	≈ 875
	500	≈ 625
	1 000	≈ 250
Bi-articulated bus, BRT service	100	≈ 600
	500	≈ 250
	1 000	≈ 250

In order to get a clear idea of how the different type of buses fare relative to each other, figure 33 below was developed from data obtained from the model. It shows the B/C<sub>1</sub> ratios for the three types of buses operating on a London style bus lane service compared to a base case scenario operating in mixed traffic with a flow of 100 vehicles per hour per lane. Single buses are shown in red, with the articulated buses shown in blue whilst bi-articulated buses are shown in green. This colour scheme to denote the different types of buses will be used throughout the study report.

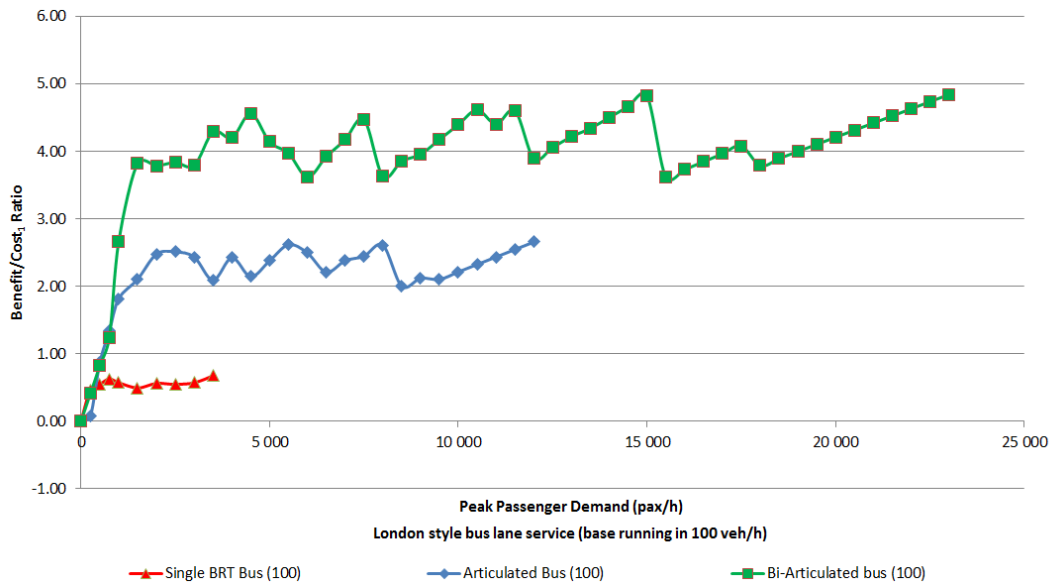


Figure 4.11: B/C<sub>1</sub> Ratio (excl. capital cost) for London style bus lane services– base service operating in 100 veh/h

Bi-articulated buses clearly have the advantage with an average B/C<sub>1</sub> ratio of 3.70, compared to an average B/C<sub>1</sub> ratio of 2.05 for articulated buses and 0.56 for single BRT buses. Referring to figures 4.5, 4.6 and 4.7, it is clear that if the size of bus increase, less buses are required to operate each service, for the same passenger demand. This in turn brings down the operational costs for the service. Figure 4.2 however shows that the peak operational speed for a single bus is faster than for an articulated bus, whilst a bi-articulated bus proves to be the slowest of the three types of buses. However, this benefit in increased speed, which in turn translates to a monetised travel time reduction is not large enough to surpass the additional costs gained with the required additional buses.

It was observed from the previous graphs that should the traffic volume for the base case increase, the B/C<sub>1</sub> ratio will also increase. Figure 4.12 below show these increases for the three types of buses operating on a London style bus lane service, with an increase in base case traffic volumes of 500 and 1 000 vehicles per hour per lane. The increase in the benefit-cost ratio for an increase in the level of traffic congestion is due to the increase in delay experienced by the base case, the traditional bus service, operating in mixed traffic.



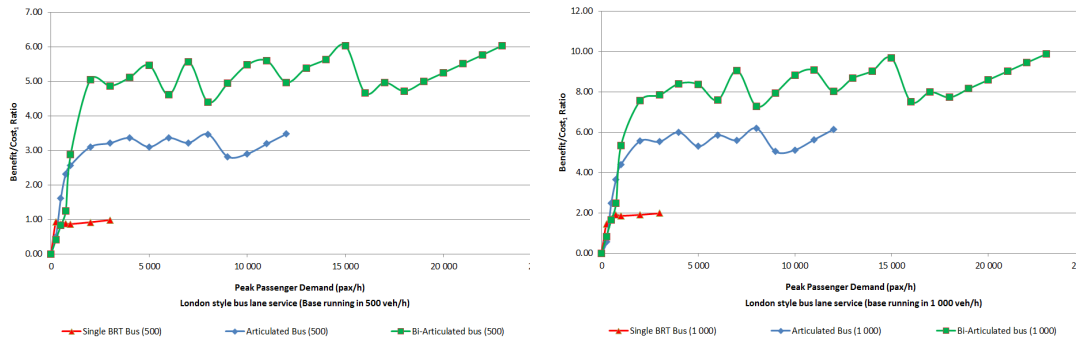


Figure 4.12: B/C<sub>1</sub> Ratio for London style bus lane services – base service operating in 500 and 1 000 veh/h

Once again one can observe that the B/C<sub>1</sub> ratio increases as the base case scenario's mixed lane traffic increases. Figures 4.13, 4.14 and 4.15 below show the variation of the B/C<sub>1</sub> ratio for each of the type of buses operating in a London style bus lane service, compared to a base case scenario operating in traffic flows of 100, 500 and 1 000 vehicles per hour.

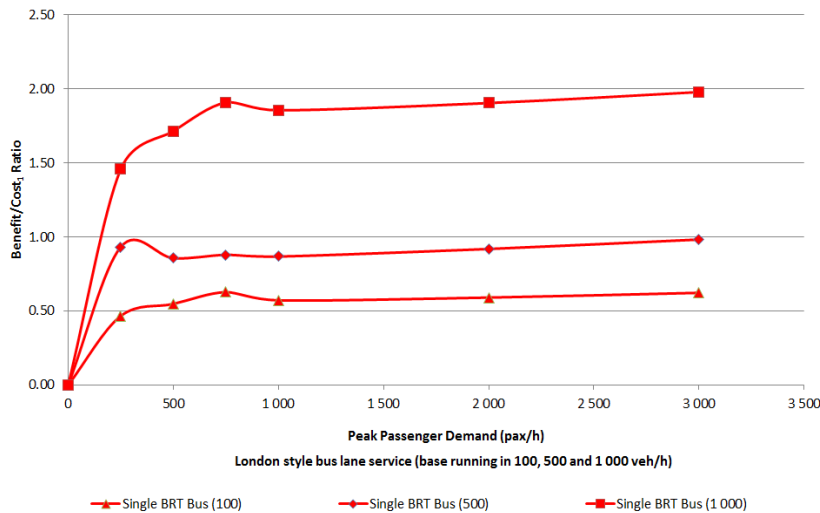


Figure 4.13: B/C<sub>1</sub> variation for single buses on London style bus lane services

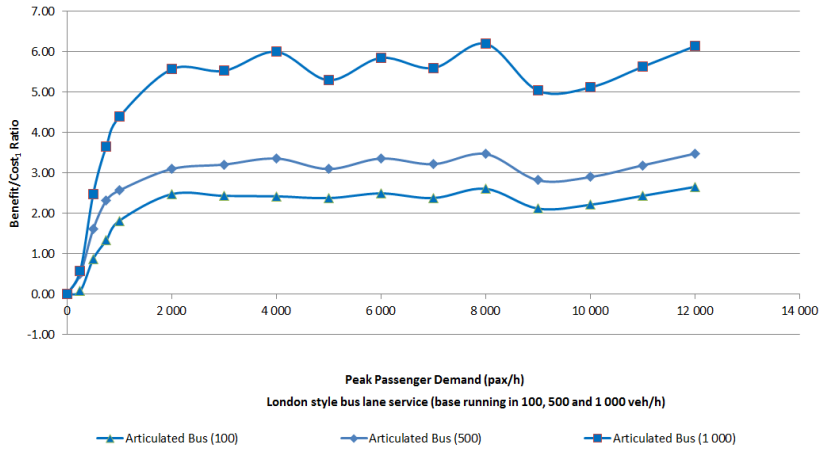


Figure 4.14:  $B/C_1$  variation for articulated buses on London style bus lane services



Figure 4.15:  $B/C_1$  variation for bi-articulated buses on London style bus lane services

Once all the relevant values are known, one can develop a comparison between the type of services and buses. Figure 4.16 below shows such a comparison where the  $B/C_1$  ratio for the three types of buses, operating on both a London style bus lane service and a BRT service, are compared to the base case mixed traffic service. Single buses are denoted in red, with articulated buses shown in blue and bi-articulated buses shown in green.

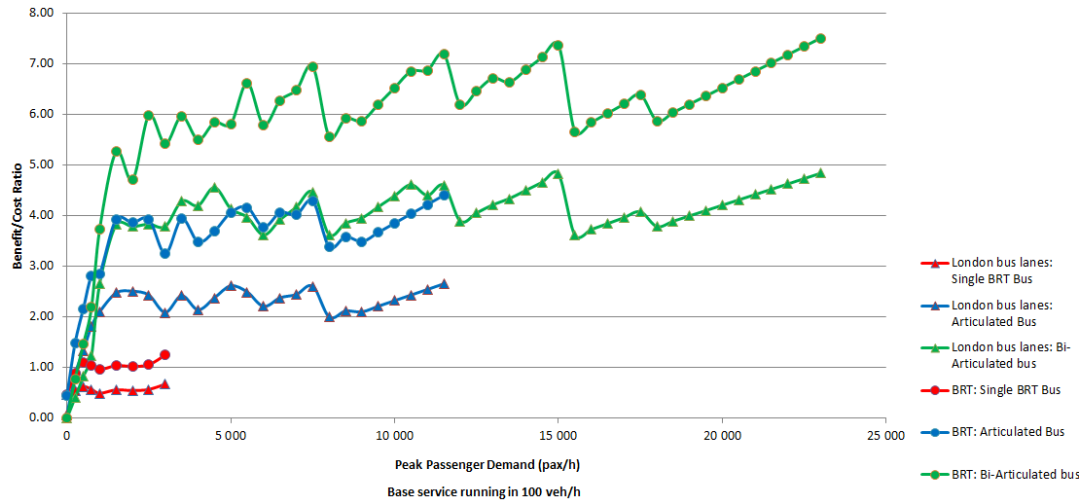


Figure 4.16: B/C<sub>1</sub> comparison

As previously discussed, when comparing the same type of bus, on different types of services, the BRT service shows better B/C<sub>1</sub> ratios than the London style bus lane service. Data obtained from the model, for a base case scenario operating in a mixed traffic flow of 100 vehicles per hour, shows that the highest B/C<sub>1</sub> scenario is that of a bi-articulated bus operated on a BRT service. The lowest B/C<sub>1</sub> ratio is that of a single bus operated on a London style bus lane service, followed closely by a single bus operated on a BRT service.

However, a very interesting outcome is derived from the data whereby the model data shows similar B/C<sub>1</sub> ratios for an articulated bus operated on a BRT service compared to the B/C<sub>1</sub> ratio for a bi-articulated bus operated on a London style bus lane service. This can be ascribed to the faster travel time of the smaller articulated bus, compared to the slower bi-articulated bus, as well as the faster travel time for a BRT service, compared to a London style bus lane service. On the costing side, the bi-articulated bus service is cheaper to operate than the articulated service due to the lower number of buses required. It should be noted that the B/C<sub>1</sub> ratio excludes capital expenditure as it only comprises of operational costs as part of the C<sub>1</sub> portion of the B/C<sub>1</sub> calculation. Figure 4.17 below is exactly the same as the figure 4.16 above, it is only focussing on the passenger demand up to 4 000 passengers per hour. One can clearly observe how similar the B/C<sub>1</sub> trend of the articulated bus operating on a BRT line and the bi-articulated bus operating on a London style bus lane service compares.

