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FACULTY OF ENGINEERING AND THE ENVIRONMENT

A Comparative Assessment for Innovative Public Transport Technologies

by

Xucheng Li

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ABSTRACT

FACULTY OF ENGINEERING AND THE ENVIRONMENT

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A Comparative Assessment for Innovative Public Transport Technologies

Xucheng Li

Increasing urbanization around the world has raised the passenger demand for public transport. Although travelling by private vehicles dominates market share in most cities and car ownership has increased dramatically, public transport is still an important and cost-effective option, especially in large cities. As a result of that, many public transport technologies, including conventional bus services and innovative public transport technologies, are available to meet this demand.

Due to the land use and financial constraints of public transport development in large cities, transport planners and decision makers need to think twice before choosing the most cost-effective public transport mode for the local transport network. Therefore it is necessary to have a comprehensive assessment to evaluate the performance of different public transport technologies, both from the operator's and society's point of view.

This thesis demonstrates the development of the comparative assessment for comparing the performance of various public transport technologies based on their characteristics and the condition of local transport network. The comparative assessment is made up of three models: Spreadsheet Cost Model, Demand Supply Model and Microscopic Simulation Model. The Spreadsheet Cost Model is constructed in Microsoft Excel and calculates the social and operator cost of public transport systems in strategy level. The Demand Supply Model evaluates the relationship between services supplied from the operator and the passenger demand level by using the demand elasticity with respect to generalised passenger journey time. The Microscopic Simulation Model determines the level of service of the public transport system on the local network by using a microscopic simulation model in VISSIM, which has been created, calibrated and validated based on the data collected from the main corridor of Nanning, China. The three models were integrated in the comparative assessment which is then able to quantify the performance differences between public transport technologies operating on local transport network.

The comparative assessment was applied to compare the existing conventional bus service with a conceptually innovative public transport technology, Straddle Bus, on the main corridor (Minzu Avenue) in Nanning, China, in terms of social and operator cost, level of service and forecasted endogenous passenger demand level. The result shows that implementation of Straddle bus in Nanning is able to meet the public transport passenger demand that is increasing rapidly in the city. Detailed interpretations of the comparative assessment results have been given, as well as the suggestions for transport planners and decision makers in Nanning city, as an example of the usefulness of the comparative assessment.

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DECLARATION OF AUTHORSHIP

I, Xucheng Li

declare that this thesis and the work presented in it are my own and has been generated by me as the result of my own original research.

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I confirm that:

1. This work was done wholly or mainly while in candidature for a research degree at this University;
2. Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
3. Where I have consulted the published work of others, this is always clearly attributed;
4. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
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Signed:

Date:

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ABBREVIATION

AEC	Average External Cost
API	Application Programming Interface
AOC	Average Operator Cost
ASC	Average Social Cost
ATOC	Association of Train Operating Companies
AUC	Average User Cost
AVL	Automatic Vehicle Location
BART	Bay Area Rapid Transit
BRT	Bus Rapid Transit
CBD	Central Business District
CIPFA	Chartered Institute of Public Finance and Accountancy
CRF	Capital Recovery Factor
DfT	Department for Transport
DLR	Docklands Light Railway
DSM	Demand Supply Model
DRACULA	Dynamic Route Assignment Combining User Learning and microsimulation
DRT	Demand Responsive Transport
ENCTS	English National Concessionary Travel Scheme
FLOWSIM	Fuzzy Logic based Motorway Simulation

GLT	Guided Light Transit
HGV	Heavy Good Vehicles
HR	Heavy Rail
ITS	Intelligent Transportation Systems
IVT	In-Vehicle Time
K-S test	Kolmogorov-Smirnov test
LTDS	London Travel Demand Survey
LR	Light Rail
LRV	Light Rail Vehicle
MSC	Mode Specific Constant
MSM	Microscopic Simulation Model
NCTAR2010	Nanning Comprehensive Transport Annual Report – 2010
NPV	Net Present Value
O-D	Origin – Destination
OECD	Organisation for Economic Co-operation and Development
PARAMICS	PARAllel MICroscopic Simulation
PDFH	Passenger Demand Forecasting Handbook
PPP	Purchasing Power Parity
PRT	Personal Rapid Transit
PT	Public Transport
RMSE	Root-Mean-Square Error

RPI	Retail Price Index
SACTRA	Standing Advisory Committee on Trunk Road Appraisal
SCM	Spreadsheet Cost Model
SCOOT	Split Cycle Offset Optimisation Technique
SIMBOL	SImulation Model for Bus priority at traffic signals
SMARTEST	Simulation Modelling Applied to Road Transport European Scheme Tests
TC	Total Cost
TEST	Tools for Evaluating Strategically Integrated Public Transport
TEC	Total External Cost
TfL	Transport for London
TOC	Total Operator Cost
TSC	Total Social Cost
TSGB	Transport Statistics Great Britain
TSS	Transport Simulation Systems
TRB	Transportation Research Board
TUC	Total User Cost
ULTra	Urban Light Transit
VB	Visual Basic
VoT	Value of Time
WebTAG	Web Transport Analysis Guidance
WKT	Walking Time

WTT	Waiting Time

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CHAPTER 1 INTRODUCTION

1.1 Introductory Comments

This thesis aims to develop and provide a comprehensive comparative assessment to evaluate the costs and benefits of operating different public transport technologies in the local transport system. Because of the rapid development of technology and increasing demands for travelling, intermediate public transport technology rather than conventional bus and heavy rail transit has come into people's focus. As many of them have specific features that stand out from other public transport technologies, it is an essential issue for transport planners and decision makers to find out the most cost-effective one for the conditions of the local transport network.

In this first chapter, the necessities of developing a comprehensive comparative model will be discussed. The discussion starts with reviewing the long term trends in transport with particular references to public transport including bus and rail, and then followed by briefly reviewing the technological developments in public transport technologies. Research aims and main activities are outlined, and the structure of the thesis is provided at the end of this chapter.

1.2 Background Trends

Public transport is one of the most important means of daily travel for purposes such as commuting, shopping and education especially in large cities where the costs of travelling by private vehicles are extremely high due to the lack of space. The trend of passenger travelling in the UK are collected and summarised in Transport Statistics Great Britain (Department for Transport, 2012), and the volume of passenger transport by mode in the UK from 1952 to 2011 is shown in Figure 1-1.

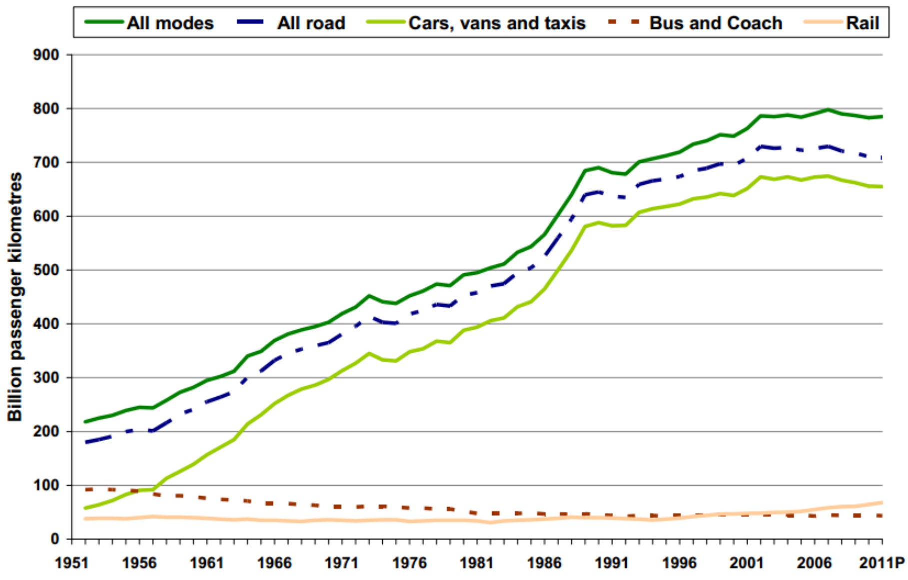


Figure 1-1 Passenger transport by mode in the UK from 1952 to 2011

(source: Department for Transport, 2012)

From this passenger travelling trend we can see that, travelling by private vehicles grew dramatically since 1952 from approximately 60 billion to 655 billion passenger kilometres in 2011, as private cars are much more affordable to normal people. The passenger kilometres by cars, vans and taxis also exceeded the passenger kilometres by bus and coach for the first time in 1956. However, the passenger kilometres made by the private vehicles tend to be much steadier during the last 10 years in Figure 1-1, growing from 651 billion in 2001 to 655 billion in 2011.

Although the operation of the First Generation Trams had been closed and only the Blackpool Tramway is still operating, passenger kilometres by all rail transits did not change too much until the privatisation in 1994/1995. After the privatisation, passenger kilometres travelled by national rail doubled by the end of 2011, even though the Hatfield crash in 2000 caused an interruption in the upward trend (DfT, 2012). For the London Underground service, passenger trips have increased by 53.3% from 764 billion to 1,171 billion since the privatisation in 1994/1995. Other than the heavy rail technology, the light rail and modern tram services in the UK have also developed significantly since the privatisation, and the passenger trips have grown by 223.8% from 63 billion to 204 billion, especially the Docklands Light Railway (DLR) that serves the redeveloped Docklands area of London, as shown in Figure 1-2.

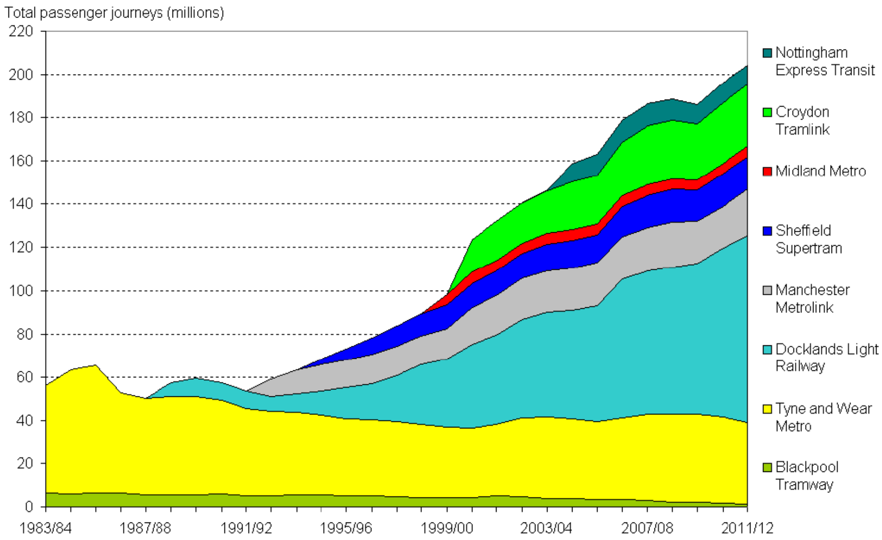


Figure 1-2 Annual share of light rail and tram passenger journeys

(source: Department for Transport, 2012)

Passenger kilometres on local bus services in the UK in 2010 have decreased by approximately 50% since 1952, according to Figure 1-1. Local bus only has a share of 6% of the total passenger kilometres in the UK in 2012, down from the peak of 42% in 1952, due to the great share growth of private transport modes. However, there is still an approximately 13% growth in the passenger journeys since 2004/2005 for the conventional bus services, which is mainly due to the 29% growth in the London area and the increasing concessionary travel outside London after the introduction of English National Concessionary Travel Scheme (ENCTS) (Department for Transport, 2010), and the bus journeys in London now account for half of all bus passenger journeys in England (Department for Transport, 2012).

Based on the trend of passenger travelling in the UK shown in Figure 1-1, private vehicles are becoming more and more popular. This is also because the private vehicles are much more affordable nowadays while the costs of fares increase, as shown in Figure 1-3.

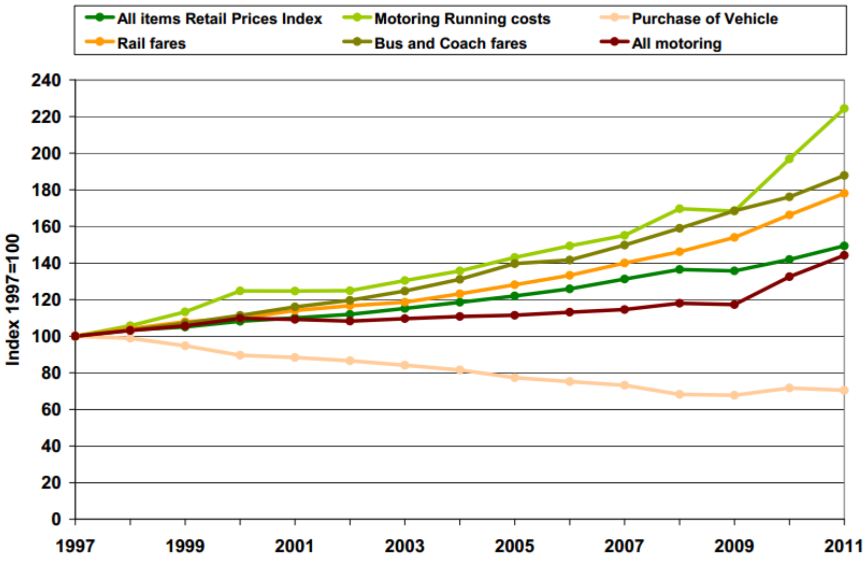


Figure 1-3 Changes in the cost of living and in the cost of transport: 1997 to 2011

(source: Department for Transport, 2012)

The flexibility of private vehicles in term of the destinations served and the lack of the need for timetables is a great advantage compared to public transport services (Vuchic, 1999). From the users' point of view, this flexibility means they don't have to spend extra time in accessing and waiting, and therefore gain more user benefits. However, in conjunction with the fast pace of modern society and the urbanisation, the issue of congestions and lack of parking space has increased the costs of using private vehicles, especially in high density traffic areas and metropolitan areas, as shown by the London Travel Demand Survey (LTDS) (Transport for London, 2011) in Table 1-1.

Table 1-1 Mode share percentage of trips by London residents

	2005/06	2006/07	2007/08	2008/09	2009/10
National Rail	4.3	4.1	4.0	4.7	4.8
Underground/DLR	6.5	6.6	7.0	7.7	7.2
Bus/tram	13.7	14.0	13.8	15.4	14.9
Taxi/other	1.1	1.5	1.3	1.1	1.3
Car driver	29.0	27.7	27.5	25.9	25.9
Car passenger	12.7	13.6	13.4	12.3	12.9
Motorcycle	0.6	0.7	0.6	0.5	0.5
Cycle	1.5	1.7	1.9	1.9	2.1
Walk	30.6	30.2	30.5	30.4	30.4
All modes	**100**	**100**	**100**	**100**	**100**

(source: adapted from TfL, 2011)

It is shown in Table 1-1 that the share of trips by car in London went down from 29% of the total trips to 25.9% while other modes, especially public transport modes increased between 2005 and 2010. Therefore, it shows that the demand of efficient public transport technologies is much higher in the large cities, which is shown as the increasing passenger kilometres and mode shares of London Underground, DLR line and local bus services of the London area.

1.3 Public Transport Technologies

As one of the most important modes of daily travelling, public transport technologies have drawn great attentions from operators and decision makers, especially with respect to the costs of public transport modes. The benefits of developing public transport have also been recognised by governments all around the world. Many new innovative forms of public transport have been developed to meet various passenger requirements. Those public transport modes other than the conventional bus system and heavy rail system are briefly reviewed in this section.

1.3.1 Personal Rapid Transit

ULTra (Urban Light Transit) Personal Rapid Transit (PRT) system in London Heathrow Airport was opened in late spring 2010 which is the first PRT operating in the world and works as a feeder service for people between the business car park and the terminals and takes only 5 to 6 minutes to travel along approximately 1.2 miles (ULTraGlobalPRT, 2011).

Figure 1-4 PRT vehicles at London Heathrow Airport Terminal 5

PRT provides a taxi-like demand responsive service for small size group of passengers for short distance travels. As the PRT vehicles are driverless, electric and quiet, operating costs are lower compared to conventional forms of public transport. For the public transport users, the PRT technology is able to provide a modal shift transport with high quality of service. The highly efficient “on-demand” operation of PRT is able to provide a very short waiting time service while the segregated guideway provides congestion-free transport and therefore very low in-vehicle time (NICHES+, 2010). However, as the capacity of each PRT vehicle is only for 4 people and their luggage, PRT technology is not suitable for high levels of passenger demand.

1.3.2 Bus Rapid Transit

Conventional bus system had a long history, with horse-drawn buses from 1820s and the first internal combustion engine bus in 1895 (Eckermann, 2001). The rapid development of science technology along with the demand of high quality transport has led to the introduction of many high quality bus-based systems.

A guided bus system, “Leeds Superbus” has been operated in Leeds since 1995 by First Group. This guided bus service provides a segregated “guidedway” for the buses in order to reduce the delays due to traffic congestion at peak periods. Priority is also given to the bus approaching the junction to increase the operating speed of the service.

Figure 1-5 Leeds “Superbus” guided bus system

(source: www.leeds.gov.uk)

Due to the additional infrastructure compared to conventional bus service, this guided bus system saves up to 3 minutes per bus in the afternoon peak with the 450 metres outbound guideway and up to 5 minutes in the morning peak with the 800 metres inbound guidedway[1]. This 450 m outbound and 800 m inbound Guided Bus system in Leeds ensures punctuality and reliability and increases the attractiveness of bus services by providing a segregated busway, which reduces journey time by 33% and increases patronage by 40% (Currie and Wallis, 2008).

Brett and Menzies (2014) undertook a usage analysis by using questionnaire for the guided bus system in Cambridgeshire, which is the world's longest guided busway opened on 7 August 2011. With a total of 855 responses from the guided bus passengers, they have found that the high-quality guided bus system is able to compete effectively with the private car, as 74% respondents agreed that the guided busway is quicker than using a car and 78% agreed that the arrival time was more reliable. As a result of the good level of service of the guided busway in Cambridgeshire, although more than 70% of the respondents are able to travel by a car, they still made their journey by the guided bus system (Brett and Menzies, 2014).

A cost-effective technology, Bus Rapid Transit (BRT), is also a public transport service for medium levels of passenger demand which is operating in a wide number of countries. Since the first implementation of BRT system in Curitiba, Brazil in 1974, this intermediate bus system has developed dramatically. The total track length of BRT system in 181 cities worldwide is approximately 4,675 km, which serve more than 31 million passengers per day, as shown in Table 1-2.

BRT is an emerging form of different public transport technologies, which has the high speed and reliability characteristics of a rail service while having the operating flexibility and lower cost of a conventional bus service (Deng and Nelson, 2011). The performance of BRT systems was evaluated and compared with other public transport technologies. After assessing BRT systems around the world, Hensher (2007) suggested that BRT is able to provide high level of service while has less burden on taxpayers in subsidies. The capital investment cost for the construction of a BRT system is 4 to 20 times less than a tram or light rail system and 10 to 100 times lower than a metro system (Wright and Hook, 2007). As a result of the lower capital cost and shorter construction period than rail-based public transit, BRT has been considered as an immediate and affordable public transport technologies to solve the growing passenger demands,

[1] See http://www.leeds.gov.uk/residents/Pages/GuidedBus.aspx

especially in developing countries with budget constraints, for example Jakarta (Indonesia), Pune (India), Delhi (India), Beijing (China), Hangzhou (China) and Kunming (China) (Deng and Nelson, 2010). The environmental performance of the guided bus system is also better than light rail if both vehicle emissions and power station emissions are included (Hodgson et al., 2012).

Table 1-2 Existing BRT services worldwide by regions

Regions	Passengers / day	Number of cities	Length (km)
Africa	242,000 (0.77%)	3 (1.65%)	80 (1.71%)
Asia	8,845,822 (27.06%)	36 (19.88%)	1,295 (27.7%)
Europe	1,785,829 (5.69%)	51 (28.17%)	799 (17.09%)
Latin America	19,523,761 (62.25%)	59 (32.59%)	1,610 (34.43%)
Northern America	891,035 (2.84%)	26 (14.36%)	797 (17.04)
Oceania	430,041 (1.37%)	6 (3.31%)	94 (2.01%)
Total	31,358,488 (100%)	181 (100%)	4675 (100%)

(Source: adapted from www.brtdata.org, accessed 10/10/2014)

Although BRT systems require additional costs than conventional bus services, upgrading to BRT system offers better performance. The BRT runs on a segregated busway with dedicated stops which results in a maximum running speed of up to 100kph and no congestions in peak hours (Currie, 2006). The implementation of TransMilenio BRT system in Bogotá has increased average travel speed by approximately 15 km/h to 26.7 km/h (Cain et al., 2007). As the BRT system is able to provide a less congested service even in the peak period, it is able to attract more passengers to use the service. Demand has reached 15,000 per hour after only 5 years operation of the BRT system in Brisbane while the long term maximum peak hour demand was forecasted to be 10,000 per hour (Currie, 2006).

1.3.3 Light Rapid Transit

Light rail systems were developed and implemented all around the world to meet higher levels of demand than conventional bus system in urban and interurban areas. The light rail transit has been defined by Transportation Research Board (TRB) as:

Light rail transit is a metropolitan electric railway system characterized by its ability to operate single cars or short trains along exclusive rights-of-way at ground level, on aerial structures, in subways or, occasionally, in streets, and to board and discharge passengers at track or car-floor level (TRB, 1989).

In the UK, many cities have provided light rail service to passengers, which include Birmingham-Wolverhampton Midland Metro, Blackpool tramway, Manchester Metrolink, Sheffield Supertram and London Docklands Light Railway (DLR line). Due to the rail-based technology, light rail transit is able to provide a faster service while carrying more passenger than the conventional bus. This characteristic make the light rail service a very attractive form of public transport in the mid/high level of passenger demand. The light rail system operating in Greater Manchester (Metrolink) provides more frequent services as well as cheaper fares than the previous heavy rail system while maintaining competitiveness in terms of operating speed and punctuality, and because of these characteristics the Metrolink successfully achieved its ridership projections while most new urban rail systems failed to reach their initial targets (Knowles, 2007). Since the operation started in May 2000 of the Croydon Tramlink in London, it attracted a large number of passengers and had experienced a significant increase in mode shares for the journey-to-work, and the passenger journeys have increased by 81.3% to 27.2 million from 2000 to 2009 (Lee and Senior, 2013).

Figure 1-6 Manchester Metrolink

(source: www.metrolink.co.uk)

1.3.4 Other Public Transport Technologies

Straddle Bus is a new invention launched at the 13th Beijing International High-tech Expo in 2010 which is also aiming to provide a high quality of service at high levels of passenger demand.

Figure 1-7 Conceptual image of Straddle Bus

The Straddle Bus is designed to be able to operate above the traffic with girder-like legs straddling the road and leaves room for general traffic with multiply car-unit similar to light rail transit. It is believed to be able to solve the traffic congestion in metropolises such as Beijing and London by having fewer interactions with other forms of transport, while carrying many more people than conventional buses with lower construction cost than new underground line or rapid transit lanes (McDermon, 2010).

Due to the specific characteristics of different types of public transport, they are more feasible at distinct demand levels as the capacities and costs are differ, as shown in Figure 1-8.

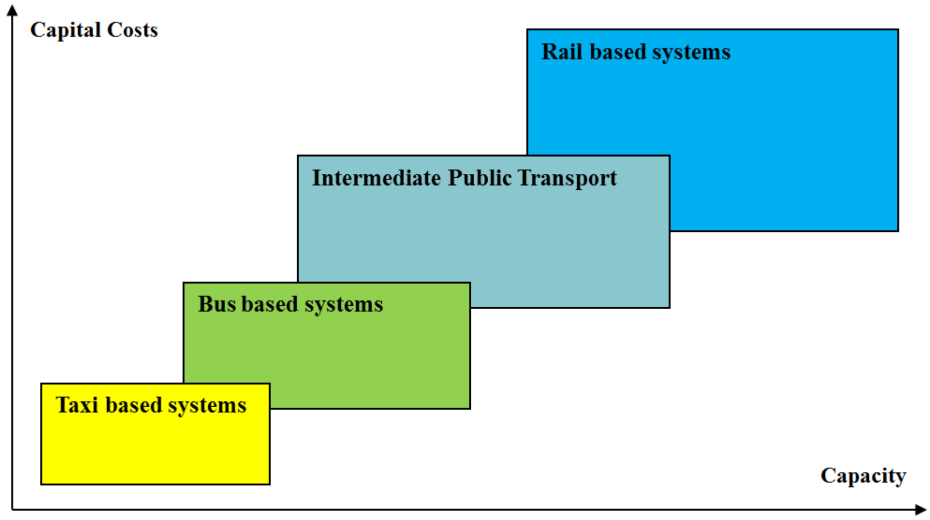


Figure 1-8 Schematic taxonomy of public transport modes

It is difficult for operators and decision makers to judge the most cost-effective public transport technology for the local network without a comprehensive method to quantify the benefits of both the operator and the passengers. The cost of public transport technologies consists of not only the costs of operators (which may be transferred on to passengers in terms of fares) but also the costs borne by society in general (Jakob et al. 2006) which is the total social cost.

Therefore, comparing different public transport technologies, including those existing public transport routes and proposed conceptual innovative forms in a strategic planning level in the same situation to select the most appropriate mode is an essential issue. The operators and the transport planners can make decision on adopting the most feasible public transport mode for the local transport network by identifying the benefits for both operators and users in terms of cost in a well-developed and comprehensive cost model.

1.4 Research Objectives

The main aim of this thesis is to build up a comparative assessment model to analyse the feasibility of different public transport technologies in the same operating environment to compare their financial and social cost through a series of cost functions and simulations. In this way, the assessment can provide valuable financial data for decision makers when they are dealing with different public transport technologies include conventional buses and innovative rail transit in the same operating network. Public transport technologies can be innovative in different ways. For example, Demand Responsive Transport (DRT) is innovative in its user-oriented characteristics. The Straddle Bus is able to run above the general traffic to avoid congestion, which is innovative in the operating environment. As most of the public transport technologies are fixed line public transport systems, this thesis will focus on comparing and modelling fixed line public transport technologies.

The comparative assessment developed in this thesis makes use of three models. The first model, Spreadsheet Cost Model (SCM) is in Microsoft Excel that calculates the theoretical social and financial costs of different public transport modes operating on a stand-alone urban corridor according to user input or default vehicle characteristics and unit costs including operator cost, user cost and external cost. The second model, Demand Supply Model (DSM) is to calculate the endogenous demand level based on the demand elasticity rather than using an exogenous input demand level. Exogenous demand means the demand level is an external fixed input where endogenous demand means the passenger demand level is influenced by factors under the operator's control such as travel time and waiting time, and it is therefore variables with respect to level of service. The third model, Microscopic Simulation Model (MSM) is a traffic simulation model for an urban network with real data. Output from the simulation model such as average operating speed, passenger waiting time and travel time are substituted back to the other two models to obtain the endogenous demand level as well as the total social cost of different public transport technologies for comparison.

The research objectives for this thesis are specified as:

1) To investigate the social cost, including operator, user and external costs, of the fixed line public transport technologies for different user demand level.
2) To evaluate the interactions between the public transport technologies and the public transport users, in order to find out how the performance of the public transport system would affect the user demand levels.

3) To develop a traffic simulation model of fixed line innovative public transport technologies, hence illustrating out how the specific characteristics of fixed line innovative public transport technologies can be represented in such a model.
4) To apply the models to a real network to demonstrate the usefulness of the comparative assessment in analysing and quantifying the benefits of different public transport technologies in a given traffic network.

In order to achieve the research objectives listed above, the following activities have been undertaken:

a) Reviewed literature on operator cost, user cost, external cost and social cost model to identify the knowledge gaps. Reviewed traffic simulation packages to select the most suitable simulation tool.
b) Built up Spreadsheet Cost Model and Demand Supply Model by using computer programming to evaluate the social and operator costs for different public transport technologies in various endogenous demand levels.
c) Collected data from a field survey, including geometry data, traffic signal data, traffic volume data and public transport passenger data.
d) Built up the simulation model in the selected simulation package, and then calibrated and validated the simulation model by using the field data.
e) Applied the comparative assessment in a real traffic network and evaluated the results from the models.

1.5 Comparative Assessment Structure

The comparative assessment will be made of three models: Spreadsheet Cost Model, Demand Supply Model and Microscopic Simulation Model. These three models would be closely interacting with each other to analyse the performance of different public transport technologies. The SCM is the core model in this thesis, as the comparative assessment evaluates the performance of different public transport technologies in terms of social and operator costs. As a theoretical model, SCM has some drawbacks compared to the realistic traffic network.

First of all, as a strategic level model, it only considers a segregated corridor without any interaction with other traffic and any signalised junction or roundabout. This assumption could be true for rail-based public transport technologies and for guided buses. However, conventional buses would normally have large amounts of interactions between other vehicles such as cars, motorcycles and sometimes pedestrians. Therefore, the actual social cost calculations should take the interactions into account.

The second drawback is the passenger demand level would actually be endogenous rather than the assumed exogenous in SCM. This means the actual number of passengers that use public transportation would vary rather than be fixed. Users would consider if the vehicles are worth taking and make decisions according to their user benefits which mainly include the passenger waiting time (WTT), in-vehicle time (IVT) and walking time (WKT) to the station. As a result of that, the actual passenger demand would increase or decrease for different levels of service. For example, when the traffic flow is low and the public transport vehicles can be operating at a very high speed and an appropriate service interval, the actual passengers that are willing to take the public transport mode might be higher than the fixed demand. However, the passenger numbers would be lower than the exogenous demand if the road is very congested and the passenger waiting time is relatively high.

Once the two main drawbacks are overcome, SCM can provide valuable results to predict and evaluate the performance of the public transport system for decision makers. For the first drawback, MSM is required to calculate the vehicle interactions and the actual average running speed of the vehicles. Traffic speed is one of the important outputs in the simulation model as well as the travel time and waiting time for public transportation passengers. These outputs are the main differences between the theoretical model and the real world traffic network and they are also the internal variables in SCM. The outputs from MSM can then be used in SCM for the desired level of demand to calculate a more accurate total social cost at that level to form a more comprehensive comparative assessment. For the second drawback, DSM can evaluate the actual passenger demand level according to the services supplied by the operator which are calculated from SCM. Therefore, the passenger demand level will also become a dependent variable in the comparative assessment to represent the willingness of the passengers in the current level of service.

The logical structure of the completed comparative assessment is shown in Figure 1-9.

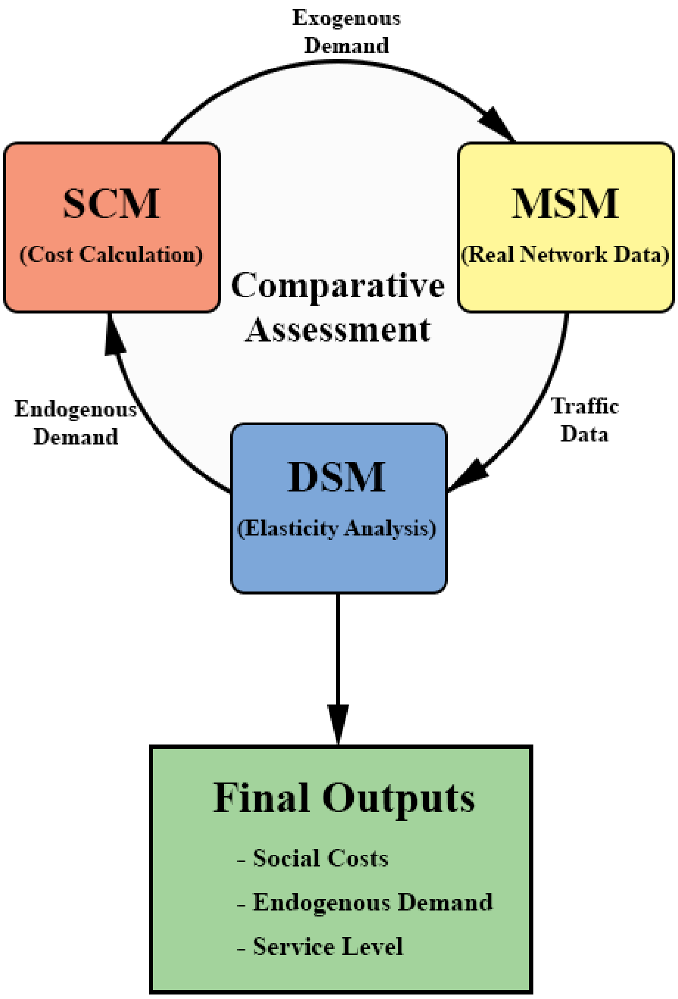


Figure 1-9 Operating procedure of the completed assessment

The comparative assessment begins with providing exogenous passenger demand level and required service frequency data to the simulation model from the SCM, and then MSM calculates the traffic data (travel time, operating speed, etc.) for DSM to evaluate the endogenous demand. Once the endogenous demand result from the DSM matches the exogenous demand from the SCM, final output will be produced from the comparative assessment to show the social and operator cost of the public transport technology on the local transport network.

1.6 Thesis Layout

To present this thesis in a logical order, this dissertation has been divided into 8 chapters. The contents of each chapter are summarised below to provide a brief introduction and guide through the dissertation.

Chapter 1 Introduction

Chapter 1 introduces the background of this thesis that many innovative and intermediate public transport technologies are available for transport planning and each of them has advantages in different ways which make this assessment necessary. Research objectives are listed in this chapter together with the description of the structure of the whole thesis.

Chapter 2 Review of Public Transport Technology Cost Models

Chapter 2 reviews the previous studies of modelling public transit costs, including cost functions for public transportation operation and comparisons of different public transport technologies in different transport networks.

Chapter 3 Review of Traffic Simulation Models

Chapter 3 discusses different traffic simulation approaches, which include microscopic, mesoscopic and macroscopic approaches. The reasons of choosing microscopic approach are discussed in this chapter. In order to select the most appropriate modelling software, existing microscopic traffic simulation packages were reviews together with the calibration and validation procedure of microscopic traffic simulation models.

Chapter 4 Spreadsheet Cost Model

Chapter 4 describes the details of SCM including the default data used, structure of the model and the operation procedure of the spreadsheet model. The improvements of the speed equation and passenger waiting time equation based on previous work are also presented in this chapter.

Chapter 5 Demand Supply Model

This chapter focuses on explaining the demand and supply analysis for the endogenous demand. The elasticity analysis for the passenger WTT and IVT are shown as well as the impact to the actual demand level due to the supply of the public transport services. The link between this analysis and SCM is also presented in this chapter.

Chapter 6 Microscopic Simulation Model

Chapter 6 demonstrates the detailed traffic network of the simulation model. The calibration and validation of the microscopic simulation model are also described in this chapter.

Chapter 7 Comparative Assessment Application

This chapter shows the application of the comparative assessment. A comparison between the existing conventional bus service and a conceptual innovative public transport technology, Straddle bus, on the main corridor of Nanning, China is assessed as a case study of this comparative assessment.

Chapter 8 Conclusions

The final chapter is to summarise the whole research and discuss the main achievements according to the research objectives shown in Chapter 1. Potential future work is also discussed and recommended.

CHAPTER 2 REVIEW OF PUBLIC TRANSPORT TECHNOLOGY COST MODELS

2.1 Introduction

In order to clarify all components of the total cost of public transport system to better develop the cost model, it is necessary to review the related literatures in public transport technology cost modelling. The total costs of a public transport system, including the cost for the public transport operators and users have been taken into account, as well as the costs to the external environment.

Different public transport technologies, especially innovative modes, have specific advantages in different operating environments and passenger demand levels, as a result of the different design features. Therefore, comparing the benefits for both operator and user is a big issue for public transport planners and operators. Many famous transportation economics textbooks have discussed and provided cost models for different forms of transport as a solution of evaluating the benefits for users and operators (Meyer et al., 1965; Jansson, 1984; Small, 1992; Meyer and Miller, 2001; Vuchic, 2005; Bruun, 2007; White, 2009).

This chapter is going to discuss the approaches in previous studies include mathematical models for evaluating the total cost of public transport technology and the modal comparison between different public transport modes. Conclusions were drawn to help build a comprehensive cost model for comparing the costs and benefits of different public transport technologies.

2.2 Cost Function

There are a number of measurements can be used to evaluate the advantages of a public transport technology. The social and financial cost of public transport services is an important measurement for public transport planners and operators, which is able to represent the benefits and performance of public transport services. A number of previous studies have built up cost functions, including operator costs, user costs and external costs of public transport system in various transport networks.

2.2.1 Operator Cost

Examining the costs of a public transport operator is of great interest to many researchers and public transport operating companies. The evaluation of the total operator cost can be categorised into engineering approach, accounting approach and productivity approach. An engineering approach to a cost model is to evaluate the total cost of the project or the service over a specific time period, typically increments of one year over the entire lifetime of the project (Bruun, 2007). An accounting approach assumes the cost of the public transport operator is a linear function of a few intermediate variables of the public transport operation such as peak vehicle requirement and route miles, and therefore the total cost can be obtained by multiplying the intermediate variables with the unit cost (Small, 1992). A productivity approach evaluates the costs of public transport operator as a function of output, of two or three input variables based on the operation of the public transit service (Small, 1992).

Engineering approach

Meyer et al. (1965) undertook a pioneering study on developing a detailed cost function of operating a particular urban transportation technology in an engineering approach in their research. They identified the costs of performing a particular form of urban transportation depended on the number of vehicle, the total travel distance, the costs of the structure, and the maintenance costs. Therefore, the operator cost takes the required vehicular units, the miles they travelled and the road structure costs as well as the costs of maintaining those structures into account, and the functional cost relationships given by Meyer et al. (1965) are:

$$TC = \alpha nU + \beta M + \gamma L + S$$

where,

$TC =$ total cost for some specified time period (usually, for convenience, taken to be one year);

$U =$ number of basic vehicle groups needed;

$M =$ miles of vehicle travel during the period;

$L =$ lane-miles or track-miles of roadway or roadbed needed;

$S =$ structure and related costs (for example, highways, roadbed, right-of-way);

$n =$ the number of vehicular units operating as a coordinated group or train (that is, n usually equals 1 for bus and auto operations today and is usually greater than 1 for rail);

$\alpha =$ costs per period per vehicular unit employed;

$\beta =$ direct costs assignable on the basis of miles of travel performed;

$\gamma =$ costs assignable on the basis of miles of roadway or roadbed required.

In order to calculate the total cost of operating a public transport service, the number of basic vehicle groups needed (*U*), the mile of vehicle travel during the period (*M*), the length of the lane or track required (*L*) and the structure and related costs requirement (*S*) all needed to be calculated. The parameter *U* and *M* can be calculated from the level of passenger demand and the track length is dependent on the local network. The structure and related costs (*S*) are calculated by summing up the maintenance cost and capital cost with a capital recovery factor (CRF) to obtain the equivalent annual cost with an assumed 6% interest rate. However, the capital investment costs for vehicles are not evaluated by using CRF in the cost model. Their work considered the operating cost of performing a particular form of urban transportation and the calculations of these cost parameters in a line-haul system are detailed in their research, including other non-structural costs in the line-haul system for rail and bus transits.

A more comprehensive cost function for the cost of public transport technologies was developed in the TEST (Tools for Evaluating Strategically Integrated Public Transport) project by Brand and Preston (2001, 2002a, 2002b, 2003a, 2003b, 2006). A stand-alone model was developed in their works, which calculates the costs of public transport technologies operating on a stand-alone corridor without network. In order to take all related costs into account, the operator cost in the TEST project includes the costs that arose during the operating stage and the capital investments of the public transport technology (both infrastructure and vehicle). As the calculation of the costs is using annual data in the TEST project, the operator costs are evaluated in engineering approach and the capital investments use amortised costs calculated by using the economic life for the fleet and the infrastructure and an assumed annual interest rate. The operating costs of the public transport technology are divided into time-related cost, distance-related cost, vehicle-related cost and route-maintenance related cost. With the intermediate variables calculated in the stand-alone model, the total operator costs are calculated by the formulae:

$$TOC = OC^T + OC^D + OC^V + OC^R + CC^{ann}$$

$$CC^{ann} = CC^{total} \frac{DR}{1 - \frac{1}{(1+DR)^{EL}}}$$

where,

TOC = total annual operator costs;

OC^T = time-related operating costs arose during operation;

OC^D = distance-related operating costs arose during operation;

OC^V = vehicle-related operating costs arose during operation;

OC^R = route-maintenance related operating costs arose during operation;

DR = discount rate for capital investment of vehicles and infrastructures;

EL = economic life expectancy of capital investment of vehicles and infrastructures;

CC^{total} = total capital investment costs of vehicles and infrastructures;

CC^{ann} = annual capital investment costs of vehicles and infrastructures;

With the user input values for unit operating costs, capital investment, economic life expectancy and discount rate, this cost model can generate the total operator costs for the current passenger demand level on an annual basis. This separation of the operating costs generated during operation and the capital investment is able to evaluate the operator cost of the public transport technology precisely for the current year by using the unit costs and capital investment costs obtained from the operators.

A cost model for a radial public transport network was developed by Tirachini et al. (2010) to compare operator and users costs of light rail, heavy rail and bus rapid transit. As the model is for a radial public transport network rather than a single route corridor, the operator cost is calculated based on the fleet size requirement, which depends on the total passenger demand in the peak period. The expression for the operator's cost in their work is made up of four components:

$$C_O = c_0 n + c_1 \eta \max B_t + \sum_{t=1}^{T} D_t (c_{2t} B_t + c_{3t} V_t B_t)$$

where,

C_O = the total operator cost;

c_0 = fixed costs of the public transit line (infrastructure capital cost and land cost);

n = the number of lines of the public transport technology;

c_1 = maximum rolling stock capital cost;

η = factor that accounts for a reserve fleet to deal with unexpected breakdowns or maintenance;

B_t = fleet size requirement of the period;

c_{2t} = unit operator cost per vehicle hour;

c_{3t} = unit operator cost per vehicle kilometre to account for running costs;

V_t = commercial speed.

This operator cost function for a radial public transport network considers similar costs components compared to the TEST project. The first two parts of this cost function calculate the fixed capital investment for the whole public transport service system by using a 7% discount rate and assumed asset lives of the infrastructure and the rolling stock, which is the capital investment costs calculated in the TEST project, and the last two components of this cost function calculate the operating costs generated during the operation stage based on the fleet size requirement.

Accounting approach

Small (1992) provided and discussed the cost functions of public transit, along with reviews of other cost function studies. He gave a linear operator cost functions of public transit in accounting approach rather than the engineering approach by Meyer et al. (1965). The provided accounting approach assumes the total cost function is linear, and with intermediate outputs route-miles (RM), peak vehicles requirements (PV), vehicle-hours (VH) and vehicle-miles (VM) with constants c_1, c_2, c_3 and c_4 to distinguish the cost differences between public transport technologies for each term.

$$Cost = c_1RM + c_2PV + c_3VH + c_4VM$$

By calculating these four intermediate outputs based on the performance of the public transit, the cost of providing bus or rail transit service can be examined by multiplying them with unit capital cost and unit operating cost. Therefore, the operator cost calculation, including the capital investment cost in this approach focuses on the cost of the public transit agencies rather than the cost of the public transport technology.

Small (1992) also specified the costs for vehicle-hour/train-hour highly depend on the balance of peak and off-peak service. Therefore the calculation for the vehicle-hour/train-hour cost should consider the peak and off-peak period separately, and the equation becomes:

$$Cost = c_1RM + c_2PV + c_bVH_b + c_pVH_p + c_4VM$$

where c_b and c_p are the unit cost of vehicle-hour in off-peak and peak, respectively.

Other than the cost parameters above, Small (1992) also suggested that to calculate the short-run variable costs for highway travel, costs borne primarily by users and other social costs should also be taken into account. Those extra costs contain the fuel and maintenance costs for private vehicle users, vehicle capital costs for private vehicles, the time costs which are considerably larger than running costs in congested traffic and schedule-delay costs when congestion is severe on their trips.

White (2009) gave cost allocation methods in engineering approach for ground transportation services, including bus and rail industries and provided a practical example for bus operator cost calculation. For the operator cost of bus industry, White (2009) summarised the typical cost structure of the Chartered Institute of Public Finance and Accountancy (CIPFA) from CIPFA (1979), which is shown in Table 2-1.

Table 2-1 An example of the CIPFA bus cost structure

Category	**Main Components**	**Basis of variation**
Variable costs	Crew wages, bus servicing Fuel, tyres, third party insurance	Time Distance
Semi-variable costs	Bus maintenance Depreciation and leasing	Time Peak vehicle
Fixed costs	Administration staff and welfare Buildings and general	Time Peak vehicle
Interest on capital debt		Peak vehicle

(Source: adapted from White, 2009)

In the bus cost allocation example, by assuming a 15-year bus life and a straight-line depreciation, the total operator cost is calculated as the sum of the time-based driver costs, distance-based costs, depreciation charges, profit margin and fixed depot costs. By dividing the total operator costs by the total hours run per year and the total kilometres run per year, the total average operator cost can then be obtained. For the rail cost allocation, the cost of the train operating company also have similar cost elements, such as train crew, fuel cost and rolling stock maintenance. However, the train operating company has responsibility of the operation and construction of the train station, which causes additional related costs in capital investment and operating costs, and these costs made up of about 35% to 40% of the total costs of the train operating company (White, 2009).

Productivity approach

Viton (1980) developed a cost function for Bay Area Rapid Transit (BART) system in San Francisco, USA by using productivity approach. The cost function developed is based on the Cobb-Douglas production function of the output (vehicle-miles):

$$Y = AL^{\alpha}E^{\beta}T^{\gamma}$$

where,

Y = total output production (vehicle miles in this example);

L = man-hours of labour;

E = kilowatt-hours of electricity;

T = miles of track;

A = total factor productivity;

α, β and γ = output elasticities.

As cost is a function of output, the cost function of the public transport operator uses the output from the production function as well as the price of the parameters:

$$C = c(Y, P_L, P_E, P_T)$$

where P_L, P_E and P_T are factor prices corresponding to the input requirements of the production function. In order to avoid the restriction on economic effects of interest in transportation by the Cobb-Douglas production function, Viton (1980) provided a translog (transcendental logarithmic) function to allow freedom of all the economic effects without imposing the unwanted assumptions.

$$\begin{aligned}\bar{C} = A_0 + A_Y Y^* + A_E(P_E^* - P_L^*) + A_T T^* \\ +A_{YY}\frac{1}{2}Y^{*2} + A_{YT}Y^*T^* \\ +A_{YL}Y^*(P_L^* - P_E^*) \\ +A_{TT}\frac{1}{2}T^{*2} + A_{TL}Y^*(P_L^* - P_E^*) \\ +A_{LL}(\frac{1}{2}P_E^{*2} - P_E^*P_L^* + \frac{1}{2}P_L^{*2})\end{aligned}$$

where A_0, A_Y, A_E, A_T, A_{YY}, A_{YT}, A_{YL}, A_{TT}, A_{TL} and A_{LL} are parameters obtained by combining cost and factor share equations and the variables with star are defined as, for example, $Y^* = lnY - ln\bar{Y}$ and $\bar{Y}$ is the sample mean of Y. By using different observations of rapid rail system in the US and data obtained from Bureau of Labor Statistics and Federal Power Commission, Viton (1980) used this equation to estimate both short-run and long-run cost for the operation of the BART system.

There are many other studies that adopted the productivity approach, for example to estimate cost frontiers and efficiency scores for public transit firms (De Borger et al., 2008), to estimate the cost function of the bus operator of Transantiago in Santiago, Chile (Batarce and Galilea, 2013) and to determine the productivity and efficiency of European railway companies (Cantos et al, 1999; Cantos et al, 2002), and previous studies on rail-based transport by using productivity approach was reviewed by Oum et al (1999) and a comprehensive review was conducted by De Borger et al. (2002).

2.2.2 User Cost

To evaluate the total cost of a public transport facility, Jansson (1984) outlined that the total social cost is equal to the sum of the producer cost and the user cost. This is because in addition to the costs of the public transport operator, the total cost also includes the disutility that travellers incur by using the public transport service (Vuchic, 1999). Cost functions including user inputs were discussed by Small (1992) that, transit users also suffer time costs which should be included in the calculation of the total cost of providing bus or rail transit service, and these time costs include accessing/egressing time costs, waiting for vehicle time costs, riding in vehicle time costs and possibly transferring between vehicle time costs. The combination of these time costs are defined as generalised cost, which represents the time spent by the passengers in travelling by the public transport service in monetary form (ATOC, 2009).

The user cost structure is discussed by Jansson (1984) that the total user costs of travelling by the public transport service is a function of transport volume (Q), user cost per journey (h), occupancy rate (φ), number of vehicles (N) and overall speed of vehicles (V):

$$TC^{user} = Q \times h(\varphi, N, V)$$

and the average user cost per unit of transport (AC^{user}) can be calculated as:

$$AC^{user} = f(D) + w(F) + q(\varphi, F) + t(\varphi, V) + c_h$$

where,

$f(D)$ = feeder transport cost as a function of the density of service D;

$w(F)$ = waiting cost as a function of the service frequency F;

$q(\varphi, F)$ = queuing cost as a function of the occupancy rate φ, and F;

$t(\varphi, V)$ = travel time cost as a function of φ, and the average operating speed V;

c_h = handling charges.

In this way, the user cost calculation considers all incurred disutilities, which are the walking time, waiting time, in-vehicle time and transferring time of the users by travelling with the public transport service. These time costs are also defined as generalised time costs, which should be taken into account for the calculation of the total social cost of providing the public transport service.

The TEST project by Brand & Preston (2006) also assessed total user cost as part of the total social cost of providing a public transport technology on a local corridor. As the main supply from the public transit users are time, the stand-alone model in the TEST project calculates the time spent by the users of using the public transport service. It takes passenger generalised journey time, including access/egress time, waiting time and in-vehicle time into account and then converts them into costs by using the value of time for passengers. The generalised journey time is calculated according to the average operating speed and the service frequency of the public transport technology, which are the intermediate outputs based on the level of passenger demand and the performance of the public transport technology. The equations for calculating the user costs are:

$$UC = \left(T^{IV} + f^{wait}T^{wait} + f^{walk}T^{walk}\right) \times VoT$$

where,

UC = users cost of using the public transport technology;

T^{IV} = users' time spent in the vehicle while travelling;

T^{wait} = users' time spent in waiting for the vehicle, including dwell time;

T^{walk} = users' time spent in the walking to and from the public transport stop/station;

f^{wait} = weighting factor to account for perception of waiting time vs. in-vehicle time;

f^{walk} = weighting factor to account for perception of walking time vs. in-vehicle time;

VoT = users value of in-vehicle time.

The equations for calculating each generalised journey time element: IVT, WKT and WTT are also detailed in the TEST project as:

$$T^{IV} = \frac{JL}{V^{All}}$$

$$T^{walk} = (\frac{W^{route}}{4} + \frac{D^{Stop}}{4}) / \, V^{walk}$$

$$T^{wait} = \frac{H^{freq}}{2} + T^{Stop}$$

where,

JL = average journey length for each passenger;

V^{All} = average operating speed of the public transport technology;

W^{route} = average width of route influence along the corridor;

D^{Stop} = average distance between each public transport stop/station;

V^{walk} = mean passenger walking speed;

H^{freq} = service interval of the public transport technology at current demand level;

T^{Stop} = average dwell time at current demand level;

By using a user defined average journey length per passenger, the passenger IVT is calculated by dividing the average journey length by the average operating speed. The passenger walking time is calculated by assuming a 0.6 km route influence width rectangular corridor and different distance between stops/stations for different public transport technologies in a grid matrix network, and then divided by the mean passenger walking speed. Assuming the random arrival of passengers, the WTT is calculated as half of the service headway plus the service dwell time for each stop. By calculating the users' time supply of accessing/egressing, waiting and travelling in the public transport vehicle and then converting them into costs, the total user costs are evaluated in the stand-alone model of the TEST project.

The passenger waiting time calculated here is highly related to the intermediate variables service frequency and dwell time. When the passenger demand level increases, the service frequency also increases and hence reduces the average passenger waiting time cost, which reflects the Mohring effect that the public transport service is subject to increasing returns to scale when the passenger's wait time is considered in the cost function (Mohring, 1972). However, this waiting time formula did not represent the waiting time cost in very high and very low passenger demand level. In the low passenger demand level, the public transport service supplied is in low frequency for high capacity transit, and passengers will time their journeys to wait for a specific departure to avoid suffering an extremely high waiting time cost with a threshold of about 4-5 scheduled services each hour (Balcombe et al., 2004). In the high passenger demand level, passengers may experience crowding in boarding the public transport vehicle and they may have to spend extra time to wait for the next service. This leads to an extra waiting time cost rather than just half of the service headway and the dwell time.

Tirachini et al. (2010) also evaluates the passenger's generalised time cost for a radial public transport network. In their model, the total passenger waiting time cost for all periods is derived as:

$$C_w = P_w \sum_{t=1}^{T} D_t (t_{0t} + t_{1t} \frac{\varepsilon_t}{f_t}) y_t$$

$$t_{0t} = \begin{cases} 0 & if\ f \ \geq 5\ veh/h \\ t_w & if\ 0 < f \ < 5\ veh/h \end{cases}$$

$$t_{1t} = \begin{cases} 1 & if\ f \ \geq 5\ veh/h \\ \mu & if\ 0 < f \ < 5\ veh/h \end{cases}$$

where,

C_w = total passenger waiting time;

P_w = value of station or active waiting time savings;

t = the selected time period;

D_t = the duration of the time period t;

ε_t = usually 0.5, and then the average waiting time is half of the headway;

f_t = service frequency;

y_t = the demand of the time period t;

t_w = fixed safety threshold time that passengers spend waiting at stations for the expected arrival of the vehicle;

μ = the ratio of the value of home waiting time to the value of station waiting time.

This passenger waiting time equation by Tirachini et al. (2010) uses a fixed safety threshold passenger waiting time t_w and a ratio $\mu = P_h/P_w$ of the value of home waiting time to station waiting time. Therefore the passengers' behaviour of timing their arrival to the station for the planning vehicle is considered in this equation, and the users' waiting time cost in low frequency can be demonstrated.