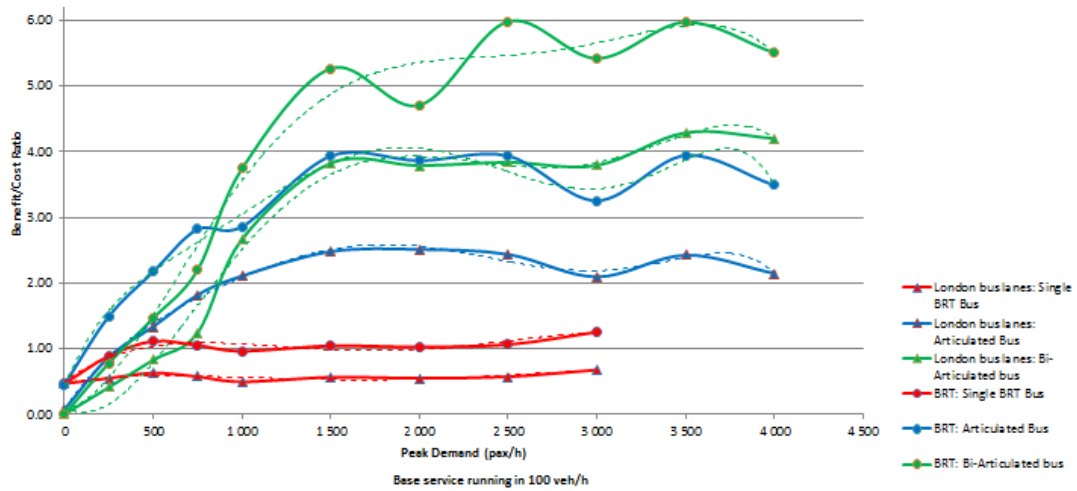


Figure 4.17: B/C<sub>1</sub> comparison (below 4 000 passengers per hour)

Should traffic on the base case scenario increase, a similar pattern remains where the B/C<sub>1</sub> trend of an articulated bus, operating on a BRT line, is very similar to a bi-articulated bus operating on a London style bus lane service. Below are graphical representations of the model data for increases in base case traffic volumes to 500 and 1 000 vehicles per hour, shown in figure 4.18.

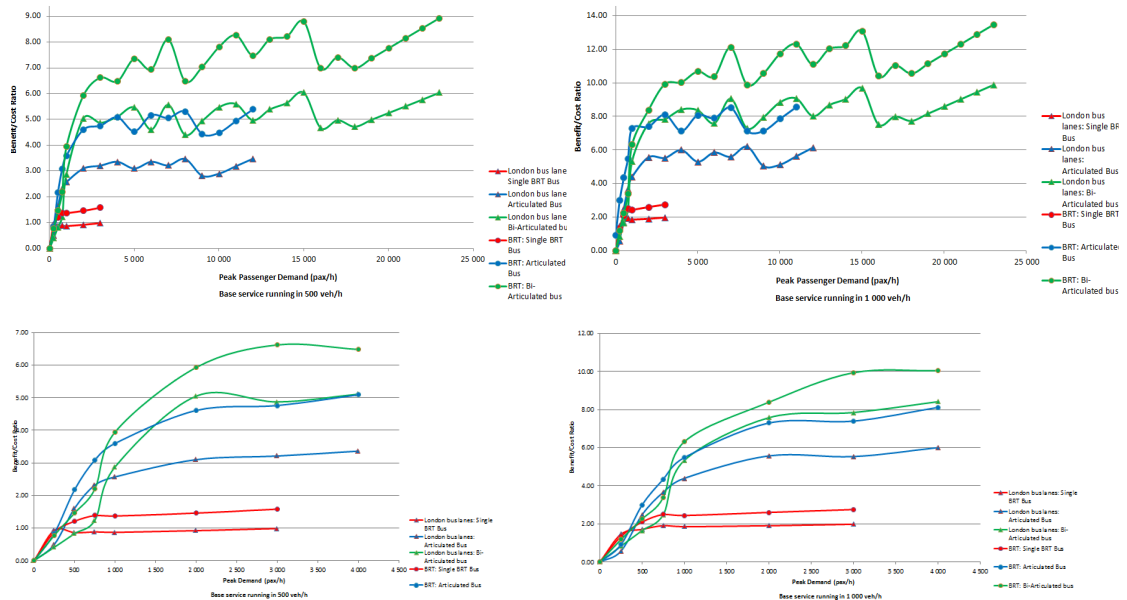


Figure 4.18: B/C<sub>1</sub> comparison (with increased base case traffic)

In summary, various factors play a role in the economic feasibility of a bus service. When only considering the operational cost of a service, thereby excluding the infrastructure expenditure, the operational feasibility can be considered by operators. In other words, for a specific demand, and a specific level of traffic congestion, what level of bus service would be the most feasible, and what size of bus will work the best?

From the analysis of the data, obtained from the model, it showed that smaller buses have a faster travel time, when operating in the same level of service, at the same level of congestion. If the level of congestion for the base case traditional bus service increase, both the other services' benefit-cost-ratios increase. If the same buses are used, and the type of service is upgraded, say for instance from a London style bus lane service, to a BRT service, the upgraded service yields a better cost-benefit ratio. If different buses are used on different types of services, the  $B/C_1$  ratios vary. For example, when a lower level service, using a larger bus is compared to a higher level service, using a smaller bus. This can clearly be seen where a bi-articulated bus, being operated on a London style bus lane service, has a  $B/C_1$  ratio very similar to an articulated bus being operated on a BRT service.

#### 4.6 Benefit-Cost Ratio<sub>2</sub>

In the previous section, the  $B/C_1$  ratio (equation 3.6) was used to calculate, graphically represent and compare the modelled information. This section will now look at the impact that the addition of infrastructure costs (equation 3.7) will have on the model. This amended benefit-cost ratio will be referred to as  $B/C_2$ . As with the  $B/C_1$  ratio, benefits used in the  $B/C_2$  calculation are that of monetised time savings due to the reduction in travel time, compared to the base case scenario of a service operating in mixed traffic. For ease of reference, the benefit-cost ratio that only takes into account operational costs will be referred to as  $B/C_1$ , whilst the benefit-cost ratio that considers both operational cost and capital costs will be referred to as  $B/C_2$

Single buses modelled for the three types of services shows  $B/C_2$  ratios as presented in figure 4.19 below. The values shown in this graph are that of a comparison between a base value for a service operated in mixed traffic, and a mixed traffic flow of 100 vehicles per hour.

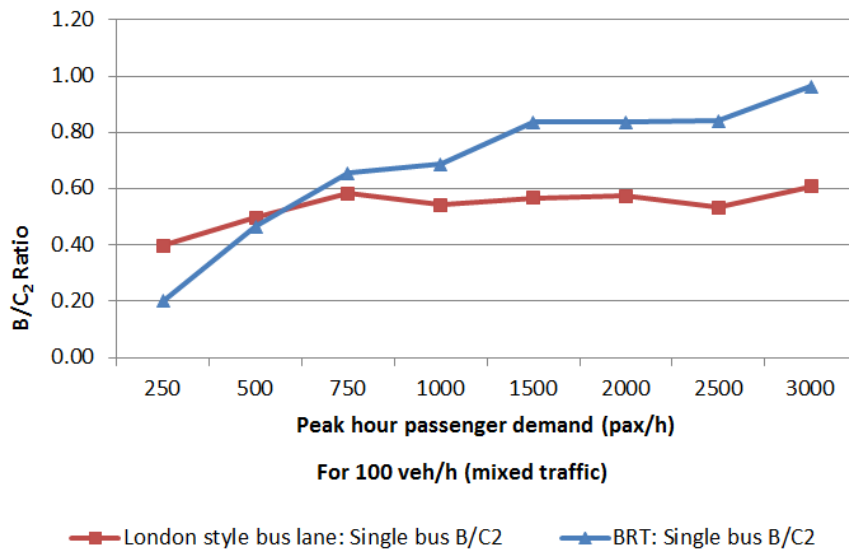


Figure 4.19: B/C<sub>2</sub> Ratio (incl. capital cost) for single buses – 100 veh/h mixed traffic

Other than what was presented on the B/C<sub>1</sub> graph, the B/C<sub>2</sub> ratio clearly shows a passenger demand range where the London style bus lane service has a better B/C<sub>2</sub> ratio than a BRT service. From the modelled data, for a base case operating in mixed traffic flow of 100 vehicles per hour, the critical passenger volume where a BRT service has a better B/C<sub>2</sub> ratio than for a London style bus lane service, is approximately 600 peak passengers per hour. Due to the additional costs involved, with the inclusion of infrastructure costs, the economic feasibility of a BRT service at low passenger demand is worse off than a London style bus lane service. Neither one of these two services, operating a single bus, has a benefit-cost ratio exceeding one.

For an increase of base case mixed lane traffic to 500 and 1 000 vehicles per hour, the intersection point where a BRT type service becomes more beneficial, moves to approximately 750 peak hour passengers for 500 mixed lane vehicles per hour. For 1 000 base case mixed lane vehicles per hour, the intersection point moves to 1 300 peak hour passengers. Figure 4.20 below shows the B/C<sub>2</sub> ratios for base case mixed traffic volumes of 500 and 1 000 vehicles per hour.

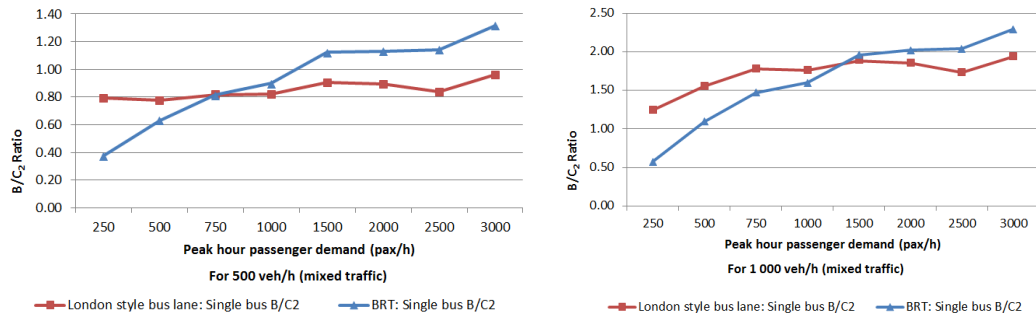


Figure 4.20: B/C<sub>2</sub> Ratio (incl. capital cost) for single buses – increased mixed traffic

A similar trend was observed were the benefit-cost ratio (B/C<sub>2</sub>) for a BRT service surpasses a London style bus lane service at a certain passenger volume. This was observed for the single bus, the articulated bus as well as the bi-articulated bus. From the data obtained during the modelling of the B/C<sub>2</sub> ratio, the majority of the services, operating in different levels of traffic congestion, exceeded the B/C<sub>1</sub> ratio of one, except for single buses. Table 4.4 below shows at which critical passenger volumes the BRT service surpasses the B/C<sub>2</sub> ratio for a London style bus lane service.

Table 4.4: Approximate B/C<sub>2</sub> critical passenger volume for BRT and London style services

	Mixed traffic flow: (veh/h/ln)		
	100	500	1 000
<b>Single bus:</b> Approximate critical passenger volume where the B/C <sub>2</sub> of BRT becomes better than for a London style bus lane service (peak pax/h)	600	750	1 300
<b>Articulated bus:</b> Approximate critical passenger volume where the B/C <sub>2</sub> of BRT becomes better than for a London style bus lane service (peak pax/h)	2 000	2 500	3 500
<b>Bi-articulated bus:</b> Approximate critical passenger volume where the B/C <sub>2</sub> of BRT becomes better than for a London style bus lane service (peak pax/h)	4 500	5 000	5 500

Unlike the  $B/C_1$  ratio where only operational costs form part of the economic evaluation, the  $B/C_2$  ratio includes the infrastructure costs. Due to the higher level of infrastructure provision for a BRT service, the economic feasibility of a BRT service at low passenger demand is worse off than for a London style bus lane service. This gap in the economic feasibility between a London style bus lane service and a BRT service is incrementally decreased until somewhere along the line of increased passenger demand, the BRT service becomes more beneficial.

Identical to the  $B/C_1$  comparison, the  $B/C_2$  ratios for the three types of buses, operating on a London style bus lane service, were compared to a base case scenario operating in mixed traffic with a flow of 100 vehicles per hour per lane. A very similar result is portrayed to that of the case with the  $B/C_1$  ratio comparison. The  $B/C_2$  ratio of a bi-articulated bus, operating on a London style bus lane service is shown to be better than any of the other two types of buses, as seen in figure 4.21 below. Single BRT buses operating on a London style bus lane service is shown to have the worst  $B/C_2$  ratio. Single buses are shown in red, with the articulated buses show in blue, whilst bi-articulated buses are shown in green.

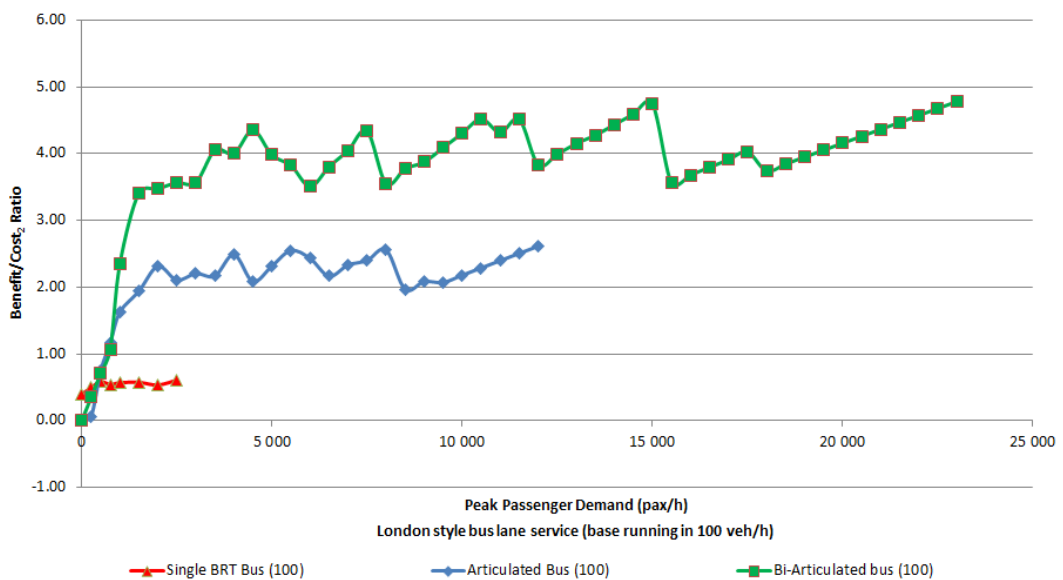
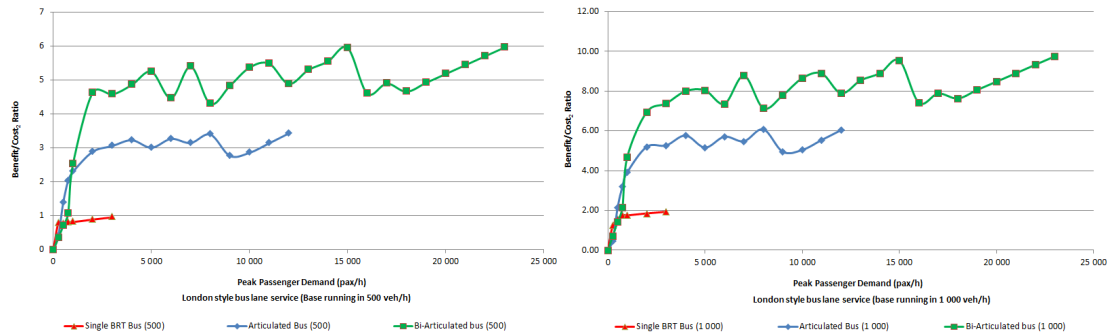


Figure 4.21:  $B/C_2$  Ratio (incl. capital cost) for London style bus lane services



For an increase in traffic volumes for the base case to 500 and 1 000 vehicles per hour, the same trend emerges. For buses operating on a London style bus lane service, bi-articulated buses is shown to have the greatest  $B/C_2$  ratio, followed by articulated buses with single BRT buses having the lowest  $B/C_2$  ratio of the three types of buses. Figure 4.22 below shows these results for increased base case traffic to 500 and 1 000 vehicles per hour.



**Figure 4.22:  $B/C_2$  Ratio for London style bus lane services – base service operating in 500 and 1 000 veh/h**

All three types of buses were also compared when modelled on a BRT type service. Although the  $B/C_2$  ratios differ from the London style service, similar trends can be observed. Bi-articulated buses still has the advantage with a better  $B/C_2$  ratio when compared to articulated and single BRT buses. Single BRT buses remains the least beneficial with the lowest  $B/C_2$  ratio when operated on a BRT service.

In comparing the  $B/C_2$  ratios for the three types of buses operating on all three types of bus services, a slightly different picture is presented than for the  $B/C_1$  comparison. In the previous section, similar  $B/C_1$  ratios were calculated for both an articulated bus operating in a BRT service and a bi-articulated bus operating in a London style bus lane service. Results obtained for the  $B/C_2$  ratio comparison (including capital expenditure) indicate that a bi-articulated bus operated on a London style bus lane service has a better  $B/C_2$  ratio than a BRT service using articulated buses. Figure 4.23 below shows the combined modelled results for the  $B/C_2$  comparison.

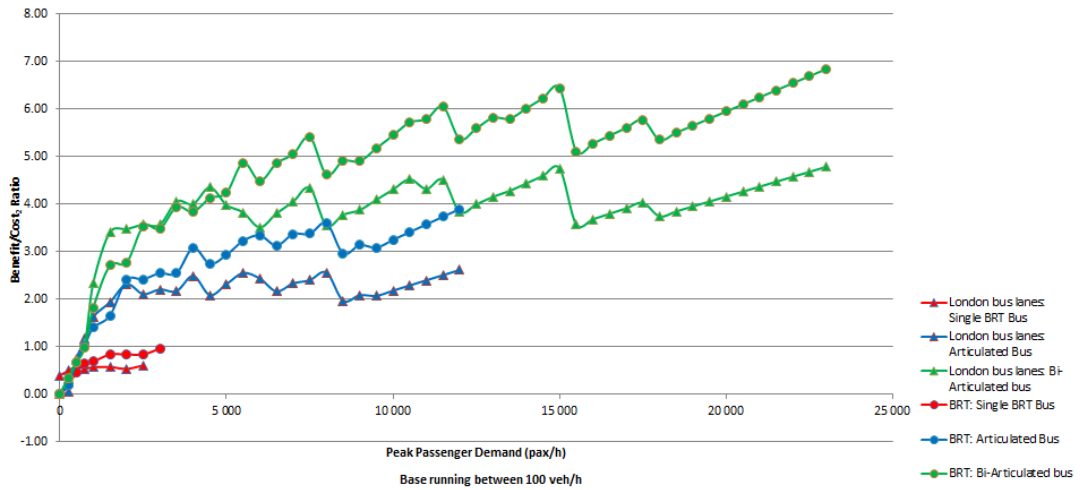


Figure 4.23: B/C<sub>2</sub> comparison

Using the same graph as shown in figure 4.23 above, when focussing on a passenger demand up to 5 000 peak hour passengers, the overall image once again changes. The data now shows that bi-articulated buses for both London style bus lane services, and BRT services has very similar B/C<sub>2</sub> ratios up to a peak hour passenger demand of 5 000 passengers, with the London style bus lane service showing a slight advantage. Although the B/C<sub>2</sub> ratio difference is greater, a similar trend can be seen for both articulated and single buses.

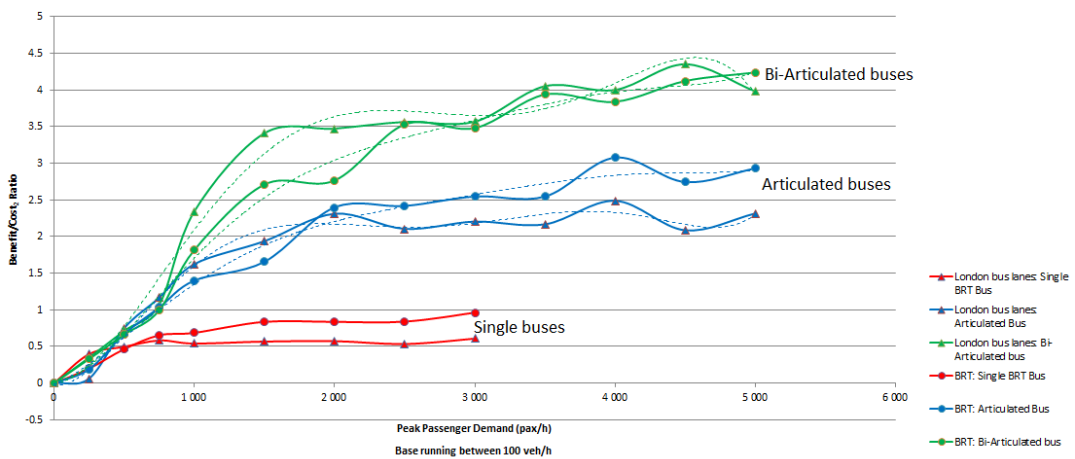


Figure 4.24: B/C<sub>2</sub> comparison (up to 5000 passengers per hour)

Should traffic on the base case increase to 500 and 1 000 vehicles per hour, the results shown in figure 4.25 below are produced by the model. It is observed from the data that these trends remain very similar with the increase in traffic.