However, this waiting time equation still does not pick up the possibility that the passengers may experience congestion in boarding the public transport vehicle. So the potential extra waiting time costs in high passenger demand level or high density area are still not considered in this cost model.

2.2.3 External Environment Cost

Except the costs of operator and user, there are also unpaid costs to be considered for calculating the total cost of travelling by a public transport technology. The unpaid cost of travelling refers to the negative impacts or costs imposed by third parties and the society, which are more difficult to be quantified into monetary than the operator and user costs (Vuchic, 1999). In order to evaluate all costs generated due to providing a public transport service, the impacts to the external environment should also be considered, other than the costs for just operator and users. These related social costs include accidents cost for potential traffic accidents, parking costs for the requirement of parking facilities, local government services and environmental externalities like air-pollution costs and noise-pollution costs (Small, 1992; Becker, 2002; Litman, 2002).

Building the social cost of public transport modes research of Jansson (1984) to consider both operator cost and user cost for the total social cost, an extra cost has been taken into account in the TEST project, as total external cost which is used to consider the costs that people other than the road users to pay for using the public transport modes, including impacts of the target public transport technology to the environment, including air pollution, noise pollution, climate change effect and potential traffic accident costs. As those four impact components are mainly associated with the level of traffic volume (vehicle-kilometre), the total external cost is calculated by using the sum of the unit external cost of different public transport technologies found in previous studies (Sansom et al., 2001; NERA, 1999) to multiply the total vehicle kilometre in the period.

The transport costs of both private and public transport in Auckland were examined by Jakob et al. (2006). They have calculated the three largest external cost components for all on road transport, which are external accident, air pollution and climate change. The external accident cost includes loss of production, non-market costs, humanitarian costs, property damage and adjustment for non-reported injury crashes. The air pollution considers both costs due to health damage and damage to vegetation and buildings due to the transport. The climate change cost includes impacts on the long term global climate. As these three cost components account for 77% of the total external costs of a public transport service (Becker, 2002), Jakob et al. (2006) estimated the external costs of public transport in Auckland in 2001 was 0.73 New Zealand dollars per kilometre and a total external costs of 25.2 million New Zealand dollars.

Hodgson (2011) proposed a cost model to evaluate the cost and environmental performance of light rail transit and an equivalent bus-based system. To model the environmental performance of providing a light rail transit or bus-based system, six related environmental impacts by the public transport system are involved, which are noise, local air quality, greenhouse gases, land impacts, biodiversity and water environment and physical fitness and journey ambience. These environmental impacts for analysing all transport modes were based on the Web Transport Analysis Guidance (WebTAG) Unit A3 (DfT, 2014). Although the environmental impacts are not converted to cost by Hodgson (2011), the work provides a comprehensive consideration in evaluating the environmental performance of a public transport system.

2.2.4 Wider Economic Impact

As well as the operator, user and external environment costs, a new transport scheme could bring wider economic impacts to both public transport users and wider society. The term “Wider Impacts” of the transport is defined by the DfT as the economic impacts of transport that are additional to transport user benefits and external costs (such as accident and air and noise pollution). These types of impacts are categorised as: agglomeration, output change in imperfectly competitive markets, and tax revenues arising from labour market impacts (DfT, 2014).

The relationship between the investment of transport infrastructure and the growth in the economy has been of long standing interest to governments to find out the potential benefits of the projects. For example, The UK government required the Standing

Advisory Committee on Trunk Road Appraisal (SACTRA) to investigate the impacts of transport projects and policies on the performance of the economy in 1996 (SACTRA, 1999). The report concluded that the important economic effects which were not captured in conventional cost and benefit analysis should be considered for transport schemes. The Eddington Transport Study (Eddington, 2006) also picked up the benefits of transport networks and corridors to the GDP of the UK. Eddington (2006) recommended that the government should ensure a good performance of the transport systems in order to deliver a good economy and environment. By investigating the user benefits, productivity effects and investment and employment effects of transport project appraisals, Venables et al (2014) suggested that transport appraisals should identify clearly the economic impacts of the project and estimate the detailed impacts to the private sector investment and land-use changes.

The wider economic impact is therefore an important part to be considered in a new public transport system option. To evaluate the wider economic impacts of the public transport option, the DfT (2014) summarised that two groups of data should be considered in wider impact assessment: economic data and transport model data. The economic data involves the productivity of labour, employment numbers in the affected area and agglomeration elasticities for calculating the results from the changes brought by the public transport service. The transport model data includes the generalised cost of users (including fares) and passenger demand information for each mode before and after the implementation of the public transport system across the entire network rather than just for the corridor where improvements have taken place.

However, the wider economic impacts were not considered in this model, as the large amount of economic data required to be collected at a network scale for the wider impact assessment are largely unavailable for the case study of Straddle Bus demonstrated in Chapter 7. Furthermore, the Eddington Transport Study suggests that the typical uplift in Net Economic Benefits from urban transport improvements is around 24%. Although this can be important at the margins, this is unlikely to be material in terms of the difference between technologies as wider economic benefits are likely to be inversely related to average social costs. Moreover, incorporating wider economic benefits within the total social cost framework adopted would not be straightforward. Therefore, this thesis will focus on just the operator, user and external costs of a public transport option without considering the wider economic impacts of the public transport technology.

2.2.5 Summary

Previous studies of cost model approaches have been discussed in this section. The operator cost should include both capital investment cost for vehicles and infrastructure and costs arose during operating stage. In practice, the boundaries between engineering, accounting and productivity approaches are blurred. Similar to the engineering approach of calculating operator cost, the accounting approach also requires a breakdown of public transport system details, such as the length of route/track and fleet size requirement, in order to generate the intermediate output of route-miles, peak vehicle requirements, vehicle-hours and vehicle-miles. However, this calculation may not be suitable for some innovative public transport systems such as DRT, which has no fixed service frequency and fixed route. In that case, it would be difficult to evaluate the operator cost with such approaches. The cost function will then have to be modified to suit the public transport technology to evaluate such innovative operating methods. As this thesis is focussed on the fixed line public transport technologies, the cost function for the non-fixed line public transport systems is not considered.

Based on the previous literature, an engineering approach is more suitable for evaluating the costs for different fixed line public transport technology while an accounting approach and a productivity approach are more suitable to evaluate the costs of the public transport service company as they focus more on the cost of the firms rather than the public transport technology. Therefore, an engineering approach was adopted in this thesis to calculate the operator cost of different public transport technologies.

The user cost should consider all time spent by passengers include access/egress time, WTT and IVT. Although many previous studies have identified the equations to calculate these generalised time costs, the situation that the passengers may find the incoming vehicle full and experience extra waiting time has not been considered.

The external environment cost should involve all impacts of providing a public transport service to the society. Comprehensive environmental impacts of public transport system are provided in the WebTAG Unit A3 (DfT, 2014). However, as some of the factors are highly depending on the local condition of the network and the comparative assessment is mainly focusing on the public transport technology, the external environment cost considers the cost of noise, air pollution, greenhouse gases and climate change and potential accident. The external environment cost calculation in the TEST project uses the vehicle-kilometre and the unit environmental cost found in previous environmental cost studies, which can assess the external costs according to the operation performance of the public transport technology. Therefore, the TEST method of calculating the external cost was followed in this thesis.

2.3 Transport Network

The cost and benefit analysis for different public transport technologies is a necessary procedure for transport planners and decision maker to identify the most suitable public transport service for the local transport network. This cost and benefit analysis has been previously investigated in different ways, for example a single line-haul system route of 6 miles, 10 miles and 15 miles (Meyer et al., 1965), a single 12 km urban and interurban corridor combined with a real network system in Oxfordshire, UK (Brand and Preston, 2006), an urban path for different bus lines to superimpose their services together while having different outskirt paths (Grimaldi et al., 2010) and a radial public transport network from the border to the city centre for three different public transport technologies: light rail, heavy rail and bus rapid transit (Tirachini et al., 2010).

Meyer et al. (1965) did the pioneering study in this area and investigated the line-haul operator cost for different transport modes (rail, bus and line-haul auto) on a distinct route in different population density areas. By using the cost function of providing a bus or rail-base public transit as discussed in Section 2.2.1, different combinations are assessed, including 6-mile, 10-mile and 15-mile routes with one-way and two-way service in medium and high population density areas. The overall average cost per trip for all trips for different combination are calculated with fixed hourly input demand level from 5,000 to 50,000 and compared in order to analyse the best forms of public transport in the distinct traffic situation. They have found that an automobile system with only 1.6 passengers in each car could cost less at low corridor volumes (less than 5,000 hourly passenger requirements) and rail systems are very cost effective when population densities are high and the total running distances are short. Therefore they cost least in high population density area while bus systems do better in the low and medium population density areas.

In the TEST project by Brand and Preston (2001, 2002a, 2002b, 2003a, 2003b, 2006), a stand-alone model was developed to compare the total social cost of 15 different public transport modes including conventional buses, rail based technologies (light rail and heavy rail) and PRT in strategic planning level. In conjunction with the stand-alone model, an integrated model was also developed to assess the impact of different public transport modes in a real network. The stand-alone model is based on Microsoft Excel that calculates various costs for the 15 different public transport technologies on just a single 12 km route corridor rather than a complete network for fixed daily passenger demand level up to 200,000. Unit costs used in the model are from earlier research and are inputted into the model to obtain the total social cost relationships. The second model is an integrated model using transport analysis software VIPS (now part of the wider VISUM model) and CONTRAM to build up a macroscopic simulation model and a case study of the Kidlington-Oxford-Abingdon corridor in Oxfordshire (as shown in Figure 2-1) was used in the study to validate the integrated model and compare the user benefits of “Do Nothing” and “Do Something” options for the current corridor.

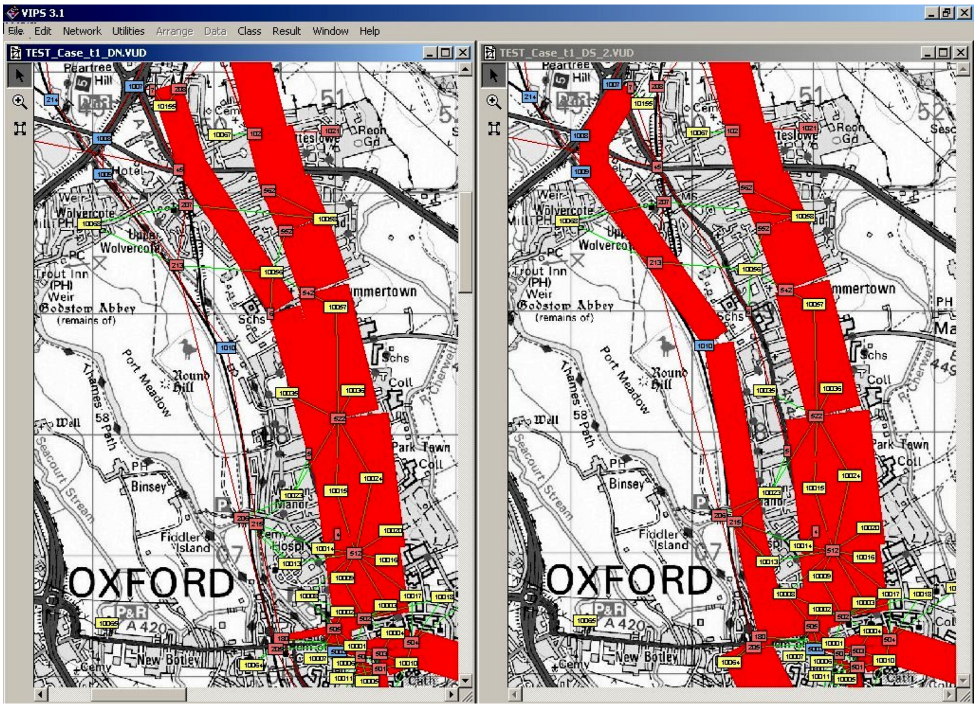


Figure 2-1 Simulated corridor in Oxfordshire, UK for "Do Nothing" (left) vs. "Do Something" (right)

(source: Brand and Preston, 2006)

According to the model developed by Brand and Preston (2006), the social costs of public transport are closely linked with the daily demand level if it is externally fixed. For example, bus technologies demonstrate their significant advantages in low average daily demand (< 40,000 passengers per day in a 12 km public transport route) by having less social cost per passenger, suburban heavy rail becomes most cost effective between 40,000 to 84,000 daily passengers and regional heavy rail has the lowest average social cost after that. The models developed are able to calculate the performance of different public transport modes and compare their user benefits and non-user benefits by substituting them into the system and obtain the total social cost difference.

A stylised cost-benefit analysis model was proposed by Grimaldi et al. (2010) to evaluate the choice between conventional bus and light rail transit in an urban path where the bus lines share the same corridor for part of their route while having different outskirt paths. The comparison is performed between keeping the formerly conventional bus services and upgrading to an alternative light rail service, which is shown in Figure 2-2 as follows.

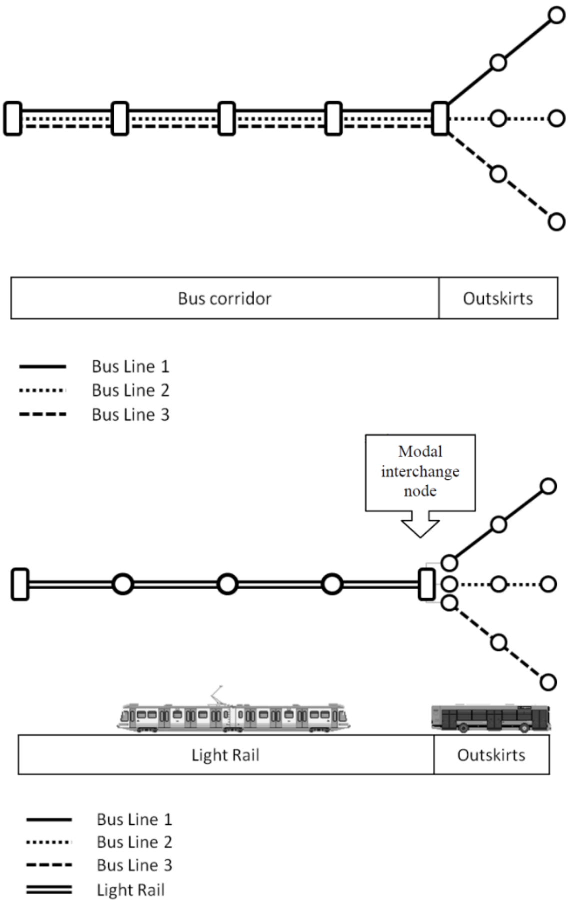


Figure 2-2 Original bus service (left) and alternative light rail service (right)

(source: adapted from Grimaldi et al., 2010)

By taking into account the investment cost of a 30 years lifetime light rail system, fixed maintenance and operating costs, passengers' generalised time costs include in-vehicle time, delay time, waiting time and modal shift time, Grimaldi et al. (2010) evaluated the total costs and benefits of the two options in terms of Net Present Value (NPV). They have found that if upgrade is from a low capacity system of bus to a higher capacity system of light rail, the total operating costs can be lower when the passenger demand is high. When the passenger demand of the corridor is lower than 6 million per year, the light rail system is not as effective as the existing bus service unless under some peculiar conditions, for example trip length above 10 km, cost less than €200 million or extreme reduction in operating costs. If the light rail system requires a capital investment over €800 million, the alternative system is only feasible if the passenger demand is above 20 million per year and without interchanges, or trip length above 15 km, or extremely high operating speed (> 30 km/h).

Tirachini et al. (2010) developed a model to compare the operator cost and the user cost of Light Rail (LR), Heavy Rail (HR) and Bus Rapid Transit (BRT) in a radial transport network in order to find out under what conditions the BRT is more cost effective than light rail and heavy rail technologies. They developed a cost function for radial transport networks as demonstrated in Section 2.2.1. Two key elements for those public transport technologies are taken into account: user cost including access/egressing time cost, waiting time cost and in-vehicle time cost, and operator cost including land and infrastructure capital costs. To comprehensively compare those costs in a radial line network, seven scenarios with different values for key parameters (for example operating speed, unit costs for infrastructure and dwell time at stations) are assumed to calculate the total costs. To calculate the passenger demand in the radial network, they divided the urban area into 4 routes and differentiated each catchment area as shown in Figure 2-3.

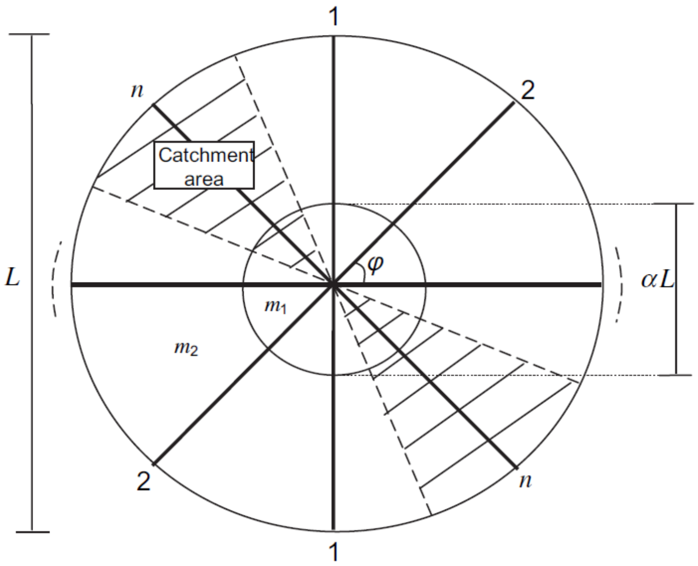


Figure 2-3 Radial public transport network

(source: Tirachini et al., 2010)

In Figure 2-3, there are n lines of the public transport service with diameter L in the radial transport network, and the Central Business District (CBD) was defined as the inner circle with diameter of αL, and α ranges from 0 to 1 to determine the demand density m_1 and m_2 per area unit inside and outside the CBD. By assuming an evenly distributed passenger demand along the public transport line, the catchment area is defined as the influence area of each line, and the total public transport passenger demand inside and outside the CBD is:

$$y_1 = \frac{\pi(\alpha L)^2}{4} m_1$$

$$y_2 = \frac{\pi L^2 (1-\alpha^2)}{4} m_2$$

where,

y_1 and y_2 represent the demand inside and outside the CBD respectively.

By calculating the required frequency with the passenger demand, total costs for each public transport services can be obtained. However, the operating speed is assumed to be fixed in different level of demand in their work. The operating speed would decrease due to more costs of the time for passengers boarding and alighting vehicle and to avoid bunching in high service frequency.

Their research found that BRT system is able to lower the waiting and access time costs for users in this radial network due to higher frequency while other rail technologies provide higher operating speed but more expensive operator costs, and the total cost of BRT would be lower if the difference in speeds is less than 9 km/h. BRT would be able to provide the lowest total cost for all demand ranges if the operating speed of Light Rail and Heavy Rail is less than 5 km/h and 9 km/h faster, respectively. For the High Rail technology, it can only be the most cost effective way of travel in the high levels of demand (over 3.2 million passengers per day for the entire radial city network) if the running speed is 10 km/h faster than BRT. In the low level of demand range (< 2 million passengers per day), the high capital investment makes it uncompetitive against Light Rail and BRT.

For comparing the choice of different public transport modes, previous studies have been done in various network types according to the feasibility of the technology and local network condition. However, all approaches discussed in this chapter used exogenous demand level as an initial input to calculate these cost without considering the impacts of the service quality to the demand level, which means the results are all based on externally fixed demand predictions. In reality, passenger demand levels are endogenous, not exogenous, and are affected by the performance of the public transport services such as the service interval and journey time. The actual average costs could be substantially different from those assuming fixed demand because actual passenger demand will vary due to the quality of service. The main reason of adopting an innovative public transport technology is the improvement in both operator and users benefits, and therefore the actual level of passenger demand should be recalculated, rather than external fixed. As passengers value their waiting time higher than the in-vehicle time (Quarmby, 1967; Wardman, 2004), passengers' waiting time cost must be estimated correctly to obtain the recalculated endogenous demand. Previous studies did not present a good approach in modelling the passengers' waiting time with high demand levels or high demand density areas where incoming vehicle could be full of passengers. In this case, low capacity public transport technologies such as PRT and conventional bus services will still have great advantages in their cost model in high passenger demand levels due to the high service frequency while there is no penalty for the boarding congestion. However, passengers may experience additional delay when they find the incoming vehicle is full at high levels of demand which may reduce the attractiveness of the public transport service and eventually affects the average costs.

In addition to the strategic level of cost modelling, the use of traffic simulation by Brand and Preston (2001, 2002a, 2002b, 2003a, 2003b, 2006) is a good way to improve the analysis results from strategic level to be more closed to the real traffic network. However, there are still some defects. Although it used a traffic simulation to evaluate the total social cost, users' benefit and non-users' benefit in a "Do Nothing" and an alternative "Do Something" scenario by taking traffic congestion, demand and modal shift changes into account, the detailed interactions between individual vehicles are not included. This is because the traffic simulation in the TEST project is at a macroscopic level rather than at microscopic level. However, some innovative public transport technologies may have strong interactions with the general traffic, for example Straddle Bus.

2.4 Conclusion

This chapter reviewed approaches to modelling the costs of providing a public transit system and in different local transport networks. In conclusion, the costs generated by public transport technologies and borne by the society have been identified in this chapter. To take all related costs of providing a public transport technology into account, total social cost which contains total operator cost, total user cost and total external cost should be considered. Among many previous works conducted to estimate these costs in a strategic level, the TEST project by Brand and Preston (2001, 2002a, 2002b, 2003a, 2003b, 2006) has developed a comprehensive model to evaluate these costs by using the intermediate variables of the public transport performance, so their method will be followed in this thesis. However, there are still improvements needed to undertake a comprehensive comparative assessment.

The passenger waiting time costs are closely related to the quality of the public transport service. When the demand level is very high or in a high demand density area, public transport users may experience extra delay because the passenger demand exceeded the capacity of the service and they are unable to board the first arriving service.

Demand level has been used in different approaches as the independent variable to calculate the final cost output. However, the relationship between operator supply and passenger demand was not assessed. To correctly predict the actual demand level rather than using an externally fixed exogenous demand, the demand – supply relationship must be considered.

A combination of strategic level modelling and traffic simulation modelling was adopted in the previous study. This cost-effective approach is able to obtain key indicators of the real network in order to assess the costs and benefits of operating a public transport service. However, it is necessary to consider a microscopic traffic simulation, as the interactions between some of the car traffic and the public transport vehicles need to be captured in the simulation model.

CHAPTER 3 REVIEW OF TRAFFIC SIMULATION MODELS

3.1 Introduction

Traffic flow simulation studies have been used since the 1950s, when the development of computers was able to provide the calculation of the complex vehicle and human behaviour in the traffic using theoretical mathematical models. Traffic simulation is defined by Drew (1968) as a dynamic representation by using a computer model for parts of the real world. Since the great development of computer technology, traffic simulation is widely used in the transportation study field. Simulation models are based on a computer to represent the operation of a realistic traffic network in a selected time period in order to offer the prediction of future traffic situation for researchers and decision makers.

As the strategic level model of the comparative assessment calculates the operating speed in a stand-alone corridor rather than in a network with signalised junctions, a traffic simulation model is required to make sure the average operating speed of the public transport service and the passenger waiting time are accurately estimated. The operation of the public transport could have significant impacts on general traffic, and therefore it is necessary to determine the effects of the operating public transport service to the local transport network. This chapter is going to review the traffic simulation approaches and the existing simulation packages and hence select the most suitable simulation software for this study.

3.2 Simulation Requirements

Before reviewing the traffic simulation approaches and the traffic simulation packages, it is necessary to identify the simulation requirements of this research, especially for simulating innovative public transport technologies operating on a local transport corridor.

As this thesis is going to demonstrate the modelling of Straddle Bus as an example of the innovative public transport technology, the following key simulation requirements have been noted.

- The traffic simulation model must be able to simulate the operation of fixed line public transport system, including the location of stops/stations, dwell time and passenger boarding and alighting.
- The traffic simulation model must be able to capture the detailed interactions and impacts between vehicles, in order to reflect the changes in users' cost and benefit.
- The traffic simulation model must be flexible and adaptable to simulate the characteristics of the innovative public transport technologies such as the right-of-way and the bus priority, as well as the impacts to other road users.

The following sections in this chapter review and discuss the relevant traffic simulation approaches and packages that are able to meet these requirements allowing the most suitable traffic simulation tool to be selected.

3.3 Simulation Approaches

The traffic simulation can be used for various purposes, and the types of traffic simulation can be divided into three different approaches depending on their accuracy and scope as macroscopic, mesoscopic and microscopic (Lieberman and Rathi, 1996).

The macroscopic traffic simulation is based on traffic flow theory to consider the whole traffic in a higher level of aggregated point of view and equations used in the model are based on hydrodynamic theory of fluids with variables as: volume, speed and density. The relationships between these three main descriptors are well explained in many transportation engineering textbooks (Sheffi, 1985; Salter and Hounsell, 1996; Ortúzar and Willumsen, 2011). The speed is the space mean speed of the vehicles, the density is the number vehicles on the distinct route per unit length and the flow is the average number of vehicles passing a fixed point on the route per unit of time which are similar if we consider the traffic flow as fluid (Sheffi, 1985). The relationship between them can be expressed as:

$$density = \frac{flow}{space\ mean\ speed}$$

This macroscopic approach would model total number of trips on the specified corridor and describe them with these three basic parameters rather than describing each individual trip in detail. This higher level of aggregation of traffic is often easier to draw reliable measures of trips making activity in general as macro-state estimation could have fewer uncertainties than a microscopic approach (Ortúzar and Willumsen, 2011).

The microscopic traffic simulation is more focused on the detailed description of each individual vehicle in the traffic flow and the interactions between each of them using their acceleration, deceleration, speed and driver behaviour, etc. The detailed movement of every individual vehicle would be simulated precisely and separately with physical parameters as well as their interaction with other individual vehicles by using some drivers' behaviour models. To describe the vehicular movement in the microscopic simulation model, the four fundamental elements involved are car-following models, free acceleration models, lane-changing models and cellular automata models, as shown in Figure 3-1.