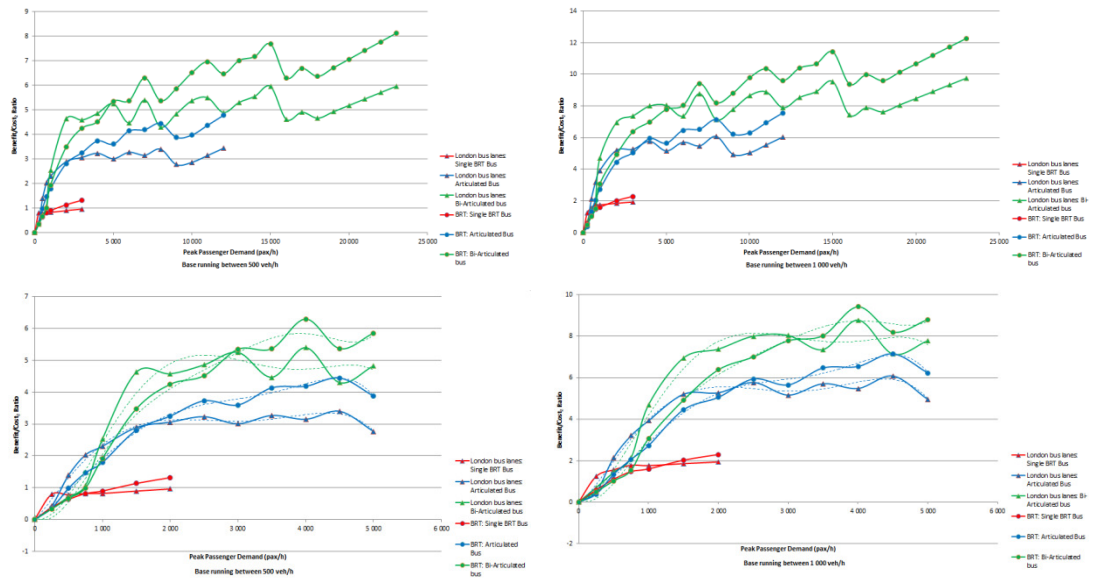


Figure 4.25: B/C<sub>2</sub> comparison (with increased base case traffic)

In summary, when including the implementation cost along with the operational cost of a service (B/C<sub>2</sub>), the data shows different trends than for the B/C<sub>1</sub> ratio. For a type of service, utilising the same size buses, the BRT service only becomes more feasible than the London style bus lane service at a specific passenger demand. Beyond that specific passenger demand, the BRT service remains the better option. As the size of the bus used increases, the critical passenger volume also increases. For an increase in traffic congestion, the same trend occurs, but with better B/C<sub>2</sub> values due to the increase in travel time of the base case.

As with the B/C<sub>1</sub> ratio, if different buses are used on different types of services, the B/C<sub>2</sub> ratios will vary. For example, when a lower level service, using a larger bus is compared to a higher level service, using a smaller bus. Unlike the B/C<sub>1</sub> ratio, where a bi-articulated bus being operated on a London style bus lane service had a very similar B/C<sub>1</sub> ratio to an articulated bus being operated on a BRT service, the B/C<sub>2</sub> ratio of the London bus lane type service now shows to be better than for the BRT. The only difference between the B/C<sub>1</sub> and B/C<sub>2</sub> values are the addition of infrastructure costs for the B/C<sub>2</sub> calculation. This

reduction in the ranking of the BRT service can therefore be accounted to the difference in the level of infrastructure costs when implementing a BRT service versus a London style bus lane service.

#### 4.7 B/C<sub>1</sub> and B/C<sub>2</sub> comparison

In the previous two sections the B/C<sub>1</sub> and B/C<sub>2</sub> ratios were calculated, individually compared and graphically presented. The sole difference between these two ratios is that the B/C<sub>2</sub> ratio includes infrastructure costs, whereas B/C<sub>1</sub> does not. In comparing the B/C<sub>1</sub> and B/C<sub>2</sub> ratios for a London style bus lane service, a very similar trend is shown for the same bus types. Bi-articulated buses, operating on a London style bus lane service, hold the best B/C<sub>1</sub> as well as B/C<sub>2</sub> ratios. As infrastructure expenditure on this type of service is not nearly as much as on BRT services, it makes sense that the B/C ratios would be very similar. Figure 4.26 below shows the B/C<sub>1</sub> and B/C<sub>2</sub> comparison of a London style bus lane service.

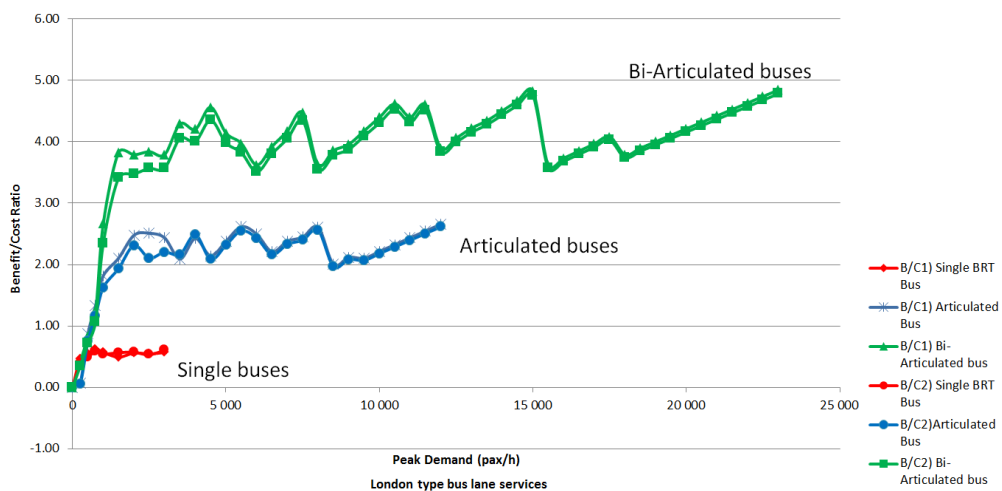


Figure 4.26: B/C<sub>1</sub> and B/C<sub>2</sub> comparison for London style bus services

In comparing the B/C<sub>1</sub> and B/C<sub>2</sub> ratios for the three types of buses operating on a BRT service, the data shows a different result. Due to the increased cost of infrastructure, compared to a London style bus lane service, the difference between the B/C<sub>1</sub> and B/C<sub>2</sub> ratios are greater, as can be seen in figure 4.27 below.

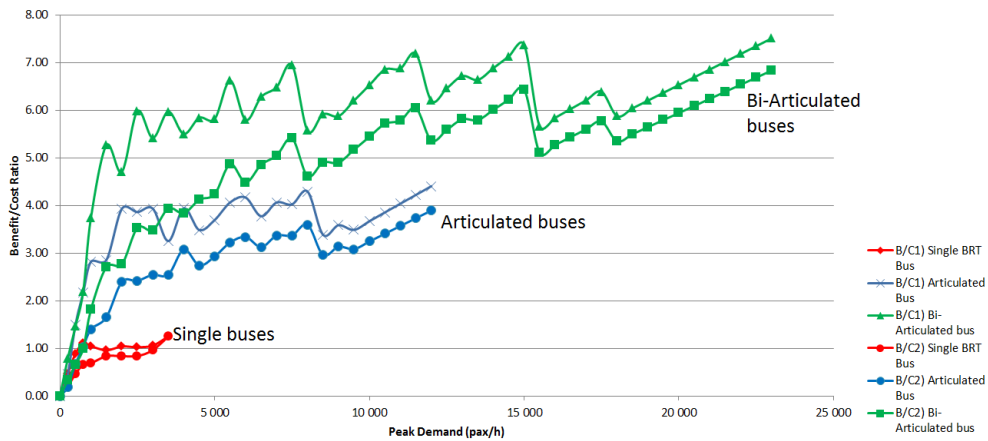


Figure 4.27: B/C<sub>1</sub> and B/C<sub>2</sub> comparison for BRT services

For the segment below 5 000 peak hour passengers, the B/C<sub>1</sub> for articulated buses has similar values than that of B/C<sub>2</sub> bi-articulated buses. In other words, for a BRT service with a peak hour passenger demand below 5 000, the operation of a bi-articulated bus (including infrastructure costs) has a similar Benefit-Cost ratio than for an articulated bus (excluding infrastructure costs), shown in figure 4.28 below.

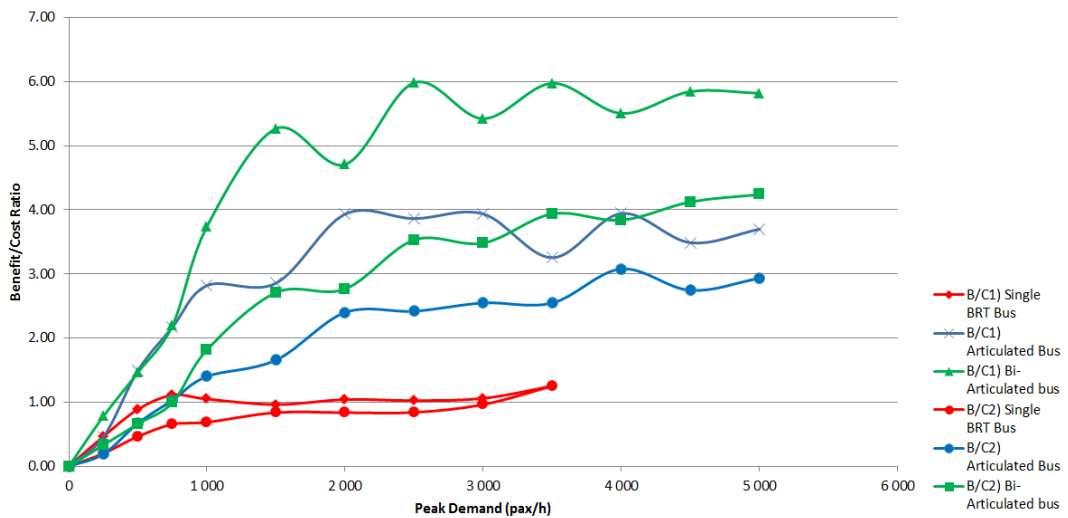


Figure 4.28: B/C<sub>1</sub> and B/C<sub>2</sub> comparison for BRT services (up to 5 000 peak hour passengers)

In summary, there is a visible difference between the benefit-cost ratios for each of the types of buses, when comparing them on a BRT type service, with the B/C<sub>2</sub> ratio being

lower than the  $B/C_1$  ratio. In comparing the same types of buses on a London style bus lane service, this difference is not so great.

#### 4.8 Hybrid

Following the results obtained from the model and graphically represented in the previous chapters, an alternative model was derived, referred to a hybrid model in this study.

The question arose as to what would be the influence on the  $B/C_1$  and  $B/C_2$  ratios, should the modelled London type bus lane service also receive traffic signal prioritisation, as it is modelled in the BRT option. Average delay due to encountering traffic signals is estimated to be around 1.2 minutes per mile (St. Jacques & Levinson, 1996). This value (minutes/km) was then removed from the model for the delay experienced by London type bus lane services. Table 3.15 refers to the capital expenditure items. With the hybrid service receiving traffic signal priority, the same as for the BRT service, the R3,6million per kilometre rate applies to the implementation of traffic signal priority for the hybrid service. The whole modelling process was repeated in order to obtain the  $B/C_1$  and  $B/C_2$  ratios for the alternative London type bus lane service model.

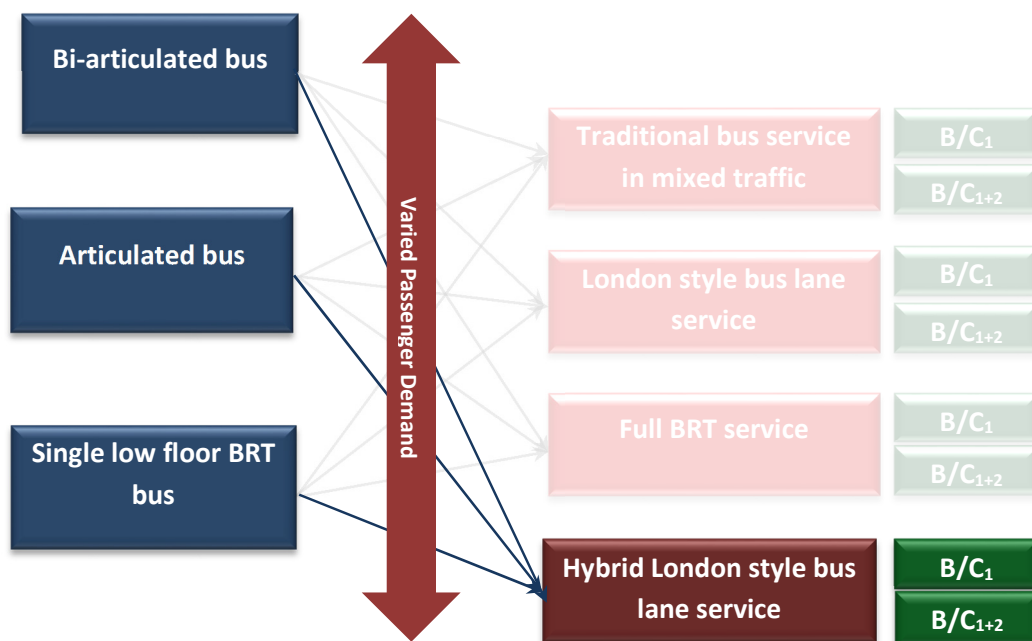


Figure 4.29: Hybrid service modelled

Data obtained from the hybrid London style bus lane service model, produced the graph shown in figure 4.30 below. The dotted opaque lines shown on figures 4.30 and 4.31 represent the original  $B/C_1$  data, obtained from the London style bus lane service. The thicker lines represent the hybrid London type bus lane model, with traffic signal prioritisation. Both the dotted lines as well as the thinner lines (original BRT values) are exactly the same as in the original model. One can now compare how the hybrid service will fare in comparison to the original London style bus lane service as well as the unchanged BRT service.

The data shows a very interesting development.  $B/C_1$  values for all three types of buses, operating on the hybrid service, have increased considerably from the original values. The increase of the hybrid London style bus lane service are so considerable that these  $B/C_1$  ratios are exceptionally close to the BRT service's  $B/C_1$  ratios.

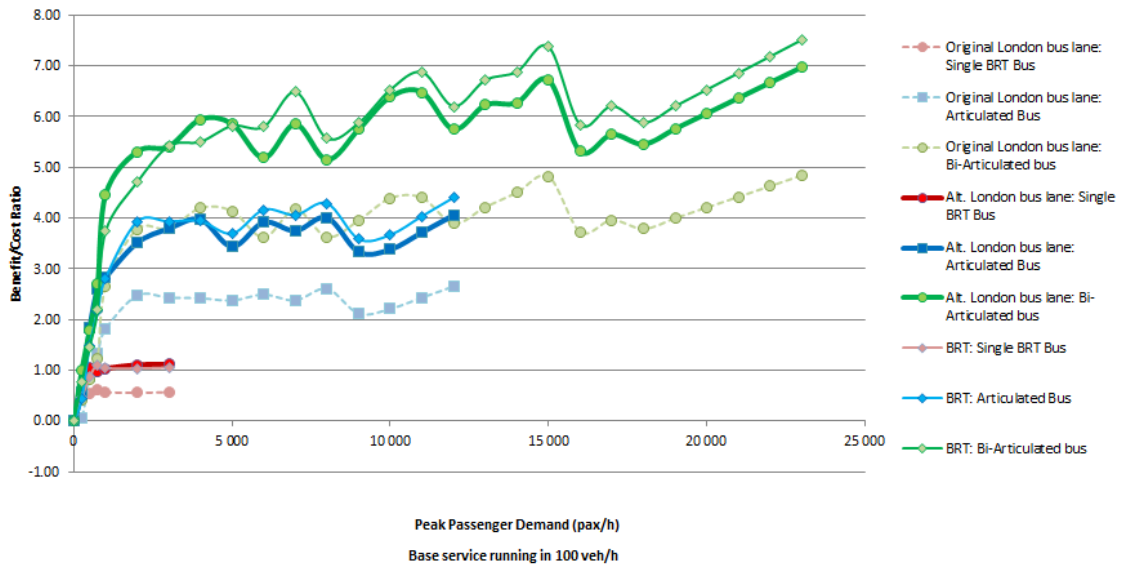


Figure 4.30:  $B/C_1$  hybrid London style bus lane service with traffic signal prioritisation

For a closer look at what happens to the  $B/C_1$  ratios at lower passenger volumes, figure 4.31 below shows an increased scale version for a peak passenger demand of up to 5 000

passengers per hour. One can observe from the data obtained how similar the B/C<sub>1</sub> ratios are for the hybrid service and the BRT services, using the same size buses.

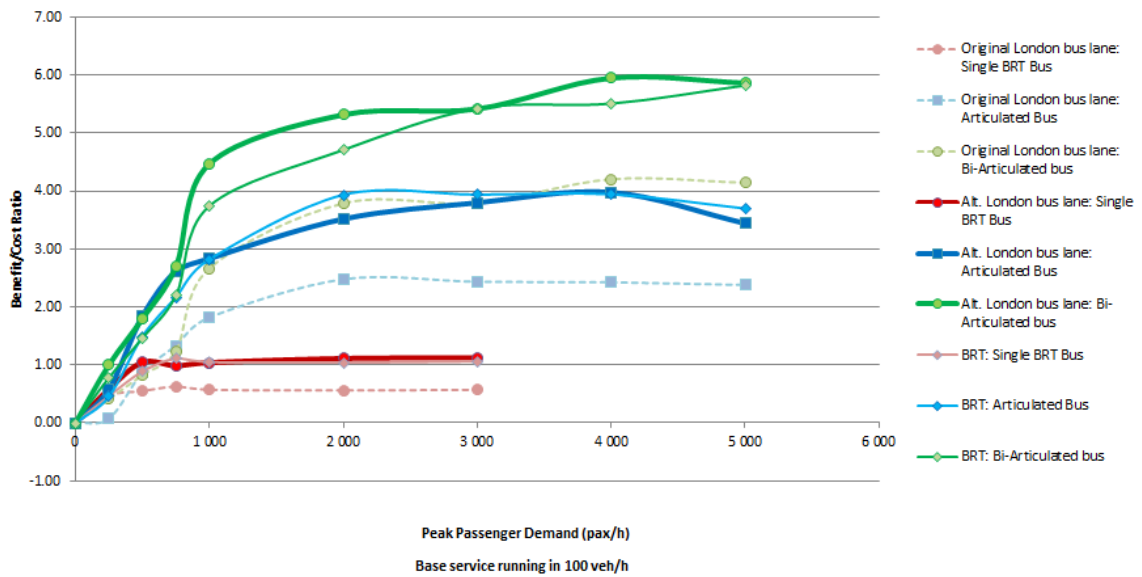


Figure 4.31: B/C<sub>1</sub> hybrid London style bus lane service with traffic signal prioritisation (up to 5 000 pax/h)

Should traffic on the base case increase, to 500 and 1 000 vehicles per hour, similar results are shown as in the graph showing 100 vehicles per hour. These results can be seen in figure 4.32 below.

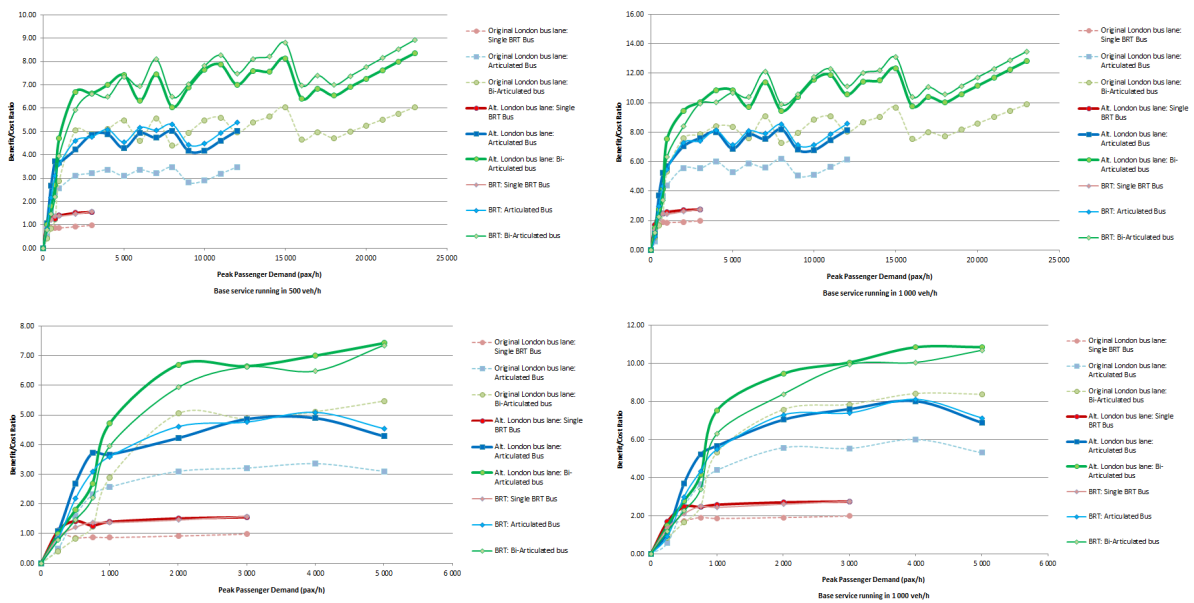


Figure 4.32: B/C<sub>1</sub> hybrid London style service with traffic signal prioritisation – increased base traffic



For the hybrid service comparison of the  $B/C_2$  ratio, even better results for the hybrid London style bus lane service are achieved, as can be seen in the graphs below. The data shows that should the London type bus lane service receive traffic signal prioritisation, the  $B/C_2$  ratios mostly shows values above that of the BRT service, seen in figures 4.33 and 4.34 below.

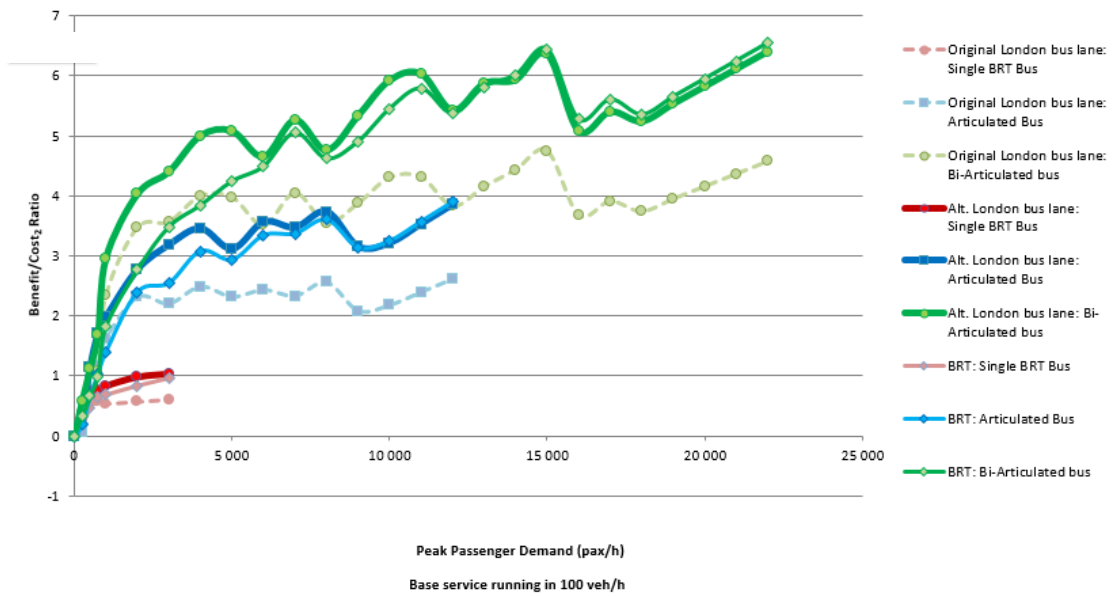


Figure 4.33:  $B/C_2$  hybrid London style bus lane service with traffic signal prioritisation

When focussing on the peak hour passenger demand below 5 000 passengers per hour, the hybrid service, operating a bi-articulated bus has a much better  $B/C_2$  ratio than that of the BRT service also operating a bi-articulated bus. The interesting observation however, is that an articulated bus, operated on the hybrid London style bus lane service has a better  $B/C_2$  ratio than that of a bi-articulated bus operated on a BRT service, up to approximately 3 500 peak passengers per hour.