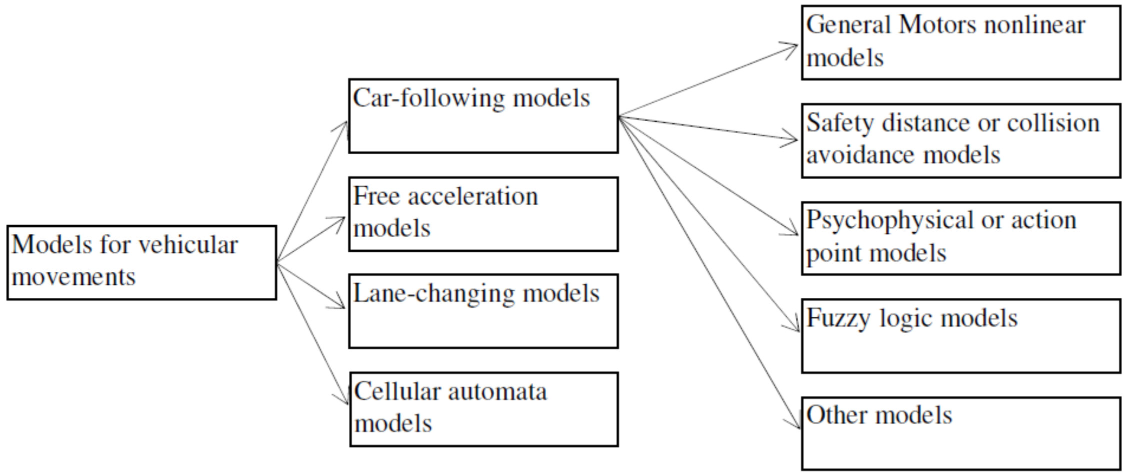


Figure 3-1 Vehicular movement models in microscopic traffic simulation

(source: Lee, 2007)

Many previous studies were undertaken and made contributions to develop these models, such as Pipes (1953), Wiedemann (1974), Ahmed (1999), Brackstone and McDonald (1999) and Toledo (2007). Different from macroscopic approach, the main purpose of using microscopic traffic simulation is for analysing the strong impacts between different vehicles or different components of the traffic. For example, if the corridor to be modelled has a large number of cyclists or pedestrians, a microscopic approach should be considered, as the cyclists or the pedestrians could have a huge impact on the road traffic.

The mesoscopic approach provides an intermediate way of traffic modelling that combines the individual vehicle analysis in microscopic simulation and the dynamics of traffic flow in macroscopic simulation (Barceló, 2010) which only specify the number of trips between origin and destination (Ortúzar and Willumsen, 2011) but with some simplifications in the individual vehicle interactions by neglecting lane changes and acceleration/deceleration and grouping up individual vehicles into cells/platoons. This simulation approach is mainly for areas with a large network where a detailed microscopic approach is infeasible or available resources are limited for the network (Burghout, 2004).

3.4 Reasons of Choosing Microscopic Simulation

For this thesis, the comparative assessment includes an innovative public transport technology, the Straddle Bus as well as the 15 different public transport modes in the TEST project. In the TEST project, a macroscopic approach was adopted. However, there are some drawbacks of using a macroscopic approach rather than a microscopic approach in this comparative assessment.

The Straddle Bus technology has the potential for significant interactions with other vehicles in the traffic flow. Straddle Bus would have its wheels straddle the road and allow other vehicles lower than 2 metres to pass underneath the deck of the bus in order to provide more traffic space while maintaining the transport capacity. This giant vehicle on the road would have impacts on the driving behaviours of other vehicles on the road, and the speed of each individual vehicle could be different due to the effect of Straddle Bus. Drivers may change their original behaviours and speeds due to the different driving environments underneath the Straddle Bus (more detailed description of Straddle Bus will be given in Chapter 4). Other than the Straddle Bus, the operating speed of the conventional bus services and the passenger waiting time are also highly related to the level of the general traffic. Therefore the interaction between each vehicle on the road should be simulated in detail.

On the other hand, lane change behaviour must be able to be modified in the simulation model. This is because in order to simulate Straddle Bus operating on road, the change in the drivers' lane changing behaviour must be taken into account. The entry to the underneath of a Straddle Bus is only at the back of the vehicle and completely blocked at the left and right side, and it is not possible to make lane changes from underneath Straddle Bus to the lane outside the bus or vice versa. Therefore, the impacts to the general traffic of blocking the lane for the lane changing vehicles must be considered in the simulation model.

Another simulation requirement of the innovative public transport technology in the model is at junctions. Some public transport technologies that share the existing road infrastructures with the car traffic such as BRT, light rail would require some priority schemes when they approach the junction, and public transport priority system is an efficient support for public transport operation (London, for example). Many previous researches have been undertaken for the modelling of priority in traffic control systems in microscopic simulation models, for example McLeod (1998), Liu et al. (1999), Shrestha (2003) and Hounsell et al. (2007). For the Straddle Bus technology, priority is also required at the junction, as the vehicle could block the left and right turning traffic due to the length of the Straddle Bus and the straddling feature. For example, the vehicles underneath Straddle Bus cannot go with the bus and have to keep waiting at the stop line when it is turning left/right for safety consideration. Therefore, priority schemes have to be applied to the Straddle Bus technology and other public transport forms with similar issues.

As a result of the listed three requirements, microscopic simulation would be a more suitable simulation approach than the macroscopic approach and mesoscopic approach for the comparative assessment, in order to capture the detailed interactions between vehicles as mentioned in Section 3.2. Microscopic simulation is able to modify the desired speed distribution for each vehicle class and each lane in order to simulate the impact of Straddle Bus on the speed for each individual vehicle. Lane changing behaviour is one of the most important parts in microscopic traffic simulation. Each individual vehicle would change lane according to the lane change choice model in the simulation tool. Features of the Straddle Bus technology can then be simulated by limiting the lane changing behaviours of the general traffic according to the position of the bus. Microscopic simulation is also capable of applying priority scheme at junctions which is required by some public transport technologies and then simulate their operation on the road with higher accuracy.

3.5 Microscopic Traffic Simulation Package Review and Selection

Since the development of computer based traffic simulation, there are a number of tools for different simulation approaches, with different points of focus on traffic characteristics such as pedestrian behaviour, public transport priority, economic return of schemes and the benefits of modern Intelligent Transportation Systems (ITS) (Algers et al, 1997). For each different traffic network or traffic situation, different software may emphasise on different aspects in the traffic network. It is crucial to understand the objectives of the traffic modelling and identify the most suitable traffic simulation package in the first place. Therefore an attentive comparison for existing traffic simulation software must be done before commencing the modelling procedure.

3.5.1 Modelling Requirements

The MSM developed in this thesis is going to be used in the case study of compare the performance of conventional bus and Straddle Bus in Nanning, China. Therefore it is necessary for the traffic simulation software to be able to provide a good simulation for public transport service in mixed traffic. As a result of the junction blocking of Straddle Bus, traffic signal control based on the position of the public transport vehicle is also required in the traffic simulation software in order to simulate the priority of the Straddle Bus at junctions. The passenger demand level is an important variable in the comparative assessment. To reflect the changes in passenger demand level from the DSM, dwell time evaluation should be based on the amount of boarding and alighting passengers. Visualisation is desirable feature to monitor the traffic simulation during model runs, in order to make sure the characteristics of the Straddle Bus are represented correctly in the model.

3.5.2 Microscopic Simulation Package Reviews

The differences among different modelling packages have been discussed and compared by many transportation modellers. Choa et al (2004) investigated and compared the differences between CORSIM, PARAMICS and VISSIM based on the simulation results on the U.S. 50 / Placerville Drive / Forni Road interchange. In their research, they found the link-connector based network in VISSIM (Figure 3-2) could avoid the inaccuracy of lane use problem in link-node based software such as CORSIM and PARAMICS. In addition, VISSIM can also provide better 3-D animation by offering more visual settings to users. Among these three models, PARAMICS and VISSIM are found to generate better results to match field survey data according to Choa et al (2004). Cheu et al (2004) compared PARAMICS and AIMSUN based on their experiences in using these two packages to model a network with a freeway and arterials. In their paper, PARAMICS is reported with better replication of actual geometry and more realistic traffic movements while AIMSUN is very easy to learn and can set up a model very quickly. A SMARTEST (Simulation Modelling Applied to Road Transport European Scheme Tests) project was carried out by the Institute for Transport Studies at the University of Leeds to develop micro-simulation tools to help solve road traffic management problems (Algers et al, 1997). In the SMARTEST project, 32 existing microscopic simulation tools were reviewed and compared to identify the different functions in these simulation tools and point out the gaps between different packages (Algers et al, 1997). Among those existing microscopic traffic simulation packages, VISSIM, AIMSUN and PARAMICS are the most typical and widely used software and have comparative capabilities (Papageorgiou et al, 2009) while other simulation software also have different focal points in the microscopic traffic simulation.

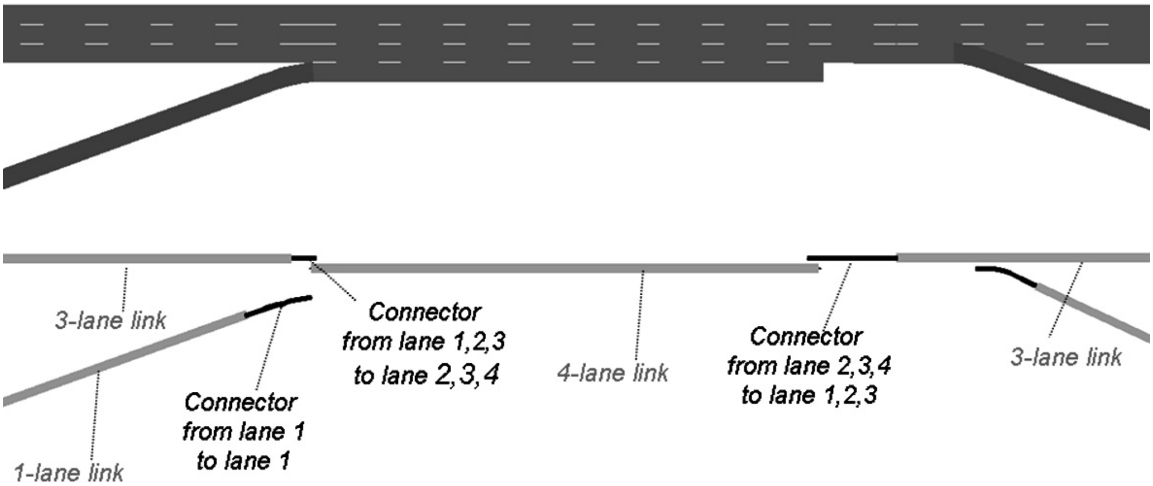


Figure 3-2 Links and connectors modelling merging in VISSIM

(Source: Barceló, 2010)

VISSIM is a microscopic simulation tool that is suitable for a broad range of traffic applications with the longest history of any microscopic simulation tool (PTV AG, 2011). The core of VISSIM is a series of theoretical models for simulating the behaviour of vehicles which was developed by Wiedemann (1974) to describe the physical and psychological car following movement of vehicles on a single lane without exits for every 0.1 to 1 second. The structure of a completed VISSIM model would be made up of three key aspects: infrastructure, traffic and control. The infrastructure block contains the detail of the road, railway and all other fixed elements in the network. The traffic block is to specify the vehicles in the traffic flow either by automatically generated traffic or O-D matrices using a dynamic assignment module (PTV AG, 2011).

The control block contains all of the information to control the traffic flow in the network such as signal data, priority, and the right of way at conflict areas. These three blocks corporate with each other in the model and operate in a given simulation time period to obtain the final outputs.

VISSIM has a lot of capability that grants it the ability to comprehensively simulate public transport technologies, for example the flexibility and convenience of setting transit routes and stops, the flexibility of bus scheduling on departure and dwell time (Feng et al, 2003). Public transport vehicles in VISSIM are treated similar to private vehicles with more characteristics added and operating on a fixed route to serve public transport stops on the selected route. The operation of buses, trams and light rail vehicles on public transport lines can be simulated and presented in a good 3-D animation. Compared to other simulation packages, the ability of VISSIM to simulate public transport network scores higher (Papageorgiou et al, 2009). The basic model of VISSIM has only the bus priority setting for conflicting public transport lines rather than green time extension or recall at a signalised junction. An external module, VisVAP, in VISSIM is also capable for modelling bus priority signal controller. VisVAP can define the signal control logic in a user friendly interface without any coding skill requirement and then generate specified control strategy including bus signal priority (PTV AG, 2013). The threshold of the detector values can be set in VisVAP. Traffic control strategy would be changed according to the traffic condition once any public transport vehicles activate the detector and then reflect to the traffic flow model. All of these settings can be done easily in the user interface in VisVAP without any program coding.

PARAMICS (PARAllel MICroscopic Simulation) is a micro-simulation developed by Quadstone Ltd. and SIAS Ltd. in Edinburgh, U.K that is capable of large network simulation of ITS (Cheu et al. 2004). These two companies developed their own version of PARAMICS called Q-PARAMICS and S-PARAMICS and provide the simulation package for outside the UK and Ireland and within the UK and Ireland, respectively. The model building procedure in PARAMICS mainly requires two inputs: network construction and vehicles demand. The network construction comprises all roads, junctions with related signals and zoning scheme, the second input contains all vehicles in the network and their origin-destination (O-D) demand matrices. An economic assessment called PEARS is available in S-PARAMICS which was developed to analyse the transportation cost including travel time cost and vehicle operating costs based on the DfT WebTAG Unit 3.5.6 – Values of Time and Operating Costs (SIAS, 2009).

Buses in PARAMICS are treated similar to other vehicles but operate on fixed routes created automatically by the software according to the provided start and end points. The bus routes are defined by the user and further intermediate links can be set if necessary. Bus priority schemes can be modelled in S-PARAMICS by using the Advanced Control Interface which "enables micro-simulation model to operate within adaptive traffic control or ITS environments" (SIAS, 2013). The Advanced Control Interface can collect the loop data and set stage times or terminate an existing stage according to the current traffic situation in the simulation network (SIAS, 2009). For Q-PARAMICS, an external module - API (Application Programming Interface) function is provided for users do their own coding and to apply external programs to the model. The bus priority scheme at junctions can then be coded and applied to the original traffic network. Some typical examples of applying bus signal priority at junctions have been done in PARAMICS (Kim et al, 2012; Chandrasekar, 2002).

AIMSUN was traffic simulation software developed by TSS – Transport Simulation Systems aiming to offer a microscopic simulator like its full name "advanced interactive microscopic simulator for urban and non-urban networks". After a long development of the software and in response to requirements from many modellers, AIMSUN now is able to simulate not just microscopic but also macroscopic and mesoscopic traffic network (TSS, 2013) and the latest version of AIMSUN is AIMSUN 8 Expert. The building process of AIMSUN models comprises two main inputs which are supply data and demand data. The supply data in AIMSUN includes all environmental information in the model and any control data related to them while the demand data are the information of all traffic users. The simulation of public transport technologies in AIMSUN requires details of each route, all departure timetables and the stop-time for each stop (Barceló, 2010).

Similar to PARAMICS, AIMSUN itself does not offer the capability of modelling bus priority scheme at junctions but is available by using the API feature. According to AIMSUN Microsimulator API Manual (TSS, 2009), external and extra functions can be coded by users with C++ or Python programming language and then inserted into the original traffic network model. Time duration, current signal stage and the type of vehicles approaching the junction can be read in AIMSUN model and achieve bus priority by determining whether a green time recall or a green time extension is necessary for the coming public transport vehicles or not.

Modelling bus priority network using AIMSUN has been done by many researchers. Arup has developed a large model incorporating route choice for Sheffield to model bus priority such as bus lanes, pre-signals and pre-emption at traffic signals (TSS, 2010). Liao and Davis (2007) analysed the bus signal priority in Minneapolis, US, with an AIMSUN model, and the bus priority scheme of their research is shown in Figure 3-3.

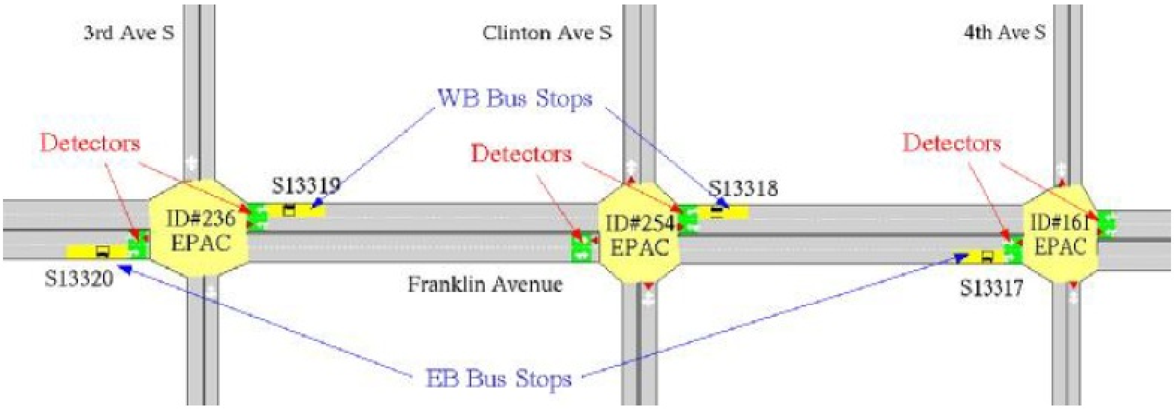


Figure 3-3 Bus stop and detector in the model

(Source: Liao and Davis, 2007)

The green areas in Figure 3-3 indicate the position of the detectors which must be identified in the Aimsun model. When a bus or any other public transport vehicles approaches the detector, priority scheme would be triggered and the signal of the next junction would be changed according to the requirement of the public transport vehicles.

In addition to these three commonly used commercial mainstream microscopic traffic simulators, there are also many other simulation packages that are capable to model the operation of public transport technologies on a corridor and produce results for the comparative assessment. However, each of them has some drawbacks in modelling the public transport technologies for this research.

DRACULA is a microscopic simulation model developed at Institute for Transport Studies, University of Leeds, which stands for Dynamic Route Assignment Combining User Learning and microsimulation. As its name indicates, the model focuses more on route choice of individual vehicles based on their choices in the past. Day to day traffic condition would be recorded and each individual trip makers would choose their route according to their experience of the traffic conditions for different routes (Liu, 2005). This is a very powerful function for modelling the drivers' behaviour in route choice. However, the comparative assessment for public transport technologies is modelled in a corridor and this feature will not make much difference. The required bus priorities in the comparative assessment such as reserved bus lanes and bus signal priority can be simulated in DRACULA as reported in the user manual (Liu, 2007).

SIMBOL is a non-commercial microscopic simulation software developed by Dr. Birendra Shrestha at the Transportation Research Group, University of Southampton. SIMBOL is short for Simulation Model for Bus Priority at Traffic Signal which is developed mainly for analysing the bus priority at signalised junctions with AVL (Automatic Vehicle Location) system (Shrestha, 2003). Although SIMBOL is a very powerful microscopic traffic simulation package for modelling bus priority scheme, it does not offer the capability to model the characteristics of various public transport technologies required in the comparative assessment.

FLOWSIM (Fuzzy Logic based Motorway Simulation) is a micro-simulation modelling tool developed by Prof. Jianping Wu at the Transportation Research Group, University of Southampton (Wu et al, 2002). Compared to other modelling packages, FLOWSIM is more focused on the drivers' behaviour on speed and gap acceptance (Cacciabue, 2007). FLOWSIM also includes its unique model for bicycle and pedestrian for networks with large numbers of cyclists and pedestrians. However, there is no literature report that FLOWSIM has the capability of modelling bus signal priority which is a necessary feature required in this research.

3.5.3 Summary

Based on the reviews of existing microscopic traffic simulation tools, VISSIM, PARAMICS and AIMSUN are widely used commercial simulation packages and meet most of the modelling requirements. However, there are still some differences among them. For example, the public transport vehicle dwell time in AIMSUN can only be calculated by using an assumed normal distribution, while in VISSIM the dwell time can be calculated by either assuming a normal distributed dwell time or based on the number of boarding and alighting passengers which is the same as the calculation method in the SCM which will be discussed in Chapter 4.

The mainstream microscopic simulation packages discussed in this section are all able to provide the basic function of simulating public transport operations in the transport network as well as producing good 3D animation to enhance the model results. After a series of considerations, VISSIM was selected based on the following three reasons.

First of all, the VISSIM licence (VISSIM 5.40) was applied and acquired from PTV AG and a number of VISSIM API modules such as dynamic assignment to distribute vehicles, COM Interface for external control of the model by using computer programming and VisVAP interface for building bus priority schemes at junctions were also provided for potential detailed simulations. By using VISSIM, large adjustment possibilities in the traffic network can be taken into account to make the integrated simulation with all kinds of traffic components more comprehensive (Thorrignac, 2008). This flexibility and adaptability of VISSIM by using the COM Interface is able to meet the requirement of modelling the characteristics of innovative public transport technologies.

The second reason is the bus priority scheme at junctions. Many public transport technologies modelled in SCM and in the simulation model require certain priority when they approach a junction which must be carefully simulated in the model. The signal control module, VisVAP interface, in VISSIM is very powerful and user friendly to simulate the bus priority scheme at junctions. In order to apply a bus priority scheme at junctions, PARAMICS and AIMSUN require API to modify the program with a lot of coding work. The VisVAP for VISSIM would be much easier to use compared to those time consuming API coding processes in PARAMICS and AIMSUN.

The third and the most important reason is the link-connector feature of the VISSIM simulation, which is very helpful in creating a simulation model for the innovative public transport technology, for example the Straddle Bus technology. This feature allows further flexibility in modelling the network with junctions, as an explicit definition of nodes is not required for junctions. The features of the innovative public transport technology can be modified for its own link without changing the general traffic. For the changes of behaviour for general traffic, the road can be split into a number of lanes and linked by connectors to allow adjusting parameters according to the position of Straddle Bus without affecting other part of the traffic.

3.6 Calibration and Validation of a Simulation Model

The development of a complete model also requires a calibration and validation process to prove the model is successfully representing the actual traffic condition and providing reliable results. The traffic condition in the real world is very complicated and many parameters must be considered. The estimation results from computer-based simulation software could be much different from the actual traffic network just because of the change in one small parameter. In order to make the estimation as close as possible to the real world scenario, model calibration and model validation are necessary for a comprehensive simulation model.

The calibration of a model is to adjust the value of parameters in the simulation model such as traffic control data, technical property of the infrastructure, drivers and pedestrian behaviours to produce similar outputs when compared to the real traffic network with the same inputs. A poorly calibrated traffic simulation model can produce an unrealistic output of the real traffic condition and mislead the people who use the result from it. The variables in the model must be well adjusted according to the real traffic situation in the calibration process. For example, the behaviour of drivers in China is different from those drivers in Europe when they are dealing with signals, car following and lane changing (Li et al, 2011).

The calibration and validation for a traffic simulation model are the most important part and the procedures are complicated. For model calibration, Hellinga (1998) proposed a process that consists of three main phases and eight component steps as presented in Figure 3-4.

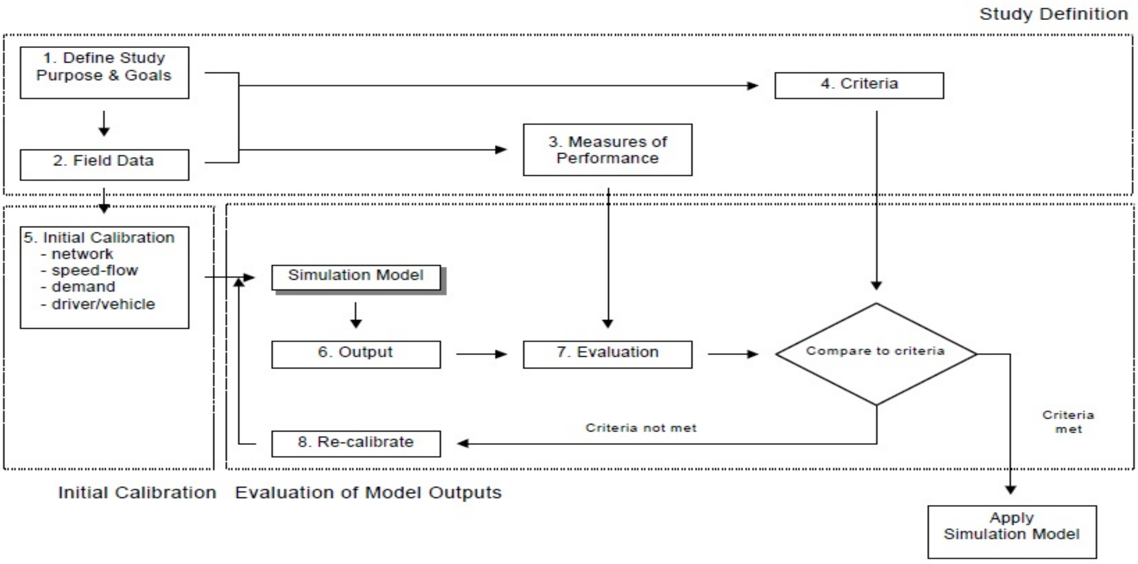


Figure 3-4 Calibration process of microscopic simulation model

(Source: Hellinga, 1998)

The proposed three phases for the calibration of microscopic simulation models are: study definition, initial calibration and evaluation of model outputs. Each phase contains different steps in the whole procedure. This calibration process gives a general way to prove the accuracy of a developed model and to reduce the scepticism from other modellers of the simulation model results. However, the validation procedure is not included in this study.

Based on the works of Hellinga (1998) and Sacks et al. (2001), Park and Schneeberger (2003) proposed a nine steps procedure for the calibration and validation of a microscopic simulation model and presented with a case study of which is widely used and recognised among transportation researchers. The nine steps are:

1) measure of effectiveness selection
2) data collection
3) calibration parameter identification
4) experimental design
5) run simulation
6) surface function development
7) candidate parameter set generation
8) evaluation

9) validation through new data collection

This nine-step procedure is recognised as a general guideline for calibrating and validating micro-simulation traffic models and it is also widely accepted by many traffic simulation researchers. Therefore, this method would be applied to the calibration and validation stages of the simulation model.

1. Measure of effectiveness selection. The first step is to decide the controllable and uncontrollable input parameters in the model and one performance measure to identify if the model is suitable for the selected real traffic network. This is because most of the research does not require the simulation model to replicate the network exactly the same as the real traffic in every aspect but at one or some important points in order to give the outputs about the concerning problems. Therefore, the calibration and validation procedure should identify all measures of effectiveness in the first place before any data is collected.

2. Data Collection. The second step is to collect data from the real traffic system. This data collection must include the one performance measurement and all identified uncontrollable parameters. Controllable parameters are optional, as they can be changed in the simulation model.

3. Calibration parameter identification. The third step is to identify all parameters needed in the calibration stage, as those parameters are going to be adjusted. This step is also going to decide the acceptable ranges for all of the controllable parameters for the calibration.

4. Experimental design. The experimental design step is used to determine the process of the simulation because as the number of combinations of those controllable parameters could be very large and the required simulation run would be very difficult to proceed. Therefore an effective simulation plan must be designed beforehand.

5. Run simulation. The fifth step is to run the simulation according to the experiment plan and then to record the average value and the standard deviation for the performance measure determined in step 1.

6. Surface function development. After collecting the performance measure results from the simulation, a surface function can be developed to present the relationship between the performance measurements and the controllable parameters.

7. Candidate parameter set generation. & 8. Evaluation. The seventh and eighth steps are to find the best related set of controllable parameter for the calibration and then to test if they can give significant good results that link to the measure of performance. Once the sets of controllable parameter are verified according to these two steps, the final data collection can be done for the model validation.

9. Validation through new data collection. A new data set for all of the verified parameter sets must be used and compared again with the output from the model in order to prove that the model is validated and able to provide accurate result to reflect the actual traffic conditions.

This procedure proposed by Park and Schneeberger (2003) strictly includes every step not just for calibration but also validation of a microscopic simulation model and acknowledged by many other transportation researchers (Toledo et al, 2004; Cunto and Saccomanno, 2008; Wang, 2012; Sun et al, 2013). As this pattern is well developed for microscopic simulation model calibration and validation, the simulation model of the comparative assessment will follow this nine-step procedure.

3.7 Conclusion

For the development of the comparative assessment, the traffic simulation package must to be able to simulate the operation of the 16 public transport technologies operating on road and produce their travel times and passenger waiting times in order to link with the SCM to assess both user’s and non-user’s costs and benefits.

As this thesis considers both conventional and innovative forms of public transport, microscopic simulation rather than macroscopic and mesoscopic simulation is adopted in order to evaluate the detailed interactions between general traffic and the public transport vehicle. The simulation packages reviewed are all very powerful in simulating microscopic traffic network. VISSIM has been chosen to be the simulation software for this comparative assessment, as it is able to provide good public transport simulation functions and good flexibility in modelling innovative public transport technology as discussed in Section 3.4. The calibration and validation of a simulation model are essential steps to prove the result generated by the model is able to reflect the actual traffic network. The nine-step calibration and validation of microscopic simulation model proposed by Park and Schneeberger (2003) is adopted as discussed in Section 3.6 and detailed procedures are going to be discussed in Chapter 6.

CHAPTER 4 SPREADSHEET COST MODEL

4.1 Introduction

In order to develop the comparative assessment for different public transport technologies, it is necessary to construct a cost model to compare the advantages and disadvantages of those public transport technologies. The cost model developed in this thesis is a theoretical and strategy level model based on Microsoft Excel to analyse the social cost of different public transport technologies in various passenger daily demand levels on a hypothetical public transport corridor without any traffic signals or junctions. As discussed in Chapter 2, the total social cost is defined as:

$$TSC = TOC + TUC + TEC$$

where TSC is the total social cost, TOC is the total operator cost, covering all capital investment by operators of the public transport service, TUC is the total user cost, including passenger walking time (WKT), waiting time (WTT) and in-vehicle time (IVT) converted into money units using values of time and TEC is the total external cost which accounts for any external impacts such as air pollution and accidents.

In this chapter, the development of this Spreadsheet Cost Model is going to be described in details, including the basic parameter values, unit cost values, intermediate variable calculation equations and the calculation of the operator, user and external cost. To help with the large amount of symbols and abbreviations used in this chapter, the selected symbols and abbreviations of the SCM can be found in Appendix C. The characteristics of Straddle Bus are described in the first place, in order to include this innovative public transport technology in the comparative assessment.

4.2 Straddle Bus Technology

Straddle Bus is a new rapid transit concept that was developed by Shenzhen Huashi Future Parking Equipment Company. This conceptual technology was published at the 13^{th} Beijing International High-tech Expo in May 2010, which was considered as the 50 best inventions of 2010 by TIME (Ramzy, 2010). The design of Straddle Bus aims to make use of the areas that above private vehicles, in order to reduce traffic congestions while maintaining the capacity of public transport services. An elaborate video of Straddle Bus was released by China TBS (2012), which describes the Straddle Bus in more details.

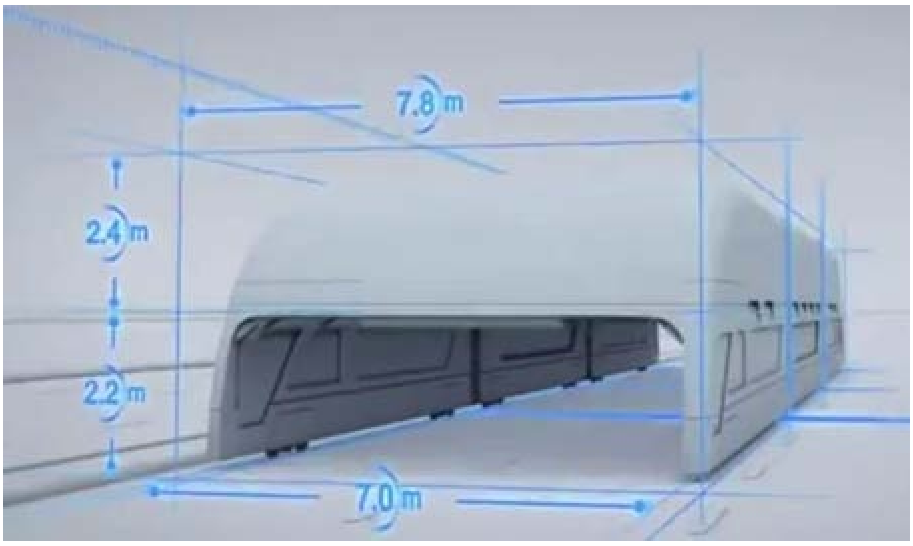


Figure 4-1 The design dimension of Straddle Bus

(source: China TBS, 2012)

The Straddle Bus is designed to straddle two lanes in urban area and have a maximum speed of about 60 km/h. However, as the Straddle Bus is designed to operate above the general traffic and avoid congestions, the average speed is believed to have significant advantages compared with conventional buses. Although the segregation advantage of underground can lead to higher operating speed than the Straddle Bus, capital infrastructure cost of the Straddle Bus system is believed to be much lower, as Straddle Bus only requires some reconstructions of the existing road surface and additional bus stop/station facilities (Sadieblooming. 2010).

The capital cost of restructuring the road surface and building elevated bus stops for Straddle Bus was estimated to be 50 million yuan per kilometre by the inventor, Youzhou Song, while the construction cost of underground is approximately 500 million yuan per kilometre in China (NetEase, Inc., 2010).

The Straddle Bus is designed to be electrically powered, with overhead lines to charge at each stop. Similar technology was applied to the trolleybus in Shanghai since 2006, which is the "supercapacitor" trolleybus. This "supercapacitor" trolleybus is able to be recharged quickly in 30 seconds when it stops at the station with the overhead charger, and the electricity obtained will guarantee a 3 – 6 km operation depending on the load and the air-conditioning of the bus (UNEP, 2010).

Figure 4-2 Overhead lines for the Straddle Bus

(source: Sadieblooming, 2010)

The entrance and exit are at the rear and the front of the Straddle Bus. As a result of that, Straddle Bus will have impacts on the turning vehicles. Therefore, the Straddle Bus is required to have connection with traffic signals to have priority at junctions, which would potentially reduce the speed of the general traffic.

Figure 4-3 Conceptual model of Straddle Bus (rear view)

(source: China TBS, 2012)

As Straddle Bus is only a conceptual technology, the operation method was proposed in two different ways: offside and nearside.

The offside approach of the Straddle Bus system would be similar to most applications of BRT – the Straddle Bus will be operating in the two offside lanes and passengers have to reach the station in the middle of the road to get on the Straddle Bus. As the Straddle Bus stops/stations need to be elevated, this approach would require a footbridge for passengers to access/egress to/from the vehicle, where additional infrastructure costs would be incurred. This approach would also affect traffic that wants to turn left (turn right in the UK case), as the movement of the Straddle Bus will block the junction. Therefore, traffic signals may also need to be redesigned to take the delay of the left turning traffic into account.

The nearside approach is more similar to the conventional bus operation, where the Straddle Bus will be operating on the two nearside lanes. In this approach, the Straddle Bus station can be located at the same place as the conventional bus and passengers do not have to reach the middle of the road as for the offside approach. As the Straddle Bus in this nearside approach will straddle the two nearside lanes, the right turning movement (left turning in the UK case) would also be blocked by the movement of the Straddle Bus when it passes the junction. Therefore, a separate lane to divert the right turning traffic would be required or the traffic signals would need to be redesigned.

The additional infrastructure costs of the operator and delays to road users due to the different design of the Straddle Bus system need to be included in the cost modelling and the microscopic traffic simulation to reflect the characteristics and impacts of the Straddle Bus technology.

As the Straddle Bus is still a conceptual technology, there is no existing Straddle Bus system all around the world. However, Straddle Bus can be an intermediate public transport for large cities such as Beijing, Shanghai, Tokyo and Hong Kong, where the demand for public transport is high while the spaces on road are precious. Therefore, it is worth to include this innovative public transport technology in the comparative assessment to find out the potential costs and benefits of the Straddle Bus by comparing with other existing public transport systems.

4.3 Basic Parameters and Unit Costs

To evaluate the social cost of different public transport technologies, the characteristics and the unit cost parameters must be identified. After reviewing the existing public transport service in the UK by Brand and Preston (2001), the characteristics of 15 public transport technologies were summarised in Brand and Preston (2003a). By reviewing the promotional video *China Straddling Bus* (Sadieblooming, 2010), Li and Preston (2014) also included this innovative public transport technology into the comparative assessment. The description of the 16 public transport technologies modelled in this SCM is shown in Table 4-1.

Table 4-1 Description of public transport technologies modelled in Spreadsheet Cost Model

Categories	Technologies	Description	Max. passenger	Max. speed (km/h)
Small Vehicle Technology	Minibus	Minibus e.g. Ford 'Transit', Mercedes 'Sprinter'	16	50
	Personal Rapid Transit	ULTra system as proposed for Cardiff and completed at Heathrow Airport.	4	40
Conventional Bus	Single-decker bus	Low floor single decker bus in mixed traffic	75	50
	Articulated bus	Low floor articulated bus in mixed traffic	90	50
	Double-decker bus	Low floor double decker bus in mixed traffic	85	50
	Single-decker bus on bus lane	Low floor single decker bus on (non-segregated) bus lanes	75	50
	Single-decker bus on busway	Low floor single decker bus on segregated busway	75	50
	Single-decker bus on guideway	Low floor single decker bus on guided busway	75	50
	Double-decker bus on guideway	Low floor double decker bus on guided busway	85	50
Light Rail Transit	Guided Light Transit	"Tram-on-tyres" type vehicle (Caen Guided Light Transit etc.)	125	50
	Straddle Bus	Assume 4-car unit straddle bus that occupies two lanes	330	60
	Modern light rail	Typical 3-car unit LRV for urban services (Croydon etc.)	220	60
	LRV tracksharing	Typical 3-car unit LRV for inter-urban services (Karlsruhe etc.)	220	60
Heavy Rail Transit	Suburban heavy rail	2 unit inter-urban heavy rail on segregated tracks	250	112
	Regional heavy rail	4 unit inter-urban heavy rail on segregated tracks	400	160
	Underground	Typical urban metro in a large city (London underground) (assume 6-car unit)	500	40

(source: Li and Preston, 2014. Details of the table can be found in Appendix D.)

As the comparative assessment is for different public transport technologies, other innovative forms of public transport can also be taken into account, for example the New Generation Transport trolleybus scheme proposed for Leeds (see www.ngtmetro.com). The summary of characteristics of the public transport technology modelled in this SCM is shown in Table 4-2.

Table 4-2 Summary of public transport technology characteristics modelled

Categories	**Technologies**	**Vehicle capacity**		**Vehicle length**	**Max. allowable vehicle speed**		**Infrastructure capacity[6]**
		Seats only (pax)	**Total (pax)**	**(m)**	**Urban (km/h)**	**Inter-urban (km/h)**	**(veh/hour)**
Small Vehicle Technology	Minibus	16	16	7.0	50	80	400
	Personal Rapid Transit[1]	4	4	3.5	40	40	1,850
Conventional Bus	Single-decker Bus	40	75	12.0	50	80	250
	Articulated Bus	60	90	18.0	50	80	167
	Double-decker Bus	78	85	12.0	50	80	250
	Single-decker bus on bus lane	40	75	12.0	50	80	250
	Single-decker bus on busway	40	75	12.0	50	80	250
	Single-decker bus on guideway	40	75	12.0	50	80	133
	Double-decker bus on guideway	78	85	12.0	50	80	133
Light Rail Transit	"Guided Light Transit"	75	125	24.5	50	80	120
	Straddle Bus	200	330	40.0	60	60	129
	Modern light rail	100	220	30.0[3]	60	100	137
	LRV tracksharing	100	220	30.0[3]	60	100	137
Heavy Rail Transit	Suburban heavy rail[2]	150	250	50.0	N/A	112	103
	Regional heavy rail	220	400	64.0[4]	N/A	160	78
	Underground	240	500	72.0[5]	40	N/A	113

Note:
1. Assumed 2 tracks/lanes.
2. Assumed 2 cars/units per train.
3. Assumed a single LRV (3 cars).
4. Assumed 4 units per train at 16m each.
5. Assumed 6 units per train at 12 each.
6. See explanation in Section 4.4, default values were obtained from Brand and Preston (2003a).

(source: Li and Preston, 2014. Details of the table can be found in Appendix D.)

The maximum capacity of the Straddle Bus technology was assumed to be 50% more than the Modern light rail technology. This is because Straddle Bus was assumed to be 4-car unit and straddle two lanes, and therefore it has a greater length and greater width while providing more seats to the passengers according to the presentation of the inventor, Youzhou Song (Sadieblooming, 2010).

To calculate the operating cost of the public transport service, it is necessary to identify the unit operating cost. Li and Preston (2014) updated the unit operating cost table of 15 public transport forms in Brand and Preston (2003a), and the default unit operating cost values used in the comparative assessment are shown in Table 4-3.

Table 4-3 Default unit operating costs in Spreadsheet Cost Model

Categories	**Cost components**	**Time-related**	**Distance-related**	**Route maintenance**	**Vehicle-related**
	Units	£ per Vehicle-hours	£ per Vehicle-kilometres	£ per Route-kilometres	£ per Peak Vehicle Requirement
Small Vehicle Technology	Minibus	10.600	0.139	2,642	4,292
	Personal Rapid Transit	1.325	0.139	2,642	661
Conventional Bus	Single-decker bus	13.250	0.277	2,642	17,168
	Articulated bus	13.913	0.305	2,642	18,885
	Double-decker bus	13.913	0.333	2,642	20,601
	Single-decker bus on bus lane	13.250	0.264	3,963	17,168
	Single-decker bus on busway	13.250	0.264	3,963	17,168
	Single-decker bus on guideway	13.581	0.264	6,605	18,026
	Double-decker bus on guideway	13.581	0.264	6,605	18,026
Light Rail Transit	Guided Light Transit	13.581	0.366	6,605	22,318
	Straddle Bus	62.219	0.661	12,880	61,835
	Modern light rail	62.219	0.661	12,880	46,376
	LRV tracksharing	62.219	0.661	10,806	90,116
Heavy Rail Transit	Suburban heavy rail	54.954	1.057	19,815	66,050
	Regional heavy rail	123.910	2.153	60,269	292,872
	Underground	84.676	4.597	541,512	106,787

(source: Li and Preston, 2014. Details of the table can be found in Appendix D.)

Note that the unit operating cost values are in the price level of year 2011. This is because the capital investment data provided for the Straddle Bus is for the price level in year 2011, and therefore all the cost values have been updated from the price level in year 2000 to the price level in year 2011 by using the Retail Price Index (RPI) differences between year 2000 and year 2011.

Based on the published RPI Detailed Reference Tables by the UK Office for National Statistics (ONS, 2011), the RPI value is 166.6 in January 2000 and 229.0 in January

2011 with a base level of 100 in January 1987. Therefore, the price increment factor is calculated as:

$$\frac{RPI_{2011}}{RPI_{2000}} = \frac{229.0}{166.6} = 1.37$$

This price increment factor of 1.37 has been applied to all cost values to update the price from the level in year 2000 to year 2011.

For the Straddle Bus, all of the default unit operating costs are assumed to be the same as modern light rail. This is because the operation of Straddle Bus is similar to modern light rail (e.g. Manchester Metrolink) which can also operate on the existing road surface with steel-wheel (Knowles, 2007) rather than the Guided Light Transit (GLT) with rubber tyre, and the insurance and maintenance of this innovative technology should be much higher than conventional buses. The total vehicle-related cost for the Straddle Bus is 1/3 higher because it has more car units (4-car unit) for one vehicle than the modern light rail (3-car unit).

A sensitivity test has been performed to investigate the differences if the default costs are developed using other light rail transit systems (e.g. GLT and LRV tracksharing). From the sensitivity test, the average operator costs range from -24% for Guided Light Transit to +10% for LRV tracksharing and the average social costs are from -7.5% for GLT to +1.9% for LRV tracksharing. The differences are not notable except the operator costs using the GLT unit costs. However, the most cost-effective demand range for Straddle Bus stays unchanged. Therefore, the default unit operating costs are assumed based on modern light rail technology.

To calculate the annual capital investment charge of the public transport technology, the capital investment costs and the economic life expectancies for both the fleet and the infrastructure is needed. Table 4-4 summaries the capital investment of the 16 public transport technologies in SCM.

Table 4-4 Default unit capital costs, economic life expectancies in Spreadsheet Cost Model

Categories	Technologies	Infrastructure costs (£m per km)	Vehicle costs (£ per vehicle)	Economic life, fleet	Economic life, infrastructur
Small Vehicle Technology	Minibus	0.66	79,260	10	25
	Personal Rapid Transit	3.05	33,025	10	25
Conventiona l Bus	Single-decker Bus	0.66	145,310	10	25
	Articulated Bus	0.66	198,150	10	25
	Double-decker Bus	0.66	198,150	10	25
	Single-decker Bus on bus lane	1.31	145,310	10	25
	Single-decker Bus on busway	6.61	145,310	10	25
	Single-decker Bus (Guided)	4.80	151,915	10	25
	Double-decker Bus (Guided)	4.80	204,755	10	25
Light Rail Transit	"Guided Light Transit"	3.30	1,453,100	15	25
	Straddle Bus	8.15	2,774,100	15	25
	Modern light rail	9.15	1,849,400	15	25
	LRV tracksharing	5.30	1,981,500	25	50
Heavy Rail Transit	Suburban heavy rail	13.21	2,377,800	25	50
	Regional heavy rail	26.42	3,302,500	25	50
	Underground	105.68	2,642,000	25	50

(source: Li and Preston, 2014. Details of the table can be found in Appendix D.)

Note that the infrastructure cost of PRT here refers to those PRT systems that operate on a guideway, which requires the construction of a certain distance of infrastructure. For the Straddle Bus technology, the infrastructure capital investment cost is estimated to be 50 million RMB per km (Sadieblooming, 2010) while the underground costs in China are about 500 million RMB per km, which is because the infrastructure of the Straddle Bus technology requires only road reconstruction and new stations.

Considering the price difference including labour costs and material costs between the UK and China, the Purchasing Power Parity (PPP) rate from the Organisation for Economic Co-operation and Development (OECD) is used. The PPP rate is an economic theory construct to consider the value of currencies which considers both the currency rates and the purchasing power of different countries (OECD, 2011).

According to the PPP rates in 2011, the PPP for the UK is 0.679 (US = 1.000) while China is 4.173 and therefore a factor of 0.163 (= 0.679 / 4.173) was used. The default infrastructure cost of Straddle Bus, including reconstruction of roads and stations/stops, is hence assumed to be £8.15 million per kilometre.

The actual vehicle cost for Straddle Bus is unknown as there is no existing service. Due to its high-tech requirement, the default vehicle cost is assumed to be 50% higher than the modern light rail to account for the extra capacity and the economic life expected for both vehicle and infrastructure are assumed to be the same, as they are both modes of rail transport operating on existing roads.

For the external environment cost calculation, the unit external cost by impact category needs to be identified. Brand and Preston (2002b) reviewed environment externalities studies of different public transport systems (Bickel and Friedrich, 1995; NERA, 1999; Sansom et al., 2001), and provided the unit external costs per vehicle-kilometre of 15 public transport technologies in Brand and Preston (2003a).

Table 4-5 Default external unit costs by impact category

Categories	Technologies	Air pollution (pence/vkm)			Noise pollution (pence/vkm)			Climate change (pence/vkm)			Accidents (pence/vkm)		
		low	central	high	low	central	high	low	central	high	low	central	high
Small Vehicle Technology	Minibus	8.7[4]	16.5[4]	25.2[4]	1.3[4]	5.8[4]	6.9[4]	1.2[4]	1.5[4]	1.7[4]	0.3	1.7	3.2
	Personal Rapid Transit	0.7[5]	1.3[5]	2.4[5]	0.5[5]	1.1[5]	1.7[5]	0.4[5]	0.8[5]	1.5[5]	-	0.1	-
Conventional Bus	SingleBus	14.5	27.6	42.1	2.8	11.8	13.9	2.1	2.4	2.8	0.3	1.7	3.2
	ArtBus	17.4[1]	33.2[1]	50.6[1]	2.8	11.8	13.9	2.5	2.9	3.3	0.3	1.7	3.2
	DoubleBus	16.0[2]	30.4[2]	46.4[2]	2.8	11.8	13.9	2.2	2.6	3.0	0.3	1.7	3.2
	SingleBus on buslane	14.5	27.6	42.1	2.8	11.8	13.9	1.8[7]	2.1[7]	2.5[7]	0.3	1.7	3.2
	SingleBus on busway	14.5	27.6	42.1	2.8	11.8	13.9	1.8[7]	2.1[7]	2.5[7]	0.3	1.7	3.2
	SingleBus (Guided)	14.5	27.6	42.1	2.8	11.8	13.9	1.8[7]	2.1[7]	2.5[7]	0.3	1.7	3.2
	DoubleBus (Guided)	16.0[2]	30.4[2]	46.4[2]	2.8	11.8	13.9	2.1[8]	2.4[8]	2.8[8]	0.3	1.7	3.2
Light Rail Transit	"Guided Light Transit"	7.3[3]	13.9[3]	21.0[3]	1.8[6]	7.8[6]	9.2[6]	2.1[3]	2.4[3]	2.8[3]	0.3	1.7	3.2
	Straddle Bus	7.1	13.3	21.0	10.0	21.8	33.6	3.7	7.5	14.9	0.5	2.6	4.8
	Modern light rail	7.1	13.3	23.6	10.0	21.8	33.6	3.7	7.5	14.9	-	0.0	-
	LRV tracksharing	7.1	13.3	23.6	10.0	21.8	33.6	3.7	7.5	14.9	-	0.0	-
Heavy Rail Transit	Suburban heavy rail	4.5	12.3	23.2	12.2	26.2	40.2	4.2	8.6	17.0	-	0.0	-
	Regional heavy rail	5.5	14.0	25.8	4.9	10.6	16.2	4.5	8.9	17.7	-	0.0	-
	Underground	-	24.8	-	-	26.3	-	-	8.3	-	-	0.0	-

Note:
1. Assumed 20% higher local air pollution emissions (mainly PM10) than single bus, mainly due to higher weight and larger engines.
2. Assumed 10% higher local air pollution emissions (mainly PM10) than single bus, mainly due to higher weight and larger engines.
3. Assumed 50% lower local air pollution emissions than single bus, mainly due to hybrid-electric propulsion. Climate change impacts similar to articulated bus.

4. Assumed 40% lower local air pollution and climate change emissions than single bus, mainly due to smaller engines and lower weight.
5. Assumed to be 10% of light rail costs.
6. Assumed 33% lower noise emissions than single bus, mainly due to quieter hybrid-electric propulsion.
7. Assumed 10% lower CO_2 emissions per km than single bus due to less congested running and therefore better fuel consumption.
8. Assumed 10% higher CO_2 emissions per km than single bus due to increased weight and engine size but less congested running and therefore better fuel consumption.

(sources: adapted from Brand and Preston (2003a) . Details of the table can be found in Appendix D.)

The default unit external costs used in the SCM for each public transport technology are shown in Table 4-5 above. The inventor of Straddle Bus claimed that there is an electric motor design similar to the technology of overhead charger in each terminal station adopted by trolley buses. As a result, the costs for Straddle Bus were assumed to be the same as modern light rail. As there is no operation history of Straddle Bus around the world, the external accident cost of Straddle Bus was assumed to be 50% higher than other modes, mainly due to the public concerns of the interactions with cars.

4.4 Intermediate Variables

The costs related to the public transport service are highly depended on the performance of the service. Therefore, it is essential to evaluate those service performance indicators as intermediate variables before calculating the operator cost, user cost and external cost in the Spreadsheet model.

4.4.1 Demand

SCM assumes the public transport service is operating on a segregated 12 km corridor without any signalised junctions or roundabouts. There are three time periods in SCM: morning peak period, evening peak period and off peak period, which is assumed based on the core operating day time services (07:00 to 18:00). The lengths of these time sectors are assumed to be 2 hours for each peak time and 7 hours for the off peak and 11 hours of steady operating period in total. The daily passenger demands are split into these time period which is 22.5% for each peak period and 55% for the off peak. The passenger demand of each time period is then calculated as:

$$Q_t = \frac{\beta \cdot Q}{T_t}$$

where,

Q_t = passenger demand in the time period *t* (passenger/hour);

β = passenger demand share of the time period *t* (%);

Q = total daily passenger demand (passengers/day);

T_t = duration of the time period *t* (hour).

The total daily passenger demand level in the SCM is assumed to be exogenous, which means it is externally fixed by the model. The calculation for each public transport technology is performed with a starting total daily passenger demand level of 1,000 and goes up to 200,000 per day with an increment of 1,000 total daily passengers, and then the service performance is calculated based on the hourly passenger demand level of the time period.

4.4.2 Service Frequency and Infrastructure Capacity

In SCM, the service frequency of the public transport technology is calculated based on the current passenger demand level of the time period and the maximum capacity of the vehicle, and the calculation formula is:

$$F_t = \frac{\alpha \cdot Q_t}{\gamma \cdot C_{veh}}$$

where,

F_t = service frequency requirement for the passenger demand level in the time period *t* (vehicle/hour);

α = supply/demand factor to allow for seasonal variation in demand (default value is assumed to be 1.1);

γ = maximum load factor of the vehicle at which level a new vehicle is required;

C_{veh} = the total passenger capacity of the vehicle, including seating and standing (passenger/vehicle).

With the hourly passenger demand in the time period, the service frequency requirement can be obtained. However, it is impossible to increase the service frequency further for the public transport technologies that have low vehicle capacity. Therefore, the service frequency cannot exceed the maximum service frequency, which is defined as the infrastructure capacity. The infrastructure capacity in terms of maximum vehicles per hour per lane (for road-based systems) / per track (for rail-based systems) for each of the public transport technology is either set (where overtaking is possible) by the user or calculated by using the safety headway (where overtaking is impossible and there is no off-line stops in a single lane system) which is calculated as:

$$H = T_{stop} + \sqrt{2L_{veh}/A} + 3.6 \cdot \frac{L_{veh}}{V_{max}} + \frac{V_{max}}{3.6 \cdot 2 \cdot A_{max}}$$

where,

H = safety headway (second);

T_{stop} = average fixed vehicle stopping time per stop/station (second);

L_{veh} = the total length of the vehicle (metre);

A = acceleration and deceleration of the public transport vehicle (metre/second^2);

V_{max} = maximum operating speed of the public transport vehicle (kilometre/hour);

A_{max} = maximum deceleration of the public transport vehicle in emergency breaking situation (metre/second^2).

This safety headway considered the minimum allowance headway in seconds by assuming no passenger boarding for each stop/stations and the public transport vehicle runs in maximum operating speed. Note that the average fixed vehicle stopping time is added to account for the public transport vehicle waiting due to driver rest stops, change in shifts or to regulate the service timetabled. Therefore, the infrastructure capacity is calculated as:

$$C_{inf} = \frac{3600}{H}$$

where,

C_{inf} = infrastructure capacity of the public transport technology (vehicle/hour).

The service frequency provided by the operator is calculated based on the current passenger demand level and restricted by the maximum of the infrastructure capacity of the public transport technology.