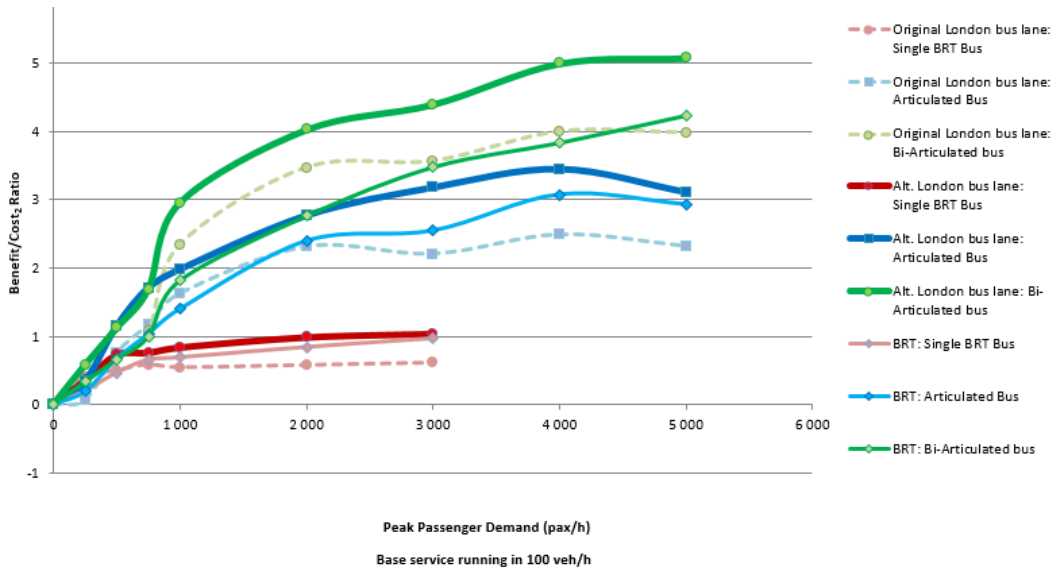
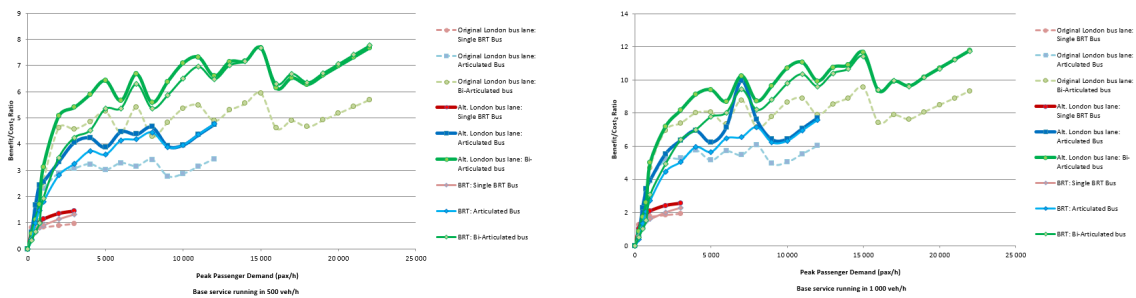
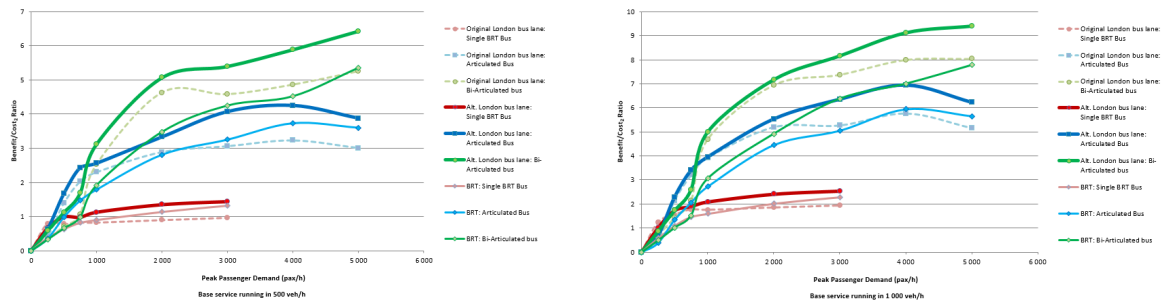


Figure 4.34: B/C<sub>2</sub> Hybrid London style bus lane service with traffic signal prioritisation (up to 5 000 pax/h)

Should traffic on the base case increase, to 500 and 1 000 vehicles per hour, similar results are shown. The critical passenger volume where the an articulated bus, operated on the hybrid London style bus lane service, has a better B/C<sub>2</sub> ratio than that of a bi-articulated bus operated on a BRT service, is moved on up to approximately 4 100 passengers per hour for a base service running in mixed traffic of 500 vehicles per hour, and 4 500 passengers per hour for a base case running in mixed traffic of 1 000 vehicles per hour. These results can be seen in figure 4.35 below.





**Figure 4.35: B/C<sub>2</sub> Hybrid London style bus lane service with traffic signal prioritisation – increased base traffic**

In summary, the hybrid service has a very similar B/C<sub>1</sub> ratio when compared to the BRT service, using the same buses. For the benefit-cost calculation, including infrastructure costs (B/C<sub>2</sub>), the hybrid service however outperforms the BRT service to such an extent that the BRT service operating a larger bus than the hybrid service only has a better B/C<sub>2</sub> past a certain critical peak hour passenger volume.

#### 4.8 Sensitivity testing

A sensitivity analysis was done in order to test the robustness of the model, as well as to understand the relationship between the variables. Two critical aspects of this model were chosen to do a sensitivity analysis on. These were the operational costs as well as the capital costs. With the addition of the hybrid model, some aspect of sensitivity testing was already done with the alteration of traffic signal delay and the impact thereof. The following alterations to the model will be made for the sensitivity analysis:

- Reduce the operational costs by 10%, everything else remains the same.
- Increase the operational costs by 10%, everything else remains the same.
- Reduce the capital costs by 10%, everything else remains the same.
- Increase the capital costs by 10%, everything else remains the same.

##### 4.8.1 Reduce operational costs by 10 percent

In theory, if the operational costs should be decreased, the benefit-cost ratio should increase (equation 3.3). No other values were altered for this analysis. For this sensitivity analysis, the operational costs were decreased by 10 percent to see

what the impact on both the  $B/C_1$  and  $B/C_2$  ratios would be. Figure 4.36 below shows how both the  $B/C$  ratios increased parallel to that of the original values.

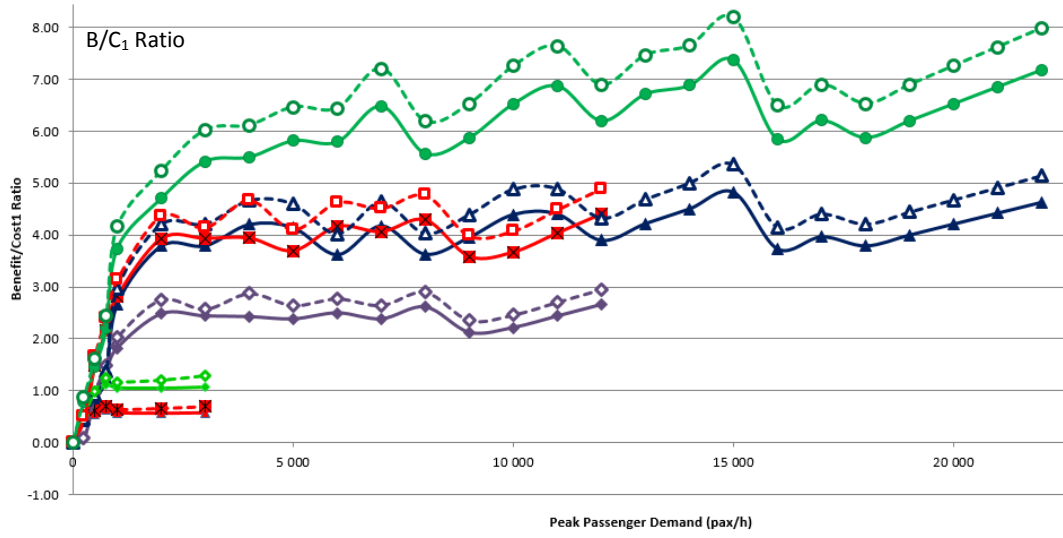


Figure 4.36: Operational costs reduced by ten percent

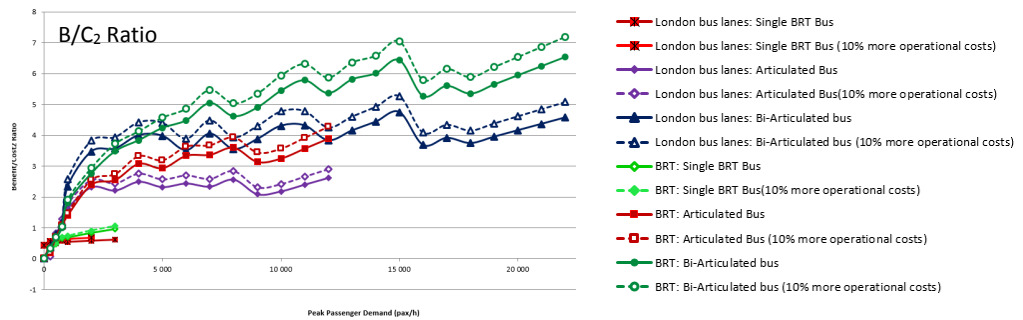


Figure 4.36 (continued): Operational costs reduced by ten percent

#### 4.8.2 Increase operational costs by 10 percent

Opposite to the values observed in the preceding chapter, if the operational costs should be increased, in theory the benefit-cost ratio should decrease (equation 3.4). As with the preceding sensitivity analysis, no other information were altered for this analysis. For this sensitivity analysis the operational costs were therefore reduced by 10 percent to see what the impact on both the  $B/C_1$  and  $B/C_2$  ratios would be. Figure 4.37 below shows how both the  $B/C$  ratios decreased parallel to that of the original values.