4.4.3 Operating Speed

The average operating speed calculation in the cost model is very important, as the quality of service highly depends on the operating speed of the public transport service. In the TEST project (Brand and Preston, 2003a), the average operation speed is associated with the required service frequency, and it is calculated with the speed-flow equation of:

$$V_{all} = V \cdot (1 - \frac{F_t}{C_{inf}})$$

where,

V_{all} = average operating speed, including all stop density and capacity restraints (kilometre/hour);

V = operating speed, including stop density restraints but no capacity restraints (kilometre/hour).

In this equation, V is the vehicle operating speed (km/h) calculated by using the default value (or user defined) of acceleration, maximum speed, station spacing, stopping time and passenger boarding/alighting time without considering the capacity of the infrastructure as:

$$V = \frac{D_{stop} \cdot 1000}{2 \cdot \frac{V_{max}}{3.6 \cdot A} + \frac{\left(D_{stop} \cdot 1000 - \frac{V_{max}}{3.6 \cdot A} \cdot \frac{V_{max}}{3.6 \cdot 2} \cdot 2\right)}{\frac{V_{max}}{3.6}} + T_{dwell}}$$

where,

T_{dwell} = average vehicle dwell time per stop/station, including average fixed vehicle stopping time and passenger boarding/alighting time (second);

D_{stop} = distance between stops (kilometre).

By assuming constant acceleration and deceleration, the calculation of vehicle operating speed considers the distance between stops, acceleration time, deceleration time, time spent at free-flow condition as well as the time spent at stop. The simplified operating speed equation is:

$$V = \frac{V_{max} \cdot A \cdot D_{stop} \cdot 1000}{(\frac{V_{max}}{3.6})^2 + A(D_{stop} \cdot 1000 + T_{dwell} \cdot \frac{V_{max}}{3.6})}$$

This vehicle operating speed does not account for any other traffic on the corridor, and it measures the speed of the public transport vehicle by using the time spent accelerate and decelerate between stops/stations and the dwell time. As the SCM is at a strategic level, the average dwell time calculation assumes a uniform distribution of the passengers in each stop/station. Therefore the average dwell time per stop/station is calculated as:

$$T_{dwell} = T_{stop} + T_{pas} \frac{Q_t}{(L_{track}/D_{stop}) \cdot F_t}$$

where,

L_{track} = total track length of the corridor (kilometre);

T_{pas} = average boarding time per passenger (second);

Note that to account for both directions of the corridor, the value of L_{track} is twice of the corridor length, which is 24 km for the 12 km corridor in the default condition. The average boarding time per passenger depends greatly on the ticketing system and the public transport technology. Due to the lack of information, the SCM assumes a uniform ticketing system, and the boarding time for each boarding passenger is fixed. For rail-based public transport system, passengers are able to board from any coach of the vehicle. As a result of that, the average boarding time per passenger for those public transport technologies that have multiple car units is calculated by the fixed boarding time divided by the number of car units.

The speed-flow equation in the TEST project is a linear function as shown above. This is because the stand-alone cost model of the TEST project assumed the public transport service is on a segregated 12 km route and the level of public transport traffic is fixed. However, the advantages of having a segregated road for the forms of public transport such as guided bus and rail-based public transport modes cannot be clearly shown in the cost model. If the service frequency requirement of the public transport service increases which means the passenger demand on the route is increased, the probability increases that not only the public transport vehicles themselves but also other traffic will delay the operating speed of the public transport services, either by causing congestion at the junctions or by blocking access in to or out of the stops.

The speed of the traffic flow can be estimated based on the number of the vehicles entering the route and the capacity of the roadway. As the travel time is highly related to the travel speed, a simple power law function can be used to demonstrate the relationship of traffic volume and travel time, and the power law function is:

$$1/S = T_0 + T_1(v/v_K)^k$$

where,

T_0, T_1, and k = parameters;

v = the traffic volume (vehicle/hour);

S = the travel speed (km/hour);

v_K = the facility capacity.

This power law function is postulated for single links in a network by the U.S Bureau of Public Roads with k = 4 and T_0/T_1 = 0.15 and widely used in many economic models (Small, 1992). Small (1992) also derived another function to express the travel time over a peak period, which is a piecewise linear function:

$$1/S = \begin{cases} T_0 & v \le v_K \\ T_0 + T_1(v/v_K - 1) & v > v_K \end{cases}$$

Parameters were estimated for both the power law function and the piecewise linear function and average maximum delay against daily vehicles were plotted by Small (1992), and the piecewise linear function was found to fit the real world data in the inner Boston area slightly better, by showing lower root-mean-squared residual for both morning and afternoon observations (Small, 1992, page 71-72).

However, these functions are for calculating the speed and travel time in mixed traffic flow, given the capacity of the roadway. Many innovative forms of public transport tend to operate on either transit lanes (guided bus, light rail etc.) or grade-separated rights-of-way (Personal Rapid Transit, underground etc.) to avoid the delay caused by other vehicles. Facility capacity will vary in different operating environments of the public transport service. For example, conventional bus service may experience congestion and the operating speed will start to decrease at a lower level of passenger demand than those bus services operating on segregated busway such as the guided bus and Bus Rapid Transit. The method of determining the lane capacity of a public transport technology in the TEST project is to consider the minimum headway without any passenger boarding. Therefore a factor should be added to account for the differences between different operating environments.

The impacts of operating environment on capacity have been investigated and reported in *Transit Capacity and Quality of Service Manual* (Kittelson & Associates, Inc., et al, 2013). There are four types of operating environments which are discussed in that manual, which are: mixed traffic, semi-exclusive, exclusive and grade separated. Mixed traffic operating environments mean the public transport mode has to share lanes at all times with general traffic, such as the conventional bus service. Semi-exclusive operating environments will have partially dedicated facilities for transit use, but are also available for other vehicles at certain times, such as buses on bus lane and light rail line with pedestrian access. Exclusive operating environments are defined as the facilities that are dedicated for transit use at all times, but there may be some external traffic interaction at controlled locations (for example, guided bus or BRT). Grade separated operating environments have no at-grade crossings, and facilities are fully dedicated to the transit vehicles (for example, underground). Facility capacity as a percentage of base condition for different operating environments has been illustrated in the Transportation Research Board's *Transit Capacity and Quality of Service Manual* (see, Kittelson & Associates, Inc., et al, 2013, page 3-34), as shown in Table 4-6.

Table 4-6 Facility capacity as % of base condition in different operating environments

Transit Type	Mixed Traffic (urban street)	Semi-exclusive (transit lane)	Exclusive (street median)	Exclusive (private right-of-way)	Grade-separated (busway or subway)
Bus	38%	52%	61%	87%	100%
Light Rail	41%	67%	100%	92%	100%

(source: data adapted from Transit Capacity and Quality of Service Manual (Kittelson & Associates, Inc., et al, 2013))

The facility capacity is defined as the maximum possible service frequency of the public transport services calculated either by critical bus stop capacity (for bus transit) or by safety headways (for rail-based transit). The base condition for conventional bus services assumes 30s dwell time, no traffic signals, 10s clearance time and 60% dwell time variation. For rail-based technologies, the base condition assumes 3-aspect train signals, 45s dwell time and 20s operating margin (details can be found in Kittelson & Associates, Inc., et al, 2013, Chapter 6 and Chapter 8).

According to Table 4-6, facility capacity varies for different transit modes and different operating environments, and the advantages of having a segregated transit lane are shown. For example, the operating speed of the bus service in a mixed traffic environment may begin to decrease earlier than the service mode with dedicated transit lanes if we consider a piecewise speed-flow equation. This facility capacity in different operating environments can be applied in the spreadsheet cost model to represent the advantages in the operating speed and the passengers' waiting time costs of the public transport services with higher infrastructure costs.

To take the piecewise speed-flow equation and the facility capacity in different operating environments into account for the spreadsheet model, the speed-flow equation to be used in the Spreadsheet Cost Model is:

$$1/V_{all} = \begin{cases} 1/V & F_t \leq C_{fac}(= fC_{inf}) \\ 1/V + (1/V_1)\left(F_t/C_{fac} - 1\right) & F_t > C_{fac}(= fC_{inf}) \end{cases}$$

where,

$V_1 = 1/T_1$, to account for the additional time spend due to traffic congestion;

f = capacity percentages, as listed in Table 4-6;

C_{fac} = critical facility capacity (vehicle/hour), calculated by f times the infrastructure capacity C_{inf} calculated by using safety headway.

Since the spreadsheet model calculations use the operating speed of the public transport service instead of the average travel time as intermediate variable, we have:

$$V_{all} = \begin{cases} V & F \leq C_{fac} \\ \frac{V \cdot V_1}{V_1 + V \cdot (F_t/C_{fac} - 1)} & F > C_{fac} \end{cases}$$

This function is derived from the piecewise linear function for travel time and uses the original safety headway capacity in the TEST project multiplied by the capacity percentage in different operating environments. To demonstrate the difference, the relationships between speed and passenger demand of the single-decker bus in mixed traffic and the single-decker bus on a busway from the SCM are shown in Figure 4-4 and Figure 4-5.

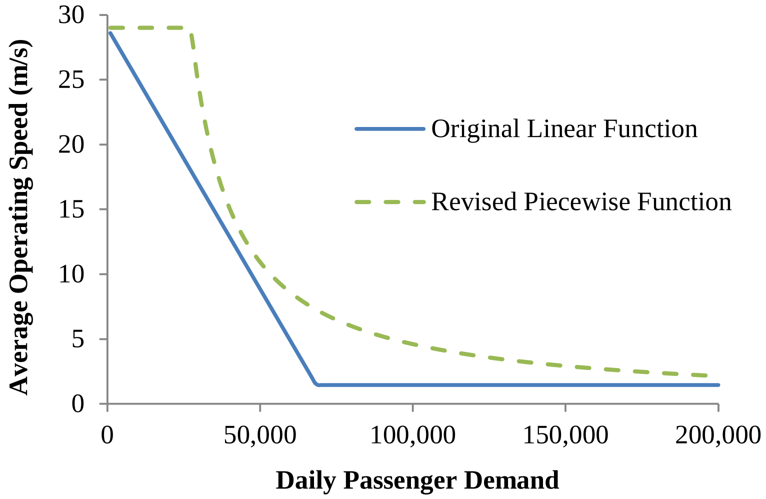


Figure 4-4 Average operating speed of single-decker bus in mixed traffic

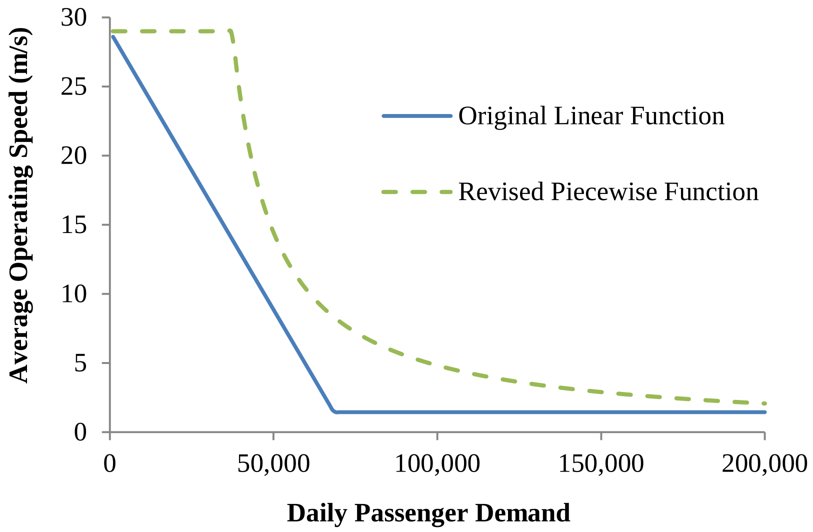


Figure 4-5 Average operating speed of single-decker bus on busway

From Figure 4-4 and Figure 4-5 we can see that, with the original linear function indicated as solid lines in the graphs, the average operating speed is the same for both public transport services, as their lane capacities (safety headways) are the same. The dashed line indicates the revised piecewise speed-flow function for average speed with the application of a facility capacity factor to account for the operating environment. For both bus services, there is no speed reduction until they reach the critical facility capacity, and then the travel time starts to increase linearly which means their average speeds decrease as a reciprocal function of flow.

By considering the operating environment of different public transport modes, the user's benefits of having a segregated lane can be shown. For a given level of passenger demand, the single-decker bus in mixed traffic will have lower (or equal when demand level is low) operating speed than the single-decker bus on busway, as shown in Figure 4-4 and Figure 4-5.

4.4.4 Intermediate Outputs

In the SCM, the social cost of the public transport technologies is associated with the parameters such as vehicle-kilometres, passenger-kilometres, peak vehicle requirement and vehicle-hours. As the capital investment charges are in annual basis, these intermediate outputs are also evaluated by using an annualisation factor.

Vehicle-kilometres

Total vehicle-kilometres (VKM) on the 12 km corridor are calculated by the total distance travelled by the total number of vehicles in all time period as:

$$VKM = a \cdot L_{track} \cdot \sum_{t} (F_t \cdot T_t)$$

where,

a = annulisation factor, default value is 261 (weekdays/year).

Passenger-kilometres

Total passenger-kilometres (PKM) are calculated by using the total passenger demand times the average public transport passenger journey length. This average public transport passenger journey length can be set by the model user or use a default value of 4 km for urban corridor. The total passenger-kilometres calculation equation is:

$$PKM = a \cdot JL \cdot \sum_{t} (Q_t \cdot T_t)$$

where,

JL = average public transport passenger journey length (kilometre).

Peak vehicle requirement

Peak vehicle requirement (PVR) is the number of public transport vehicles required to provide the service frequency on the corridor. This peak vehicle requirement is essential to calculate the maximum number of vehicles required by the operator and hence the capital investment requirement for the vehicle fleet.

$$PVR = CEILING[(MAX\left(F_t \cdot \frac{L_{track}}{V_{all}}\right) \cdot (1 + \delta)]$$

where,

δ = factor allowing for spare vehicles, default value is 10%;

$CEILING()$ = function to round up to integer values;

$MAX()$ = function to return the maximum value over the three time periods.

Vehicle-hours

Total vehicle-hours (VH) for the public transport technology are required to calculate the time-related operating costs of the operator, which is the total hours of the vehicles operating on the corridor:

$$VH = a \cdot \sum_t (F_t \cdot T_t \cdot \frac{L_{track}}{V^{all}})$$

4.5 Operator Cost

The costs of the public transport service operator involve both capital investment cost and operating cost. In order to evaluate the costs on an annual basis, the calculation will use an engineering approach. To convert the total capital investment costs to an annual basis, the capital investment cost can be amortised into annual basis by using the economic life expectancy and the default interest rate based on the length of the economic life expectancy of both the vehicle fleet and the infrastructure. For the operating cost, the unit cost data are available from previous studies. Therefore, the operating cost will be calculated by using the unit operating cost multiplied by the intermediate outputs such as vehicle-kilometres and vehicle-hours.

4.5.1 Capital Investment Cost

The capital investment costs are usually provided as the cost at the beginning of the economic life, and it is necessary to convert all costs to the 'present value' in different time period by using a discount rate of 3.5% as social time preference rate, which is given by the DfT Green Book (DfT, 2003). For those investments with life time expectancy longer than 30 years, the discount rates are given in Table 4-7.

Table 4-7 Long term discount rates

Period of years	**0 – 30**	**31 – 75**	**76 – 125**	**126 – 200**	**201 – 300**	**301+**
Discount rate	3.5%	3.0%	2.5%	2.0%	1.5%	1.0%

(Source: DfT, 2003)

The annual capital investment charges are considered for both annual infrastructure investment costs and annual vehicle investment costs.

Infrastructure investment cost

The total capital investment costs for the fixed line public transport infrastructure are calculated by using the required length of the route/track times the unit infrastructure costs:

$$CC_{inf} = \frac{L_{track} \cdot UC_{inf}}{2}$$

where,

CC_{inf} = total capital investment costs for the infrastructure (£);

UC_{inf} = unit cost per kilometre of the public transport infrastructure route/track with double lane/tracks (£/km).

Note that this capital cost of infrastructure includes all initial investments required for operating the public transport system, excluding the vehicle cost. For fixed line public transport technologies, this cost involves the infrastructures such as tracks, right-of-way and stops/stations. For the innovative public transport system without a specified route, the equation must be modified to suit the technology. For example, the total capital investment cost of a DRT (e.g. Uber style taxis) may contain the cost of setting up the demand-responsive system and obtaining the license to provide the service in the local network.

Vehicle fleet investment cost

The calculation of the public transport vehicle fleet capital investment costs uses the unit cost per vehicle and the maximum number of vehicles required, which is the peak vehicle requirement (PVR) as:

$$CC_{veh} = PVR \cdot UC_{veh}$$

where,

CC_{veh} = total capital investment costs for the vehicle fleet (£);

UC_{veh} = unit cost per vehicle of the public transport fleet (£/vehicle).

Annual capital investment charge

As the SCM evaluates the costs in an annual basis, the total investment costs are transferred into annual capital investment charge. By using the discount rate given in Table 4-7 and the economic life expectancy (default values are in Table 4-4), the total annual capital investment charge for the public transport technology is calculated as:

$$CC_{ann} = ACC_{inf} + ACC_{veh}$$

$$= CC_{inf} \frac{r(1+r)^m}{(1+r)^m - 1} + CC_{veh} \frac{r(1+r)^n}{(1+r)^n - 1}$$

where,

CC_{ann} = total annual capital investment charge of the public transport technology (£/year);

ACC_{inf} = annual capital investment charge for the infrastructure (£/year);

ACC_{veh} = annual capital investment charge for the vehicle fleet (£/year);

m = economic life expectancy of the infrastructure (years);

n = economic life expectancy of the vehicle fleet (years);

r = discount rate for capital investment (%).

4.5.2 Operating Cost

Operating cost of the public transport operator is defined as all relevant costs that arise in the operating stage of the public transport service. Based on the reviews of operator cost studies, the operating cost is made of vehicle-related cost, distance-related cost, time-related cost and route/track maintenance cost.

In the operating cost calculation, vehicle-related operating cost is based on the size of vehicle fleet, which is used to cover the maintenance, vehicle insurance and cleaning cost of the vehicle fleet. Distance-related cost is the operating costs based on the total distance travelled by the public transport vehicles that include fuel cost, tyres cost and insurance cost etc. Time-related operating costs include the cost of staff, crew and vehicle servicing that is calculated based on the total vehicle-hours of the public transport service. Route/track maintenance cost is determined based on the length of the public transport route/track to include the maintenance costs of stops/stations, road/track and signals etc.

Vehicle-related operating cost

The annual vehicle-related operating cost of the public transport operator is calculated by using the unit vehicle-related operating cost times the maximum number of vehicle required in the vehicle fleet:

$$OC_V = PVR \cdot UOC_V$$

where,

OC_V = annual vehicle-related operating costs (£/year);

UOC_V = unit vehicle-related operating cost (£/vehicle-hour).

Distance-related operating cost

In the calculation of annual distance-related operating cost, a factor has been added to account for additional fuel consumption due to congestion. By using the total distance travelled by the public transport vehicles per year, additional fuel consumption factor and the unit distance-related operating cost, the annual distance-related operating cost is determined by the equation:

$$OC_D = \beta \cdot VKM \cdot UOC_D$$

where,

OC_D = annual distance-related operating costs (£/year);

β = factor to account for additional fuel consumption in congested traffic, default value is 1.1;

UOC_D = unit distance-related operating cost (£/vehicle-kilometre).

Time-related operating cost

To take the operating costs of staff, crew and vehicle servicing that is related to the total vehicle-hour of the public transport service into account, the annual time-related operating cost is calculated as unit time-related operating cost times the annual vehicle-hour:

$$OC_T = VH \cdot UOC_T$$

where,

OC_T = annual time-related operating costs (£/year);

UOC_T = unit time-related operating cost (£/vehicle-kilometre).

Route/track maintenance cost

The annual route/track maintenance cost include all maintenance costs of the infrastructure and the public transport vehicles, which is obtained by using unit route/track maintenance cost times the total length of the public transport route/track:

$$OC_R = L_{track} \cdot UOC_R$$

where,

OC_R = annual route/track maintenance costs (£/year);

UOC_R = unit route/track maintenance cost (£/vehicle-kilometre).

Total annual operating cost

The operating costs of the public transport operator, including vehicle-related, distance-related, time-related and route/track maintenance cost are computed by using the annual intermediate outputs as explained in Section 4.4.4. With the default unit operating cost of different public transport technology provided in Table 4-3, each operating component can be determined. Hence the annual operating costs can be obtained as the sum of each operating cost component as:

$$OC = OC_V + OC_D + OC_T + OC_R$$

$$= PVR \cdot UOC_V + \beta \cdot VKM \cdot UOC_D + VH \cdot UOC_T + L_{track} \cdot UOC_R$$

where,

OC = annual operating cost (£/year).

In order to include all operator costs of providing a public transport service in the total cost, other costs such as depot costs and management costs are calculated based on the operating costs:

$$OC_{all} = OC \cdot (1 + \eta)$$

where,

OC_{all} = total annual operating cost, including other cost such as depot cost and management cost (£/year);

η = other cost factor to be added to the operating cost, default value is 5%.

Note that the percentage of other costs varies for different companies, for example, 6.7% for First Glasgow in 2005/06 (Cowie, 2009), 2.2% for Caledonian MacBrayne in 2005/06 (Cowie, 2009) and 8.46% for South Hampshire Rapid Transit in 1998 (Brand and Preston, 2002b). Therefore, the model used 5% as the default value, which can also be changed by the model user according to the condition of the public transport operator.

4.5.3 Total Operator Cost

By using the intermediate outputs per year to calculate the annual operating costs and by evaluating the total annual capital investment charges with discount rate and economic life expectancy of the public transport technology, both operating cost and capital investment cost are on an annual basis. Therefore, the total annual operator cost is calculated as the sum of total annual operating cost and total annual capital investment charge:

$$TOC = OC_{all} + CC_{ann}$$

where,

TOC = total annual operator cost, including operating cost and capital investment charge (£/year).

4.6 User Cost

As public transport passengers experience disutility in travelling which is because of the time spent related to the journey, user cost were also taken into account in the calculation of social cost. As discussed in Chapter 2, user cost should include accessing/egressing time, waiting time, in-vehicle time and transferring time. In this thesis, the shift between different public transport modes is not considered as the comparison is between public transport technologies rather than the whole network, and therefore the transferring time can be ignored. This user time cost is defined as generalised journey time cost in *Passenger Demand Forecasting Handbook* (PDFH) (ATOC, 2009) that involves WKT, WTT and IVT that passengers spent in order to finish the journey.

Walking time

Public transport passenger walking time is defined as the total time to walk to the nearest stop/station and walk from the stop/station. In the SCM, public transport corridor is assumed to be rectangular with a total length of 12 km and influence width of 0.6 km. By using the equation provided in Brand and Preston (2003a) to evaluate the walking distance from/to stop based on the average influence width and average distance between stop, the walking distance is calculated as:

$$D_{walk} = \frac{W + D_{stop}}{4}$$

where,

D_{walk} = average walking distance from/to the public transport stop/station (kilometre);

W = average influence width of the public transport corridor (kilometre);

D_{stop} = distance between stops (kilometre).

Note that the default distance between stops/stations in the SCM assumes 0.4 km for urban bus service, 1 km for urban rail service and 4 km for regional rail service. For non-fixed line public transport service, the walking distance could be different from the fixed line public transport service. For example, passengers may have to walk only a very short distance to get on the vehicle and the destination of the service could also be very close to the final destination of the user (e.g. Uber style taxi or a demand responsive bus service). In this case, this walking distance can be set by the user to be the minimum access and egress distance from/to the origin/destination, based on the public transport service modelled.

By using a standard value of walking speed of 1.2 m/s (4.32 km/h) (TfL, 2010), the average walking time is obtained by the equation:

$$T_{walk} = \frac{D_{walk}}{V_{walk}}$$

where,

T_{walk} = average walking time per passenger (hours);

V_{walk} = average walking speed (kilometre/hour).

As the total cost is on an annual basis, the total walking time is calculated by using the average walking time per passenger times the total passenger number per year. Note that a factor of 2 has been multiplied to the average walking time to account for both the distance walked from and to the stop/station.

$$TT_{walk} = 2 \cdot a \cdot Q \cdot T_{walk}$$

where,

TT_{walk} = total annual passenger walking time (hours);

Q = total daily passenger demand (passenger);

a = annulisation factor, default value is 261 (weekdays/year).

Waiting time

Passenger waiting time is one of the most important constituents of the total user cost for all public transport technologies. By assuming all public transport passengers are evenly distributed, the calculations of the passenger waiting time in the TEST project assumed a classic formula for the mean waiting time, due to lack of information and the notably strategic nature of the model version, and the formula is:

$$T_{wait} = \frac{1}{2 \cdot F_t} + \frac{T_{dwell}}{2 \cdot 3600}$$

where,

T_{wait} = average waiting time per passenger for the time period (hours);

F_t = service frequency in the time period *t* (vehicle/hour);

T_{dwell} = average vehicle dwell time per stop/station for the time period *t*, including average fixed vehicle stopping time and passenger boarding/alighting time (seconds).

This formula assumes all passengers at the stop have to wait half of the service headways plus the half of the dwell time before they start their journey. However, passengers will have different behaviour for different service frequencies. Passengers will arrive at the stop independently of the service timetable and the waiting time is half of the service headway when the public transport service is in high frequency, and passengers will time their journey for a specific departure when the service interval is long (at a threshold of 12 – 15 minutes) (Balcombe et al., 2004), and the calculation of passenger waiting time should be different when the service frequency is lower. Hence the passenger waiting time in the Spreadsheet Cost Model is calculated as:

$$T_{wait} = \begin{cases} \frac{T_{fixed}}{3600} + \frac{T_{dwell}}{2 \cdot 3600} & if\ F_t < 5 \\ \frac{1}{2 \cdot F_t} + \frac{T_{dwell}}{2 \cdot 3600} & if\ F_t \geq 5 \end{cases}$$

where,

T_{fixed} = fixed passenger waiting time (seconds).

When the service frequency of the public transport is less than 5 vehicles per hour, the waiting time is equal to a fixed passenger waiting time to account for the time that passengers spend waiting for their expected journey; when the service frequency is greater than the threshold, the passenger waiting time is calculated as half of the service headway plus the dwell time for each stop.

Suppose the service capacity can always meet the demand, this equation can correctly represent the passenger waiting time. However, passenger demand level varies at different stops for different time periods in reality. The distribution of passenger demand is cumulative and depends on the location of stops. The number of passenger loading at the stops close to the central business district could be much larger than other stops in peak time periods. There will be a probability that passengers at these stops find the incoming public transport vehicles full or with not enough space to take all waiting passengers, even though the overall capacity of the public transport service may still be higher than the total demand of the route. This situation may occur more often when the demand level is high because the vehicle capacity is fixed except for some rail-based technologies that are able to operate multiple car-units, and passengers who use lower vehicle capacity public transport services may have a higher possibility to wait longer than the expected service frequency for the busiest public transport stops.

The public transport service can be regarded as serving seats to passengers (customers) and each arrival vehicle means a bunch of customers are served. Therefore, passenger waiting time can be calculated by using queuing theory for the time spent by the queuing customers. In order to use the queuing theory for passenger waiting time calculation, the utilization rate of the system is defined as:

$$\rho = \frac{\lambda}{\mu}$$

where,

ρ = utilization rate of the system;

λ = passenger arrival rate (passenger/hour);

μ = service frequency F_t of the time period *t*.

In the queueing theory calculation, the utilization rate is less than 1. This is because when the incoming passenger number is higher than the facility capacity, the equilibrium queue length becomes unbounded and the waiting time of the late arrived passengers could be infinitely high. As this equation uses the same unit for the arrival passengers and the incoming public transport vehicles, we can assume the boarding passengers as a group by dividing a percentage of the vehicle capacity:

$$\rho = \frac{Q_t/sC_{veh}}{F_t} = \frac{Q_t}{sC_{veh}F_t}$$

where,

Q_t = passenger demand in the time period *t* (passenger/hour);

s = spare capacity percentage, which is the percentage of available spaces left for each vehicle;

C_{veh} = capacity of the vehicle, including seating and standing (passenger/vehicle);

This spare capacity is calculated as the passenger demand divided by the service frequency times the vehicle capacity. This load factor was assumed to have an initial value of 0.5 in the SCM, and an extra public transport vehicle will be provided when the passenger demand equals to half of the supply spaces. The load factor will increase when the passenger demand level rises, which is because the supply has been limited by the capacity and the passenger demand may exceed the supply. To apply the queuing theory, specifications of the system have to be made for: the arrival process, the service mechanism and the queue discipline. The arrival process and service mechanism should be defined as either a deterministic flow or some random distributions for the way in which passengers and the public transport services arrive at the stop, respectively. The queue discipline defines the method to handle the incoming customers, which can be "first come first served" or "last come first served". Glaister (1981) demonstrates the method of calculating passenger queues of travel by any mode. By assuming a "first come first served" rule of service and a Poisson process for both the passenger arrival process and the service mechanism, Glaister (1981) gives the probability of having to wait longer than time W* as:

$$P = \rho \cdot exp[-(\mu - \lambda) \cdot W^*]$$

By substituting the service interval and system utilisation rate into this equation, we have the probability of having to wait longer than one service headway as:

$$P = \frac{Q_t}{sC_{veh}F_t} \cdot exp[-\frac{(F_t - Q_t/sC_{veh})}{F_t}]$$

The parameter W^* has been substituted by $1/F_t$ which is the service interval, and the probability of having to wait for at least the third incoming vehicle can be calculated by simply replacing the W^* as $2/F_t$. As the passenger arrival is assumed as a Poisson process and the calculation considers the passenger demand in the entire corridor, this equation is able to capture the randomness of passenger distribution. To illustrate the result, the probability that the single-decker bus passengers in the peak period have to wait longer than the expected service headways at fixed demand level of 60,000 per day is shown in Figure 4-6.

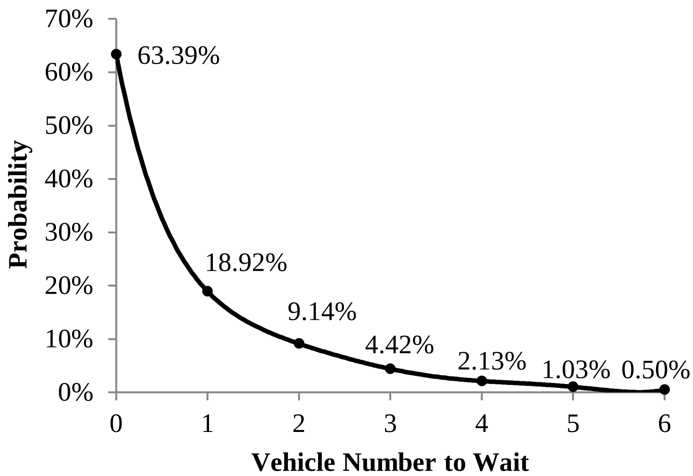


Figure 4-6 Probability of having to wait longer than service headways

Note that all parameters are using the default value in SCM which can be modified by the user to incorporate different public transport technology characteristics. Although the public transport passengers along the corridor still have to be assumed evenly distributed, this equation considers the passenger arrival process using a Poisson distribution. It is suggested that 36.61% of the total passengers have to wait for more than one service interval of the bus service by using the default values in SCM. To apply this probability into the calculation of passenger waiting time, the average waiting time for each passenger at each stop will be:

$$WT = \begin{cases} (\frac{T_{fixed}}{3600} \cdot P_0 + \sum_{i=1}^{\infty} \frac{i \cdot P_i}{F_t}) + \frac{T_{dwell}}{2 \cdot 3600} & if\ F_t < 5 \\ (\frac{1}{2 \cdot F_t} \cdot P_0 + \sum_{i=1}^{\infty} \frac{i \cdot P_i}{F_t}) + \frac{T_{dwell}}{2 \cdot 3600} & if\ F_t \geq 5 \end{cases}$$

where,

WT = average waiting time for each passenger before boarding the vehicle (hours);

i = extra vehicle numbers to be waited before boarding (vehicles);

P_0 = probability of not having to wait for extra public transport services.

P_i = probability of having to wait for the extra ith number of the public transport vehicle.

This revised waiting time equation takes the probability of having to wait longer than the expected service into account. Extra waiting time can be obtained by multiplying the probability by the service interval and the extra numbers of the services waited. This extra wait time will increase with the level of demand because the remaining capacity of the system is getting lower.

The application of queuing theory on the calculation of passenger WTT takes the situation that the incoming vehicle has not enough space for all passengers into account. Another method to calculate this extra user cost for high levels of passenger demand has been demonstrated in Tirachini et al. (2010) which considered the passengers' willingness to pay by using the crowding penalty factor to account for the extra passengers' in-vehicle time costs. Both methods considered the effect that the demand level is higher than the supply, however, passengers may not only be unable to find a seat but also unable to get on the first incoming bus due to the large queue, and this situation is very likely to happen in high population cities in the peak period.

Note that this calculation of the passenger waiting time only applies to fixed line public transport technology, even though the waiting time of the non-fixed line public transport services also suffer the delay due to high ratio of users and the service capacity which can be calculated by using the queuing theory. This is because some innovative public transport services such as DRT has no fixed service frequency, the waiting time of passenger could be highly subjected to the location of the passenger as well as the density of the service in that area. For example, passengers of the Uber style taxi may need to wait longer, if they want a taxi immediately when they are in an area with low Uber taxis service. Therefore, the waiting time equation developed here may not be applied to non-fixed line service.

To obtain the total user cost of the public transport passengers on an annual basis, the total annual waiting time is determined by:

$$TT_{wait} = a \cdot \sum_{t} Q_t \cdot T_t \cdot WT$$

where,

TT_{wait} = total annual waiting time (hours);

Q_t = passenger demand in the time period *t* (passenger/hour);

T_t = duration of the time period *t* (hour).

By summing up the passenger waiting time in different time period (morning peak, evening peak and off peak period), the total daily waiting time is obtained and hence the total annual waiting time is calculated by using the annualisation factor.

In-vehicle time

Public transport passenger's in-vehicle time is calculated by using the average passenger journey length and the average operating speed of the public transport service as well as the total passenger demand level:

$$TT_{IV} = a \cdot JL \cdot \sum_{t} \frac{Q_t \cdot T_t}{V_{all}}$$

where,

TT_{IV} = total annual in-vehicle time (hours);

JL = average public transport passenger journey length (kilometre);

V_{all} = average operating speed, including all stop density and capacity restraints (kilometre/hour);

As mentioned before, average passenger journey length is either set by the user or used default value as 4 km for urban corridor. The average operating speed considers the time spent accelerating and decelerating between stops/stations and the dwell time, and hence the average in-vehicle time per passenger in the time period is equal to the average journey length of the passenger divided by the average operating speed of the public transport service. To evaluate the in-vehicle time in annual basis, total daily in-vehicle time is calculated as the sum of each time period and then multiplied by the annualisation factor.

Total User Cost

The disutility of travelling by public transport technology is expressed in monetary terms in order to evaluate the social cost. Therefore, the definition of value of time is used as the monetary valuation of each unit of the generalised time to represent the increased total cost when the generalised time of travelling is increased (ATOC, 2009). Value of public transport time varies according to the mode that the passengers spent in, for example car, bus and rail, and the values of walking time, waiting time and in-vehicle time are also different (Wardman, 2004). Public transport passenger weights walking time and waiting time higher than in-vehicle time, and therefore the conversion from generalised time to generalised cost equation is:

$$TUC = (w_{walk} \cdot TT_{walk} + w_{wait} \cdot TT_{wait} + TT_{IV}) \cdot VoT$$

where,

TUC = total annual user cost (£/year);

w_{walk} = factor to represent the weighting perception of walking vs. in-vehicle time;

w_{wait} = factor to represent the weighting perception of waiting vs. in-vehicle time;

VoT = value of in-vehicle time for the public transport technology (£/hour).

The value of IVT in the equation can be specified by the user of the model or use the default value which is based on the British value of travel time study by Abrantes and Wardman (2011). Note that the value of IVT must be in the same year price level as other parameters. To determine the total annual user cost of the public transport technology , weighting factors with default value of 2 to reflect that passengers' WKT and WTT are valued higher than in-vehicle time are used.

By using this approach, the time spent by the users can be represented in monetary term. However, the value of time and the value of time multipliers could have changed with the use of information and communication technologies. These technologies can stimulate, reduce or modify the public transport demand and affect the behaviour of passengers. With a large amount of people having access to smartphones, they are able to keep themselves busy with the smartphone while waiting for the incoming public transport service and riding the service. Wardman (2013) reviews the value of time multiplier evidences and assembles the multipliers from 244 studies. He found that although the walk time multiplier is around the conventional wisdom of 2, the wait time is valued a little lower, with 1.75 being a suggested value. This updated suggestion of the value of time multiplier is also a sign that the development of information and communication technologies could have changed people's value of time, and the user cost modelling by using value of time could be subjected to the development of new technologies. Wardman and Lyons (2015) argue that new technologies have reduced the disutility of travel and hence have led to lower values of in-vehicle time. However, this phenomenon is likely to be most important for long-distance business travel, and less important for short-distance, non-business travel which is the focus of this thesis.

As it is difficult to estimate correctly the changes in the value of time and the value of time multipliers due to the impacts of future technologies, the SCM therefore assumes a constant value of time for IVT and value of time multipliers for WKT and WTT. However, users are able to modify the values of those parameters in the SCM according to the local situation to perform sensitivity test, or create a function for the changes in the value of time according to their estimations.

4.7 External Cost

The operation of public transport service also generates externalities which incur additional cost to the society. These externalities can be categorised into noise pollution, air pollution, climate change and external accident, which are listed in the DfT's *WebTAG unit A3 environmental impact appraisal* (DfT, 2014) and discussed in Chapter 2.

Externalities of the public transport technology are generated based on the total traffic volume. To measure the externalities of the public transport technology in monetary term, total traffic volume (vehicle-kilometre) are multiplied by the unit externality cost values provided in Table 4-5. As the vehicle-kilometre obtained from the intermediate output calculation is in annual basis, the total annual external cost is determined by the equation of:

$$TEC = (UEC_{air} + UEC_{noise} + UEC_{climate} + UEC_{accident}) \cdot VKM$$

where,

TEC = total annual external cost (£/year);

UEC_{air} = unit air pollution cost per vehicle-kilometre (£/vkm);

UEC_{noise} = unit noise pollution cost per vehicle-kilometre (£/vkm);

$UEC_{climate}$ = unit climate change cost per vehicle-kilometre (£/vkm);

$UEC_{accident}$ = unit external accident cost per vehicle-kilometre (£/vkm).

Due to different driving environment, model user can specify the unit cost for the four externalities or choose from low, central and high category from the default value table (Table 4-5) to represent the local network condition.

4.8 Average Cost Results and Operating Procedure

By summing up the total operator cost, total user cost and total external cost, the total social cost of the public transport technology is obtained. However, the total social cost does not reflect the efficiency of the public transport technology under the passenger demand level. For example, although Underground is more cost effective at high levels of passenger demand or in high population density areas than conventional single-decker bus in low level of passenger demand or in low population density, the total social cost of the Underground service is still higher because of the high demand level. Hence with total social cost, the most suitable public transport technology for the current passenger demand level cannot be shown.

Therefore, average social costs per passenger-kilometre are evaluated for different demand levels. The average social cost of the public transport technology is computed as:

$$ASC = TSC/PKM$$

As the comparative assessment is also aiming to provide comparative results for public transport operators, the efficiency of different public transport technology in the operator's point of view, which is the average operator cost per passenger-kilometre, is also computed as:

$$AOC = TOC/PKM$$

By calculating the average social cost per passenger-kilometre and the average operator cost per passenger-kilometre, the most feasible public transport technology for the distinct demand level can be identified. In order to evaluate the performance of different public transport technology in various passenger demand level, the Spreadsheet Cost Model calculates operator cost, user cost, external cost and hence social cost and average cost for each public transport technology. Figure 4-7 shows the operating procedure of the SCM.

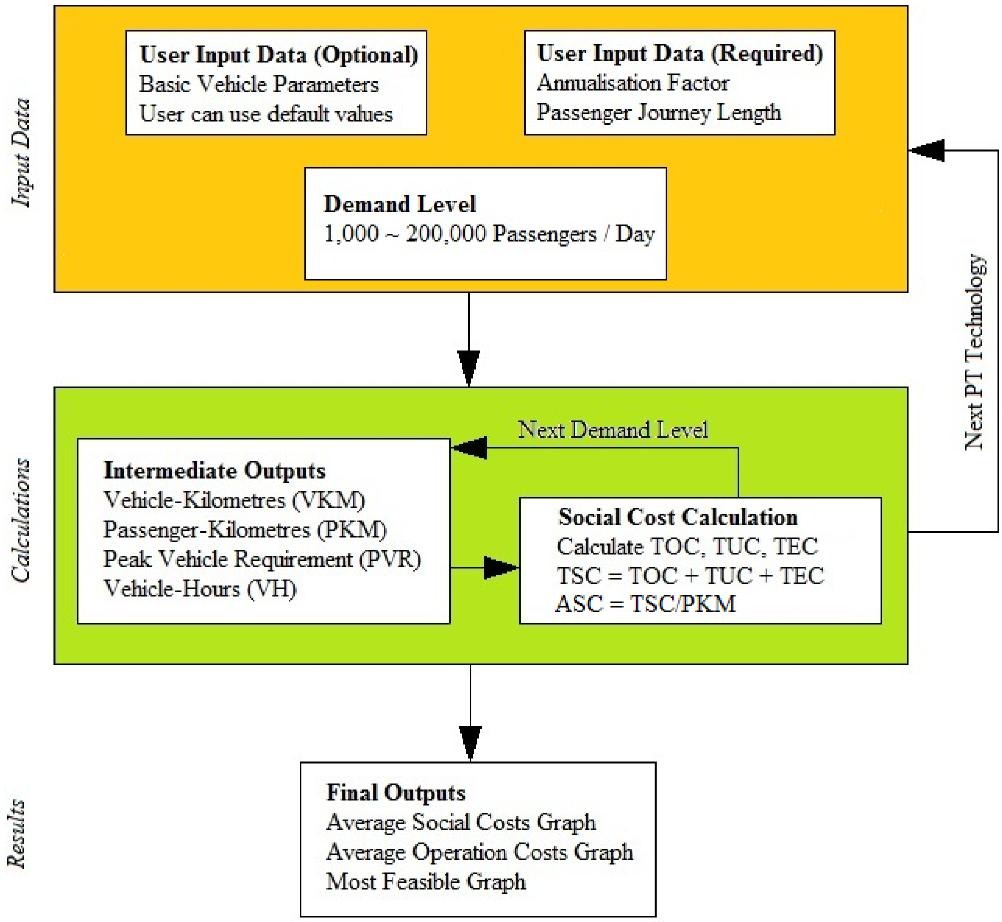


Figure 4-7 Procedure of the Spreadsheet Cost Model

The SCM calculation includes 200 demand levels from 1,000 passengers per day to 200,000 passengers per day in steps of 1,000 per day to cover the demand level range from low to high. As the Spreadsheet Cost Model uses Microsoft Excel, a macro has been coded in order to perform the calculation procedure shown in Figure 4-7.

By following the procedure shown in Figure 4-7, average social and operator cost results for the default 16 different public transport technologies are shown in Figure 4-8 and Figure 4-9. Note that the parameters are using the default values in the Spreadsheet Cost Model, which can be modified by model users for any updating technology specification or for different transport network conditions.

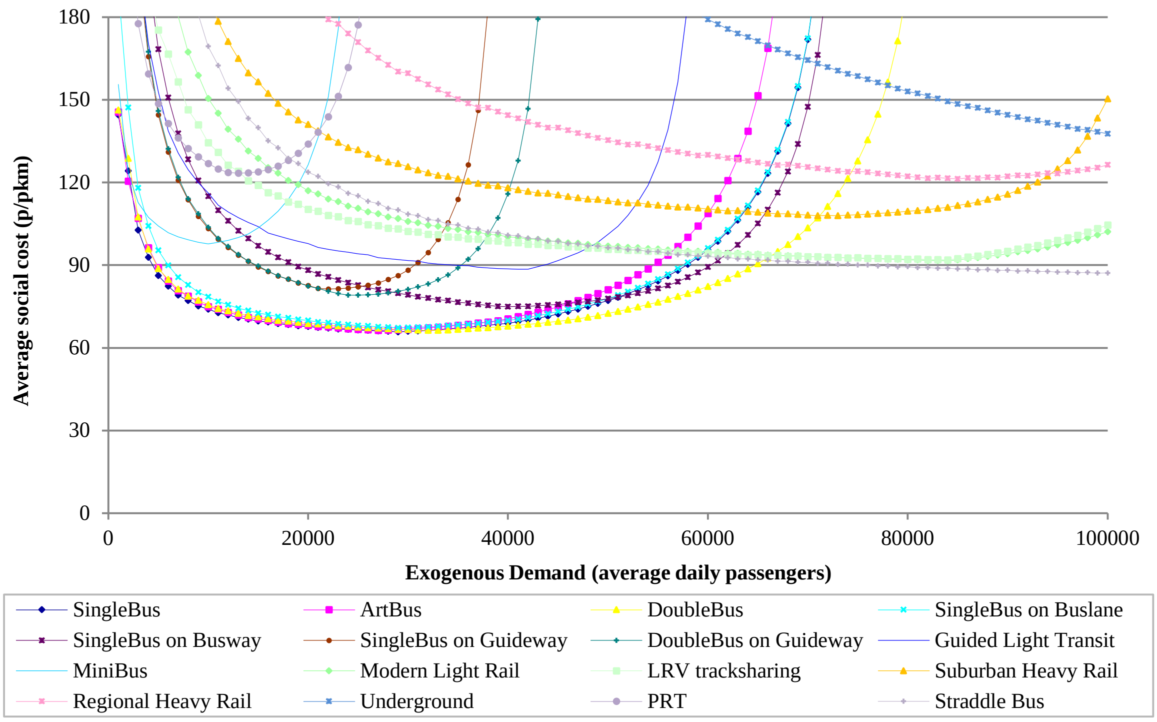


Figure 4-8 Average social cost of 16 public transport technologies on a 12 km corridor

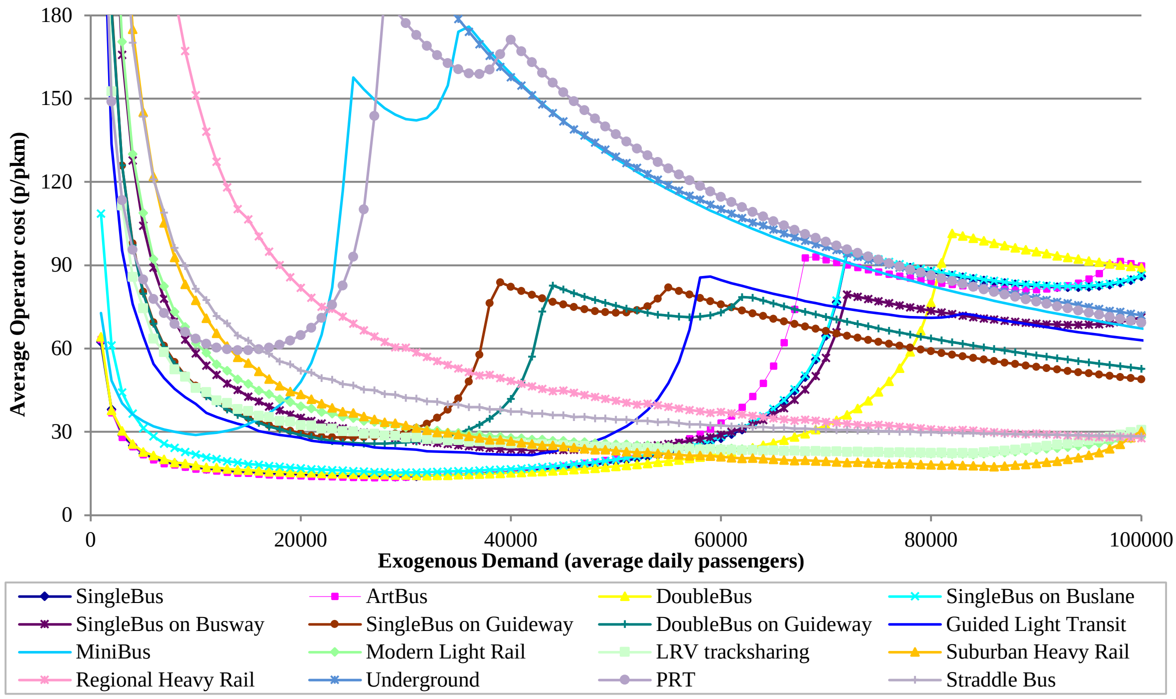


Figure 4-9 Average operator cost of 16 public transport technologies on a 12 km corridor

Figure 4-8 and Figure 4-9 demonstrate the example result graph of average social cost and average operator cost for the 16 public transport technologies modelled in SCM. To find out the public transport technology that has the lowest average cost at different exogenous demand level, the most feasible graphs are produced and shown in Figure 4-10 and Figure 4-11.

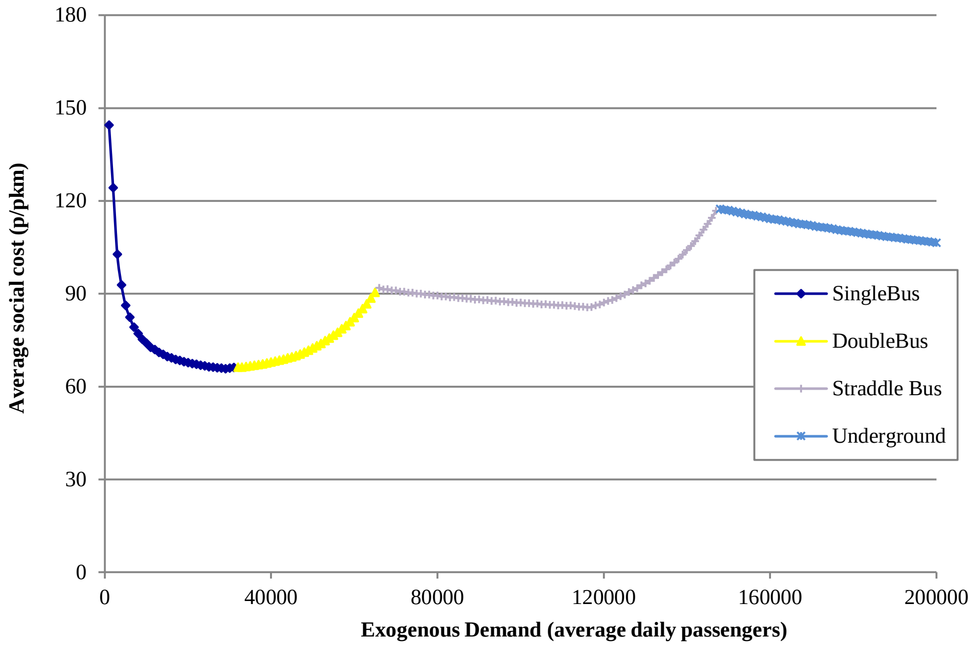


Figure 4-10 Public transport technologies with lowest average social cost on a 12 km corridor

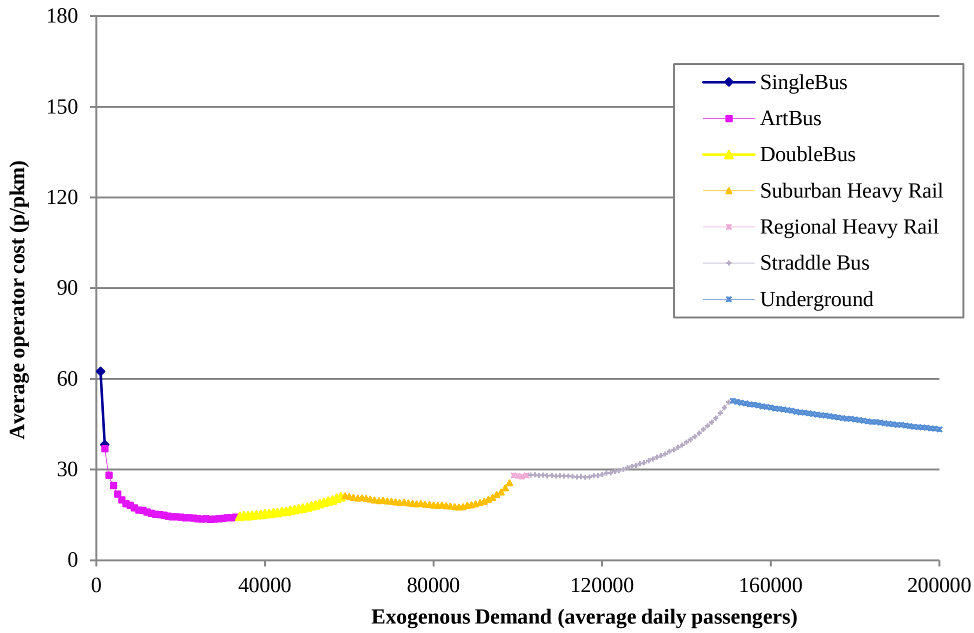


Figure 4-11 Public transport technologies with lowest average operator cost on a 12 km corridor

Note that in Figure 4-9, there are two inflection points in each public transport technology curve, which is because the maximum service frequency has been reached for peak period and off-peak period, respectively. From Figure 4-9, it shows that average operator costs will decline with the passenger demand level when the maximum value has been reached. This is because the operator costs that are related to the vehicle-kilometre will no longer increase, as the service frequency has reached the maximum value, however, the average operator cost starts to decline, as more public transport passengers were assumed to use the service because the passenger demand levels are externally fixed.

While the service frequency of the public transport services reaches the limit, the services are in a “congested” state. For example, passengers may find the incoming public transport vehicles are full, and they have to spend extra waiting time before they can get on the vehicle. As a result of the extra user costs in the “congested” state, the average social cost goes up quickly due to the extra generalised cost of public transport users. Therefore, it is necessary to conduct a demand and supply relationship analysis to determine the willingness to travel of public transport passengers, especially when the generalised cost of passengers increases dramatically in high demand levels.