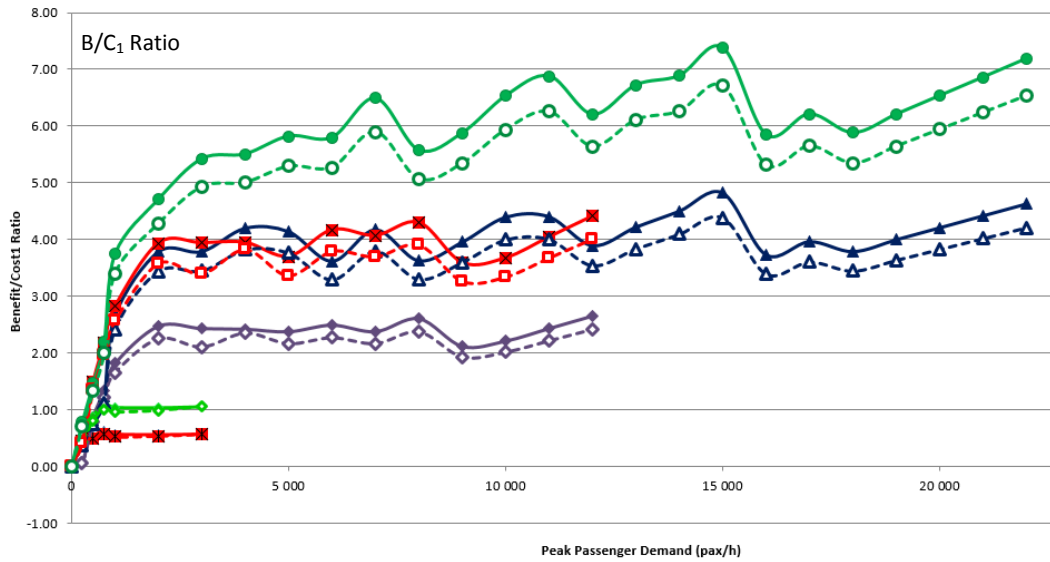


Figure 4.37: Operational costs increased by ten percent

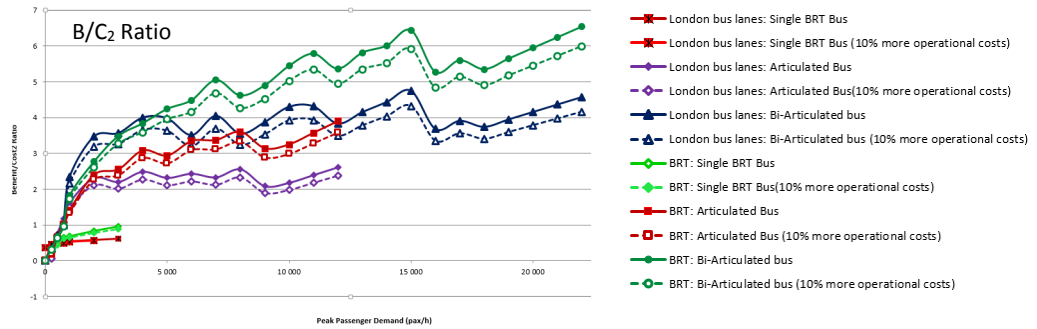


Figure 4.37 (continued): Operational costs increased by ten percent

### 4.8.3 Reduce/Increase capital costs by 10 percent

Similar to the operation cost reduction, the only values that were altered in this section was that of the reduction and increase of capital costs by 10 percent. Figure 4.38 shows a reduction in the  $B/C_2$  ratio with an increase in capital expenditure. Figure 4.39 on the other hand shows an increase in the  $B/C_2$  ratio for an increase in capital costs. The increase/decrease for the London style bus lane service is less than for the BRT service due to the more expensive BRT infrastructure costs.

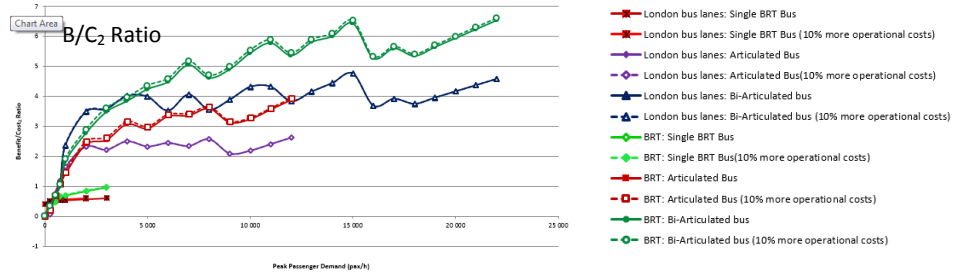


Figure 4.38: Capital costs reduced by ten percent

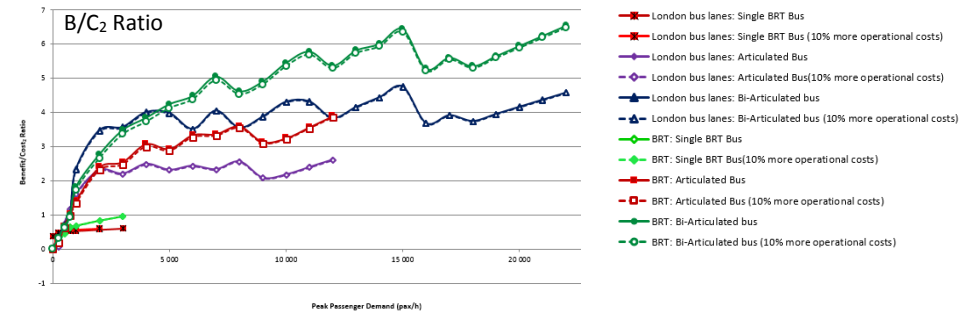


Figure 4.39: Capital costs increased by ten percent

#### 4.9 Summary

Various different scenarios were run, analysed and reported on in this study. The following scenarios will be summarised in this section:

- Benefit-cost ratio 1 (excluding infrastructure cost)
- Benefit-cost ratio 2 (including infrastructure cost)
- Benefit-cost ratio 1 comparison with benefit-cost ratio 2
- Hybrid model
- Sensitivity testing

##### 4.9.1 Benefit-Cost Ratio 1 (B/C<sub>1</sub>)

Comparing the B/C<sub>1</sub> ratios (excluding capital costs), the following observations were made:

- When comparing the different size buses, operating on the same type of service, the bi-articulated bus has the best benefit-cost ratio, with an articulated bus second, with a single bus having the lowest benefit-cost ratio.
- When comparing the different type of services, the BRT service has the best benefit-cost ratio, with a London style bus lane service second and a traditional mixed lane service having the worst benefit-cost ratio.
- Interestingly, the BRT service, operating an articulated bus, has a very similar benefit-coat ratio than for the London style bus lane service operating a bi-articulated bus.
- The BRT service, operating a bi-articulated bus has the greatest benefit-cost ratio of all the options.
- An increase in mixed traffic volume, for all the options, increases the benefit-cost ratio. The trends mentioned above remains with an increase in traffic.

#### 4.9.2 Benefit-Cost Ratio 2 (B/C<sub>2</sub>)

Comparing the B/C<sub>2</sub> ratios (including capital costs), the following observations were made:

- As with the B/C<sub>1</sub> ratio, when comparing the different size buses, operating on the same type of service, the bi-articulated bus has the best benefit-cost ratio, with an articulated bus second, with a single bus having the lowest benefit-cost ratio.
- Unlike the B/C<sub>1</sub> ratio, when comparing the different type of services, the BRT service only becomes more beneficial than the London style bus lane service at a certain passenger demand. The traditional mixed lane service still has the worst benefit-cost ratio
- A London style bus lane service, operating a bi-articulated bus service has a better benefit-cost ratio than for a BRT service operating an articulated bus.
- The BRT service, operating a bi-articulated bus has the greatest benefit-cost ratio of all the options.
- As with the B/C<sub>1</sub> ratio, an increase in mixed traffic volume, for all the options, increases the benefit-cost ratio. The trends mentioned above remains with an increase in traffic.

#### 4.9.3 Comparing the Benefit-Cost Ratio 1 ( $B/C_1$ ) and Benefit-Cost Ratio 2 ( $B/C_2$ )

Comparing the two B/C ratios with each other, the following observations were made:

- When comparing the different size buses operating on a London style bus lane service, both the benefit-cost ratios shows to be very similar, with the  $B/C_1$  ratio being slightly better. The bi-articulated bus still remains the option with the best benefit-cost ratio, with an articulated bus second, with a single bus having the lowest benefit-cost ratio.
- When comparing the different size buses operating on a BRT service, a notable reduction in the  $B/C_2$  ratio is observed, with the  $B/C_1$  ratio showing much higher values than for the  $B/C_2$  ratio. The bi-articulated bus still remains the option with the best benefit-cost ratio, with an articulated bus second, with a single bus having the lowest benefit-cost ratio.
- An interesting observation is that the  $B/C_1$  ratio for an articulated bus has a very similar ratio than the  $B/C_2$  ratio for a bi-articulated bus, up to a passenger demand of approximately 5 000 peak passengers per hour. In other words, an articulated bus, operating on a BRT system that only takes into consideration operational costs has a similar benefit-cost ratio than that of a bi-articulated bus, also operating on a BRT system, but taking into consideration the operational as well as the infrastructure costs.

#### 4.9.4 Hybrid service

During the analysis of the two B/C ratios for the hybrid service, the following observations were made:

- $B/C_1$ : When comparing the different size buses operating on the hybrid London style bus lane service, both the  $B/C_1$  ratio for the hybrid service shows a notable increase, compared to the original London style bus lane service.
- $B/C_1$ : This increase is to such an extent that the same size bus operating on a BRT as well as the hybrid service now has almost the same benefit-cost ratios, with the BRT service slightly better. In other words, an articulated bus,



operating on the hybrid service, now shows a benefit-cost ratio only slightly lower than for an articulated bus operating on a BRT service. This trend is similar to the other two size buses.

- $B/C_2$ : When comparing the different size buses operating on the hybrid London style bus lane service, both the  $B/C_2$  ratio for the hybrid service shows a notable increase, compared to the original London style bus lane service. This increase is larger than for the  $B/C_1$  ratio.
- $B/C_2$ : This increase is to such an extent that the size bus operating on the hybrid service has a better benefit-cost ratio than the BRT service, operating the same size bus. In other words, an articulated bus, operating on the hybrid service, now shows a benefit-cost ratio higher than for an articulated bus operating on a BRT service. This trend is similar to the other two size buses.
- For an increase in mixed traffic volume, the benefit-cost ratios also increase, but the trends remain the same.

#### 4.9.5 Sensitivity testing

A sensitivity test was done in order to test the robustness of the model as well as to understand the relationship between some of the variables. During this testing, the following observations were made:

- Reduction of operational costs: With a reduction in operational costs, both the benefit-cost ratios ( $B/C_1$  and  $B/C_2$ ) are increased, parallel to the original values.
- Increase of operational costs: With an increase in operational costs, both the benefit-cost ratios ( $B/C_1$  and  $B/C_2$ ) are decreased, parallel to the original values.
- Reduction of capital costs: With a reduction in capital expenditure, the benefit-cost ratio ( $B/C_2$ ) is increased, parallel to the original values.
- Increase of capital costs: With an increase in capital expenditure, the benefit-cost ratio ( $B/C_2$ ) is decreased, parallel to the original values.

## 5. CONCLUSIONS AND RECOMMENDATIONS

### 5.1 Introduction

Bus based public transport lines come in different forms and shapes. These services vary from standard single high floor buses, travelling in mixed traffic, to bi-articulated buses travelling on a comprehensive bus rapid public transport system (e.g. Bogota's TransMilenio).

The implementation of BRT systems has become quite popular with transportation planners and authorities in recent years, with South African transportation decision makers currently sharing this popular view. So much so, that all the major cities in South Africa are currently either planning, implementing or operating a BRT system.

The question therefore comes to mind, is a full BRT system always the best option, even for the smaller cities? Some are of the opinion that small incremental improvements tend to have greater cost-benefit ratios than large scale infrastructure projects (Eddington, 2006) and (Niles & Jerram, 2010).

### 5.2 Conclusions

#### Objective 1

The first objective of this study was to develop a model from which various scenarios and hybrids could be modelled. Such a model was created for this study to explore the relationship between three types of buses and three different levels of bus service provision. The three types of buses modelled for this study include single low floor BRT buses, articulated BRT buses and bi-articulated buses, with the different levels of bus services consisting of a traditional mixed lane bus service, a London style bus lane service and a full BRT service.

Factors forming part of the model includes, peak and off-peak traffic, peak and off-peak passenger demand, modelling variables, delay, line scheduling travel time savings, monetised benefits, operational and capital costs and economic evaluations. General output

of the model such as headways, average speed etc. compares well with existing systems around the world.

### **Objective 2**

The second objective of this study was to compare the different buses and services by means of an economic analysis, excluding infrastructure costs. This economic analysis is referred to the  $B/C_1$  ratio in the study. When modelling a single BRT bus, articulated bus and bi-articulated bus on a London style bus lane service, the best  $B/C_1$  ratio is achieved by the bi-articulated bus, with the single bus having the lowest ratio. With an increase in traffic, the trends remain the same as described above, although the  $B/C_1$  values increase for all three types of buses due to the additional delay experienced by the base case mixed lane bus service.

When modelling the same three types of buses on a BRT service, similar results are obtained. The best  $B/C_1$  ratio is achieved by the bi-articulated bus, followed by an articulated bus with a single bus having the lowest  $B/C_1$  ratio.

Comparing the  $B/C_1$  values for a London style bus lane service and a BRT service, the data shows that a bi-articulated bus operating on a BRT service has the best  $B/C_1$  ratio. Similar  $B/C_1$  ratios were obtained for a bi-articulated bus operating on a London style bus lane service and an articulated bus operating on a BRT service. Single buses have the worst  $B/C_1$  ratios for both a London style bus lane service as well as a BRT service.

### **Objective 3**

The third objective of this study was to compare the different buses and services by means of an economic analysis, including infrastructure costs. This economic analysis is referred to in this study as the  $B/C_2$  ratio. When modelling a single BRT bus, articulated bus and bi-articulated bus on both a London style bus lane service and a BRT service, similar observations were made to the  $B/C_1$  analysis. The data shows the best  $B/C_2$  ratio is achieved by the bi-articulated bus, followed by the articulated bus with the single bus having the lowest ratio. With an increase in traffic, although the  $B/C_2$  values increase due to the additional delay experienced by the base case mixed lane bus service, the general trend remains the same.

In comparing  $B/C_2$  ratios of the London style bus lane service with a BRT service, the bi-articulated bus operated on a BRT service remains the service with the best  $B/C_2$  ratio. Single buses utilised for both London style bus lane services as well as BRT services retains the lowest  $B/C_2$  ratios. Unlike the  $B/C_1$  ratios where an articulated bus operated on a BRT service had a very similar  $B/C_1$  ratio than that of a bi-articulated bus operated on a London style bus lane service, the  $B/C_2$  ratio now shows that the bi-articulated bus operated on a London style bus lane service has a better  $B/C_2$  ratio than that of an articulated bus operated on a BRT service. With an increase in traffic, this trend remains.

#### **Objective 4**

A fourth objective of this study was to compare the  $B/C_1$  and  $B/C_2$  ratios, developed in the previous two objectives. For a London style bus lane service, the difference between the  $B/C_1$  and  $B/C_2$  ratios are very small for the same bus types. For both the compared  $B/C_1$  and  $B/C_2$  ratios, bi-articulated buses has the greatest benefit-cost ratio, followed by an articulated bus with a single bus having the worst benefit-cost ratio.

Comparing the  $B/C_1$  and  $B/C_2$  ratios for the three types of buses operating on a BRT service, a different result is obtained than with the London style bus lane service.  $B/C_1$  ratios remain constantly higher than the  $B/C_2$  ratios. This is due to the addition of capital expenditure to the benefit-cost equation. Interestingly, for a BRT service with a passenger demand below 5 000, the  $B/C_1$  ratio for an articulated bus is very similar to the  $B/C_2$  ratio of bi-articulated bus.

#### **Hybrid model**

During the development of the model, a hybrid model was also developed by giving the London style bus lane service traffic signal priority. In the initial models only the BRT service received traffic signal priority.

Data obtained from the  $B/C_1$  comparison for this hybrid London style bus lane service shows a significant upward shift of the benefit-cost ratios for the hybrid service. So much so that the  $B/C_1$  ratios for the hybrid service comes very close to the  $B/C_1$  values of a BRT service utilising the same type of bus.

The B/C<sub>2</sub> hybrid model comparison shows an even better picture for the hybrid London style bus lane service. B/C<sub>2</sub> ratios for the hybrid service are shown to be greater than the B/C<sub>2</sub> ratios for BRT services utilising the same type of bus.

### 5.3 Areas for further research

In compiling this study, it became apparent that further research is required in some areas. Some of the proposed areas for future research includes, but is not limited to:

- With the length of the single line fixed at 10km long, it would be interesting to note what the effects would be on altered lengths of single public transport routes.
- As this study only concentrated on a single public transport line, the question then arise: What are the effects on a public transport network level?
- Table 2.8 (TRB, 2003) shows the delay experienced when passengers are boarding and alighting a bus, taken into consideration various payment methods. It would be beneficial to validate this data in a South African context.
- Table 2.6 (St. Jacques & Levinson, 1997) shows the delay caused by certain components. One of these components is the delay due to traffic signals. Further research is required in order to see how relevant these figures are to South African conditions.

### 5.4 Recommendations

It is recommended that transportation authorities and planners should seriously consider an incrementally phased approach when looking to implement a BRT system. This study proved that similar or even better benefit-cost ratios can be obtained from transportation systems that do not require as much capital expenditure as BRT systems.

Should transportation authorities and planners not consider alternatives to the implementation of a BRT system, the optimum application of finite funds will most probably not be achieved.

If limited funding is available, an incremental approach would prove to be the prudent approach. Some BRT like items, such as length of bus stops, fare collection method and

traffic signal priority has a great influence on the travel time of a bus based public transport system. As the physical segregation of the bus lane by means of infrastructure is quite a costly process, other items should first be evaluated and considered in order to see at what level of expenditure the system will prove to be beneficial.

BRT is a very effective and efficient alternative to light rail for the transportation of large volumes of passengers. South African passenger volumes tend to be much lower than for BRT corridors operating in other countries. The incremental implementation of the BRT like aspects, that proves to be the most beneficial for a certain type of project, would make sense. This will enable the implementing and operating authorities to mitigate the risk of slow or no passenger growth. If the project is implemented at a much lower cost than what a full BRT would cost, assuming the corridor has an acceptable travel time, and if passenger growth shows little or no growth, no funds were wasted in the implementation of the system. With the implementation of a full BRT system, and with little or no passenger growth from a low base such as in South African cities, the effective application of funding has not been executed.

For traffic volumes that necessitate the use of a segregated bus lane, figure 5.1 below shows what the optimal investment strategy would be, taking into consideration passenger demand, service type and vehicle selection, but excluding capital expenditure.

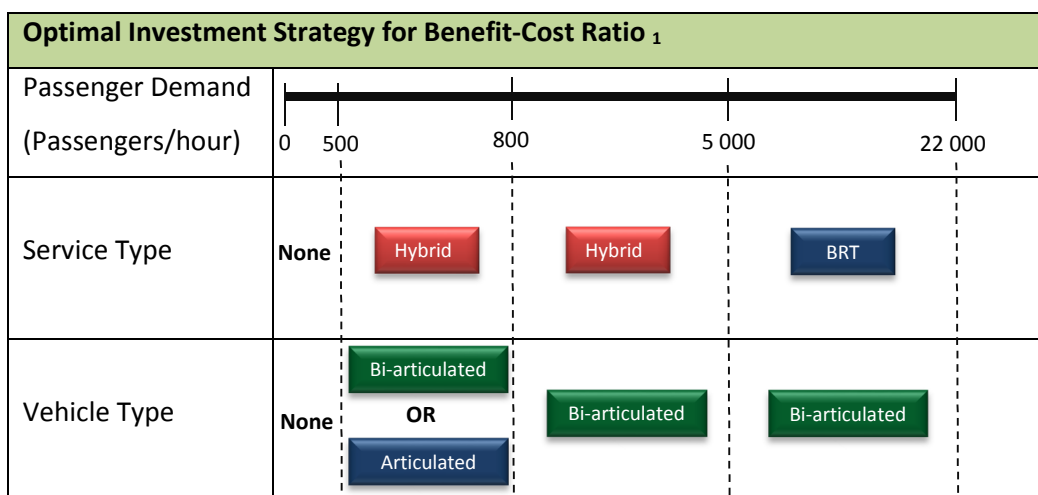


Figure 5.1: Optimal investment strategy, based on a B/C<sub>1</sub> ratio

A number of services'  $B/C_1$  ratios exceed one, between 500 and 800 passengers per hour, as shown in figure 5.1. The two services offering the highest  $B/C_1$  ratios for this passenger demand range, are for the hybrid services, operating with articulated or bi-articulated buses. From approximately 800 passengers per hour, the bi-articulated bus, operated on the hybrid service exceeds the  $B/C_1$  ratio of the articulated bus, also operating on the hybrid service. The hybrid service, operating a bi-articulated bus, has the greatest  $B/C_1$  ratio for a passenger demand of up to approximately 5 000 passengers per hour. For a passenger demand beyond 5 000 passengers per hour, the BRT service, operating a bi-articulated bus has the highest  $B/C_1$  ratio. This indicates that this service would be the most beneficial for a passenger demand exceeding 5 000 passengers per hour, when capital costs are excluded.

Should the infrastructure costs for the system be included ( $B/C_2$  ratio), the optimal investment strategy looks slightly different, as shown in figure 5.2 below.

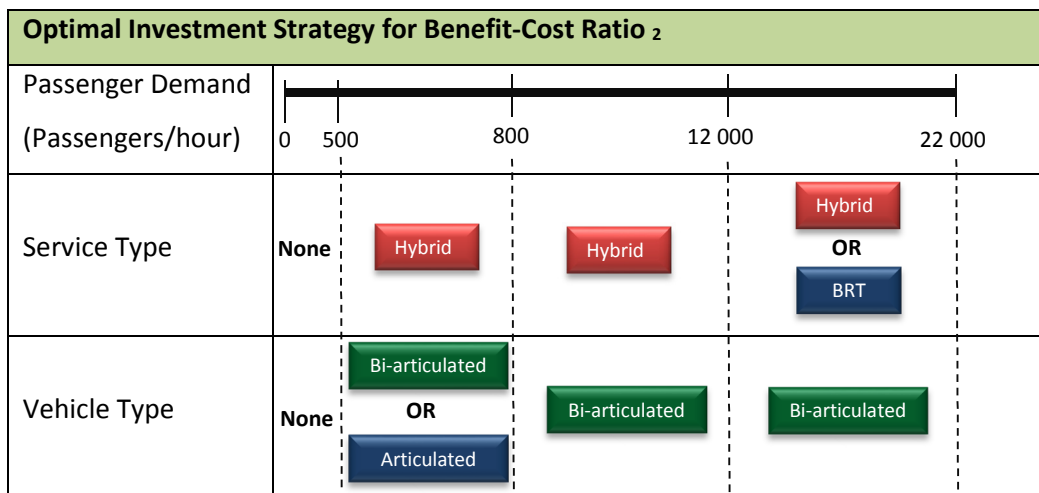


Figure 5.2: Optimal investment strategy, based on a  $B/C_2$  ratio

Should the infrastructure costs for the system be included, the two services offering the highest  $B/C_2$  ratios are for the hybrid services, operating with articulated or bi-articulated buses. From approximately 800 passengers per hour, the bi-articulated bus, operated on the hybrid service exceeds the  $B/C_2$  ratio of the articulated bus, also operating on the hybrid service. The hybrid service, operating a bi-articulated bus, has the greatest  $B/C_2$  ratio for a passenger demand of up to approximately 12 000 passengers per hour. For a passenger

demand beyond 12 000 passengers per hour, the BRT and hybrid services, both operating a bi-articulated bus has a very similar  $B/C_2$  ratio, indicating that any one of the two options could be equally beneficial.



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