4.9 Conclusion

This chapter provided the development and the detailed specification of the mathematical cost model – Spreadsheet Cost Model, which evaluates the total operator cost, total user cost, total external cost and hence total social cost and average cost for 16 different fixed line public transport technologies from demand level of 1,000 per day to 200,000 per day.

To compute the cost in the model, the performance and the intermediate outputs must be obtained in the first place. The performance of the public transport technology calculation in the SCM follows the approach in the TEST project with improvements of the average operating speed calculation from a linear speed-flow equation to a piecewise speed-flow equation to consider the advantages in different operating environment.

The total operator cost calculation in the SCM uses an engineering approach as discussed in Chapter 2 and computes operating cost and capital investment cost in annual basis separately. Operating costs of the public transport operator are measured by using the intermediate performance output multiplied by the unit operating cost.

Total initial capital investment costs are spread to each year of the economic life expectancy of both the vehicle fleet and the infrastructure to obtain annual capital investment cost.

User cost is defined as the generalised time cost of public transport users, which includes WKT, WTT and IVT in monetary terms calculated by using the passengers' value of time. In SCM, user cost calculation generally follows the calculation in the TEST project of a rectangular public transport corridor with improvements in the evaluation of passenger waiting time. By developing a new algorithm to include the passenger's behaviour in low service frequency and probability of having to wait longer than the expected service frequency by using queuing theory, the SCM is able to estimate the passenger waiting time more precisely, especially in extremely low and extremely high passenger demand levels.

Externalities are also produced with the operation of public transport service, which include air pollution, noise pollution, climate change and external accident. As the cost of the externalities depends on the total distance travelled by the public transport vehicles, total external cost is computed by using the unit external cost obtained from published sources (see Table 4-5) times the vehicle-kilometre.

Although the SCM was developed to model the costs of fixed line public transport system, it can be modified to reflect other innovative public transport, such as DRT which has no specified network.

The SCM developed in this thesis can be used individually to predict and evaluate the most feasible public transport technology with lowest average social and operator cost for the local corridor in the given demand level in strategy planning stage. As SCM is a strategic level model, some assumptions are optimistic. For example, the passenger demand levels are assumed to externally fixed and unaffected by the level of service, the theoretical corridor assumes to have no other traffic, and there are no signalised junctions or roundabouts on the corridor. Therefore, it is necessary to combine with other models to improve the accuracy of the model results, which will be discussed in the following chapters.

CHAPTER 5 DEMAND SUPPLY MODEL

5.1 Introduction

For the public transport passengers, the attractiveness of the service is closely related to the performance. The passenger demand level of the public transport service with better performance will be higher, as passengers will consider the generalised time cost of the journey and choose the service with lower cost.

As discussed in Chapter 2, many studies (Meyer et al. 1965; Brand and Preston, 2006[2]; Grimaldi et al., 2010; Tirachini et al., 2010) use passenger demand level as exogenous, which means the passenger demand level is externally fixed. This means the results from the model are based on fixed demand predictions. However, in the real world, passenger demand level is endogenous, which means the passenger demand level varies according to the performance of the service rather than being externally fixed.

The indicator of the efficiency of the public transport technology in the comparative assessment is average cost, which is based on the total cost and the passenger demand level. Therefore, it is necessary to conduct a demand supply analysis in the comparative assessment in order to obtain the actual passenger demand level and hence actual average cost for the public transport technology.

In this chapter, the modelling of public transport demand and the demand and supply relationship analysis model – the Demand Supply Model (DSM) is going be discussed. This model uses demand elasticity with respect to the generalised journey time to evaluate the actual endogenous demand level at the level of service. Calculation

[2] Brand & Preston (2006) analyses the endogenous demand in the integrated version model but not in the stand-alone cost model.

specifications and the relationship between exogenous and endogenous demand result are also outlined in this chapter.

5.2 Public Transport Demand Modelling

In the SCM, in order to analyse the transportation cost for different public transport technologies, the passenger demand and the vehicle supply have been considered as important factors. Costs and benefits would vary for each technology when the passenger demand level rises from 1,000 to 200,000 per day, step by step in the model. More vehicles would be needed for those increasing passenger numbers and this affects the total social costs for the extra vehicle numbers.

Daily passenger demand level in the model is changed in the calculation procedure for every 1,000 passengers, which means the demand is assumed to be exogenous – externally fixed by SCM. In this way, the model can easily gather the total cost data for each demand level by using macro scripts in Microsoft Excel of entering each demand level and then obtaining the corresponding operator costs, user costs and external costs for the selected public transport technology. However, the calculation of the services required has to assume the level of passenger demand as externally fixed in the first place. Without considering the demand as an endogenous variable, the calculation cannot pick up the fact that passengers' willingness to use the service would vary based on the quality of service.

The endogenous passenger demand in reality is closely related to the performance of the technology, as are user benefits such as the service frequency, passenger waiting time and in-vehicle time for the whole journey, which are also defined as generalised journey time (ATOC, 2009). Those factors would have great impacts on the passengers' willingness of using the public transport as well as their travel behaviours. For example, passengers tend to prefer the public transport technology that has the higher service frequency and therefore less waiting time cost for the passengers at the stop/station. For public transport services with high frequency, the passenger waiting time at the station is normally equal to half of the service headway because the passengers will arrive at the station/stop independently of the service schedule if the service frequency is high enough, and this passenger behaviour will change and a specific departure will be timed in order to reduce the waiting time at the station when the service headway is much wider (typically the threshold is the headway of 12 to 15 minutes) (Balcombe et al., 2004). This changing demand will eventually affect the cost of the public transport technology, as discussed in Chapter 4.

To evaluate the passenger demand level of the public transport service, the modelling of public transport demand is discussed in this section. Although a public transport service is similar to other transport forms in that can be viewed as a normal consumer good, its production process is significantly affected by the user inputs. This is because of the greater user time inputs than the actual monetary inputs they have paid to use the public transport service, and this time input would also be affected by the number of services produced (provided by the operator) to change the service frequency and network coverage (Preston, 2015). This special characteristic leads to an effect that the average user cost of public transport is reduced by the increase of the user demand of the public transport service, which was discussed by Mohring (1972) and known as the Mohring effect.

As a result of the special characteristics, the passenger demand of a public transport service will change based on the changes of the performance of the services and hence the users' time input. Therefore public transport demand needs to be measured according to these parameters rather than being externally fixed. To model the public transport demand and to forecast the change in demand due to the change in service level, two approaches are used in this thesis, which will be discussed in this section.

5.2.1 Demand Elasticity Approach

The demand elasticity approach makes use of the concept of elasticity in economics theory, by considering the public transport service as a typical consumer good. Elasticity is frequently used to measure how sensitive a factor (such as demand) is responsive to changes to another factor (such as journey time). The attractiveness of public transport technologies is significantly enhanced when the service interval is shorter, and the demand elasticity factor can show how much the demand level will grow in response to a decrease in service headway.

To estimate the public transport demand in an elasticity approach, Preston (2015) gives the basic form as:

$$Q_1 = f(P_1, P_2, \dots, P_n, JT_1, JT_2, \dots, JT_n, I, T)$$

where,

Q_1 = the demand of the public transport service;

P_1 = the price of travelling by the public transport service;

$P_2 \dots P_n$ = the price of travelling by the rival modes;

$JT_1, JT_2, \dots, JT_n$ = the journey time of travelling by public transport and by rival modes$I$ = the incoming of the public transport user;

T = taste of the public transport user to reflect their preferences of travelling by different modes.

As indicated in the equation, the public transport demand is affected by various parameters. The changes in those parameters will hence have impacts on the passenger demand. Therefore, the concept of demand elasticity needs to be introduced.

Elasticity Concept

Elasticity concept has been widely used in Transport Economics to estimate the passenger demand in response to the change in different variables. As public transport services can be considered as goods consumed by customers (passengers), price elasticity of demand for the service is used in many transport textbooks to reflect the responsiveness of passengers or potential passengers to changes in the prices (see Hensher and Button, 2008; Cowie, 2009). The passenger demand level will also be affected by various factors of both the service and passengers themselves, such as service interval, in-vehicle time, fare and income. Hence Balcombe et al. (2004) define the elasticity of demand as:

$$E_x = \frac{The\ proportional\ change\ in\ demand}{The\ proportional\ change\ in\ the\ variable\ of\ interest} = \frac{\Delta Q/Q}{\Delta x/x}$$

where,

E_x = demand elasticity with respect to factor x;

Q = current passenger demand level for the public transport technology (passengers);

ΔQ = change in the passenger demand level (passengers);

x = the variable of interest, for example passenger waiting time and passenger in-vehicle time, which affect the passenger demand level;

Δx = changes in the variable of interest.

Note that demand elasticity can be either positive or negative depending on the changes. For example, if demand elasticity with respect to the variable of interest is positive, any increase in the variable will lead to an increase in the demand, e.g. income; if demand elasticity with respect to the variable of interest is negative, demand will decrease if there is an increase in the variable, e.g. service interval, fare and in-vehicle time. By using this factor to measure consequences for passenger demand level of changes in the performance of the public transport service, the endogenous demand level can be computed for the given level of service.

However, noting that this elasticity calculation requires a given base level, as the calculation is depending on the percentage changes of the variable, this approach cannot be used to evaluate a new public transport service.

Determining Factors

Time is one of the most important factors that have impacts on the service quality of public transport, and the generalised journey time of public transport passengers is made up of three elements: access/egress time, waiting time and in-vehicle time. Passenger access/egress time is calculated as the time spent walking to/from the stop. The space between stops can be set by the user or use the default value, and the mean walking distance was assumed to be 1/4 of the spacing and the influenced width of the corridor, as discussed in Chapter 4. In practice for rail systems, some passengers will access/egress using mechanised modes. As this factor is not changed with the level of demand, the variables of interest in the elasticity equation were chosen to be the passenger waiting time of the public transport service (WTT) and the average time spent in the vehicle for each passenger (IVT) in this analysis.

The demand elasticities vary for different transport types, city sizes, vehicle kilometres and also journey purpose such as working and shopping. Studies of demand elasticities with respect to passenger WTT and passenger IVT have been conducted in many previous literatures.

Service frequency is closely related to the WTT of passengers. The demand elasticity of passenger WTT was estimated by Preston and James (2000) based on an analysis with bus data in 23 urban areas in the Great Britain. These demand elasticities with respect to WTT for UK cities analysis were reported by Balcombe et al. (2004), and the average elasticity is -0.64. This elasticity value of -0.64 means every 1% of increasing or decreasing wait time will have an effect of a 0.64% decrease or increase in the demand level. Note that the demand elasticity with respect to quality of service varies with purpose of the journey and the length of the journey. As the assumed public transport corridor is 12 km and the default value of average journey length is 4 km, the WTT elasticity of -0.64 for urban area is used in this model.

For the elasticity of the passenger IVT, less journey time is always preferred. So for any increment in the time spent on board, passenger demand level will fall, which means the journey time elasticity is always negative. Review studies have been done all around the world for different cities. The IVT elasticity for buses was estimated to be approximately -0.4 by Daugherty et al. (1999) after reviewing bus priority schemes in Great Britain. For rail transit, the IVT elasticities are relatively more sensitive compared with those for conventional buses. The average IVT elasticities for rail technologies range from -0.6 to -0.8 in the UK (Steer Davies Gleave, 1999), which means railway passengers are up to twice as sensitive as the people using bus transit if the IVT varies. Accordingly, the default demand elasticity with respect to IVT for bus users would then use -0.4, an elasticity value of -0.6 would be adopted for light rail transit and -0.8 for heavy rail transit in the DSM.

Demand Function

Passengers will consider the decision of selecting the mode to travel when confronted with alternatives. It is essential to evaluate the passenger demand level by using a demand function which contains the factors that influence the attractiveness of the public transport service.

Demand functions are generally used in economic theory. In transport economics, demand functions are used to analyse the choice of passengers if they have access to alternatives and they are able to maximise their "utility" by selecting the best among them (Balcombe et al., 2004). Therefore, the passengers will make decision based on the performance of the mode, and the demand function represents the relationship between number of trips demanded by passengers and the variables that indicates the quality of service.

The determining factors have been discussed in previous section. Hence based on the elasticity definition and the value of demand elasticity with respect to the performance of public transport service, the original model can be modified to evaluate the endogenous demand level. To evaluate the endogenous demand based on the changes of the quality of the public transport service, a constant elasticity demand function is used:

$$Q_1 = Q_0 \cdot \left(\frac{T_{wait}^1}{T_{wait}^0}\right)^{e_1} \cdot \left(\frac{T_{IV}^1}{T_{IV}^1}\right)^{e_2}$$

where,

Q_1 = endogenous demand due to the changes of passenger waiting time and passenger in-vehicle time (passenger/day);

Q_0 = input exogenous demand from 1,000 to 200,000 per day (passenger/day);

T_{wait}^1 = passenger waiting time at current demand level of the public transport mode (hours);

T_{wait}^0 = base passenger waiting time (hours);

T_{IV}^1 = passenger in-vehicle time at current demand level of the public transport mode (hours);

T_{IV}^0 = base passenger in-vehicle time (hours);

e_1 = demand elasticity with respect to passenger waiting time;

e_2 = demand elasticity with respect to passenger in-vehicle time;

This equation uses demand elasticities with respect to waiting time and in-vehicle time to calculate the difference between the fixed demand level and the endogenous demand level. By applying this equation to the SCM for every step of the exogenous demand from 1,000 to 200,000, the original demand level would change due to the elasticity factor, and then the graph of the endogenous demand against the original exogenous demand can be produced.

The endogenous demand computed from the equation will also have impacts on the quality of service of the public transport technology, therefore the DSM will be called again in the comparative assessment when the quality of service is updated in other models, and a comparative assessment application case study will be given and discussed in Chapter 7.

5.2.2 Choice Model Approach

The demand elasticity approach discussed in the previous section is able to estimate the public transport demand changes as a result of the changes in the service level. However, the comparative assessment is going to look at the detailed interactions between the public transport and other road users, and the changes in the performance of public transport service will also have impacts on the demand of other road users. This affected demand of other modes on the road will also change the service level of the public transport (for example, if the car traffic goes up, the speed of the conventional bus service might go down, due to the congestion caused by the additional car traffic) and hence the demand of the public transport service as well. Hence a choice model approach to estimate the public transport demand and the demand of other modes is also adopted in the DSM.

This choice model approach is widely used in the transportation field to evaluate how the users would choose among a set of mutually exclusive alternatives (Koppelman, 2000). In the choice model approach, the term “utility” is used to represent the attractiveness of the available alternatives to the users involved in the calculation. The utility is calculated in a user-based approach – the alternatives in the choice model do not produce utility directly, but how much the users are affected by picking each alternative will determine the indirect utility (Lancaster, 1966). For example, the observable indirect utility of car (V_{car}) can be defined as a linear combination of variables (Ortuzar and Willumsen, 2011):

$$V_{car} = 0.25 - 1.2 \cdot IVT - 2.5 \cdot ACC - 0.3 \cdot C/I + 1.1 \cdot NCAR$$

where,

IVT = user in-vehicle time;

ACC = user access time to the car;

C/I = the ratio of car cost and the income of the user;

$NCAR$ = number of cars own by a household.

Note that the coefficient in front of each variable represents the impact of a unit change in the relevant variable, and the value would be different in different network and for different modes.

Within the choice model approach, the most well-known is the Multinomial Logit Model (MNL), which assumes the probability of an alternative is chosen by the user as:

$$P_1 = \frac{e^{V_1}}{\sum_{i=1}^{n} e^{V_i}}$$

where,

P_1 = the probability that alternative 1 is chosen;

V_1 = the utility of alternative 1;

n = the number of alternatives.

By calculating the utility of each alternative where the probability of each alternative is chosen with the equations above, the preferences of users can be identified by this model. However, although the MNL model is straightforward to estimate in a wide range of travel related choice contexts, the property of independence of irrelevant alternatives (IIA) could lead to errors in estimating the probability of the alternative (Koppelman, 2000). This is also described as the "red bus and blue bus" problem (Mayberry, 1973). This problem assumes there are two available modes of travel – car and red bus, and the introduction of a blue bus service will take the passenger demand from both the car and the red bus service in equal proportions by using the MNL model while in practice the blue bus will largely draw demand from the red bus. This is because additional alternatives in the MNL model will draw demand from all other alternatives no matter if this alternative in practice has no effect on some of the alternatives. To avoid this defect of the model, the choice set must be consistent with the IIA property of the MNL model. Another solution to overcome this problem is to use a Nested Logit (NL) model rather than the MNL model, which groups similar choice alternatives in nests (Preston, 2015). By using the NL model instead of the MNL model, the structure of the “red bus and blue bus” problem will become the structure shown in the following graph:

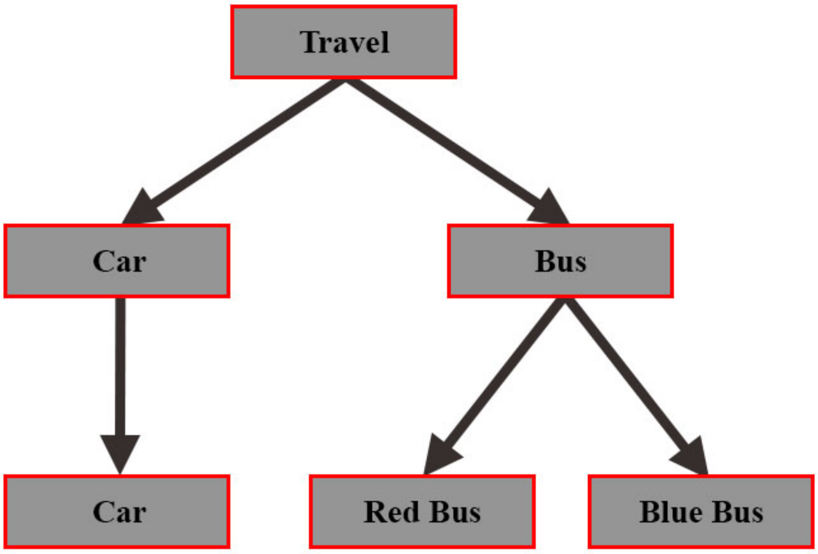


Figure 5-1 The structure of “red bus, blue bus” problem in NL model

As shown in Figure 5-1, the middle level “Car” and “Bus” are the nests in the NL model and the bottom level shows the elemental alternatives of the “red bus, blue bus” problem. By using the NL model, the introduction of new elemental alternatives will not affect the nests level to avoid the IIA problem in MNL model.

The choice model approach is able to estimate the change in demand of all modes involved in the study, which is suitable to be used in the comparative assessment to evaluate the public transport demand and the demand of other road users. However, as outlined in Chapter 4, the SCM assumes a stand-alone corridor and does not consider other traffic on the road (for example, cars). Therefore, the choice model approach cannot be demonstrated in this section. The application of the choice model to evaluate the modal shift between different modes will be shown in the case study in Chapter 7.

5.3 Endogenous Demand and Exogenous Demand Relationship

By using the endogenous demand calculation equation provided in previous section, the actual passenger demand that affected by the supply level of the vehicles, mostly the interval between services and the efficiency of the whole travel (journey time) can be computed. To demonstrate the outputs produced by the DSM, an example is given in this section.

The example follows the assumptions in the SCM that there are 16 public transport technologies available for public transport passengers on a 12 km corridor public transport network without other traffic. By using the equation in previous section and the demand elasticities with respect to WTT and IVT, the endogenous demand level can be computed. The public transport operator will change the supply based on the endogenous demand level in the long term, and the endogenous demand will changed again according to the new supply. Therefore, an iteration process was conducted for each public transport technology, as shown in Figure 5-2.

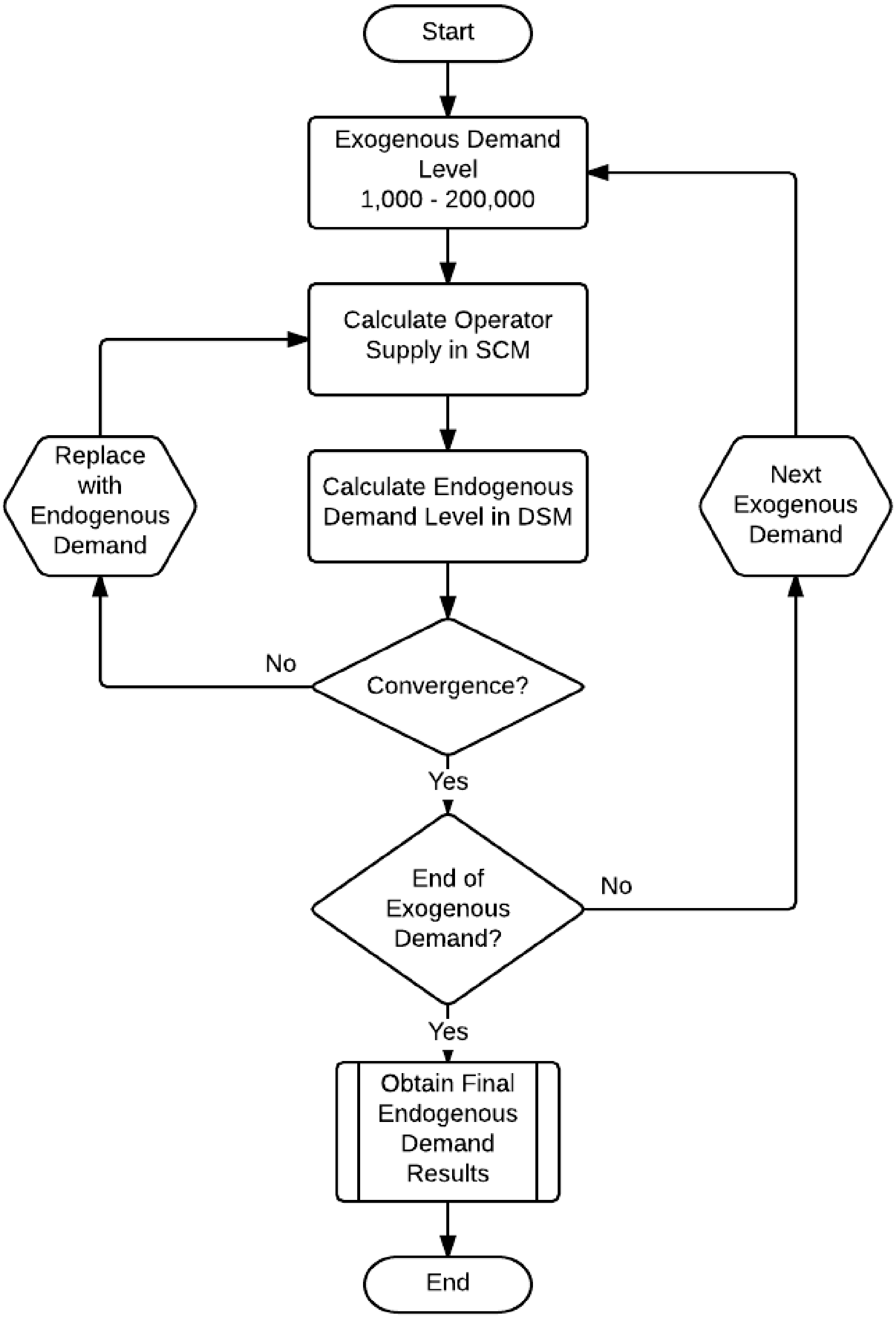


Figure 5-2 Flow chart for the endogenous demand calculation iteration

It is worth noting that the iteration for each demand level will stop once the convergence is achieved, which means the difference between the previous demand and the new endogenous demand is less than 1%. By evaluating the 200 demand levels from 1,000 to 200,000 passengers per day for the 16 public transport technologies with the procedure shown in Figure 5-2, Figure 5-3 was produced to demonstrate the endogenous demand as percentages of exogenous demand.

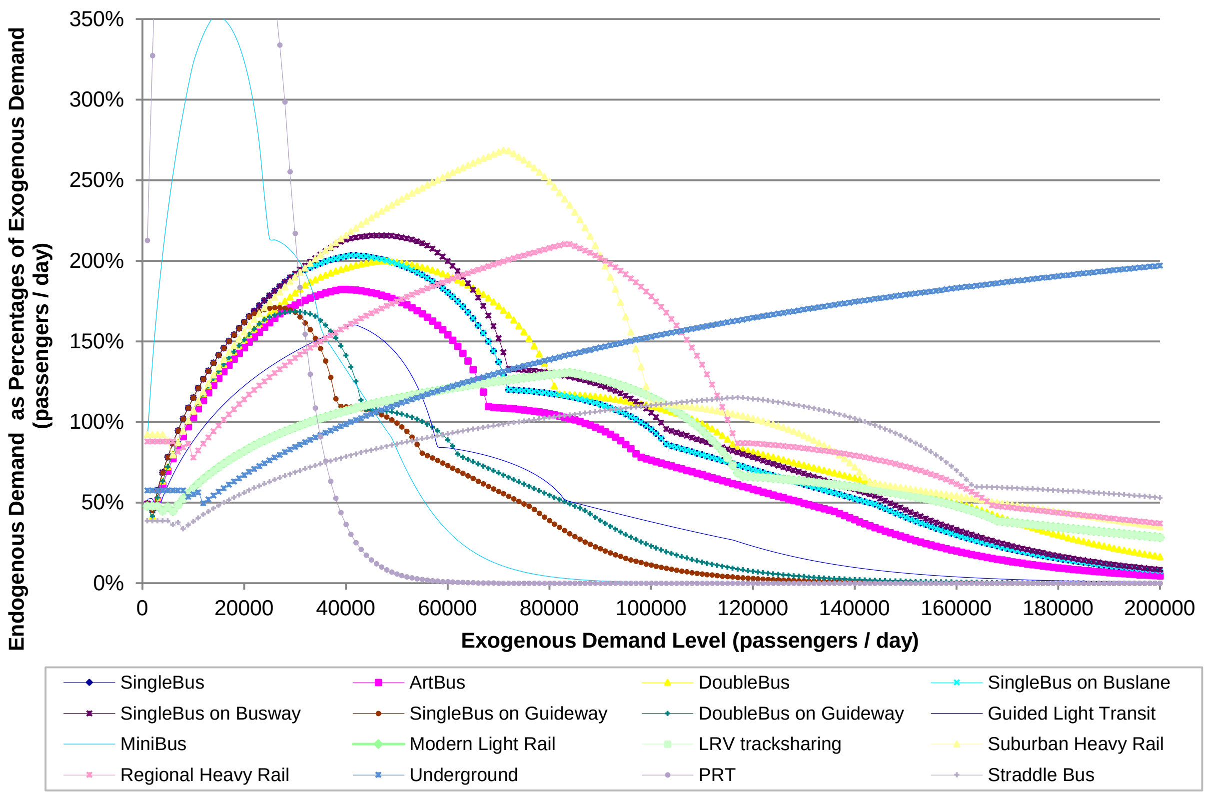


Figure 5-3 Relationship between endogenous demand and exogenous demand

In Figure 5-3, the x-axis shows the demand level when it is externally fixed and the y-axis shows the demand level when the influences of supply on demand are introduced in the model. The endogenous demand levels are shown as percentages of the current exogenous demand levels to demonstrate the relationship between them.

From Figure 5-3, exogenous demand can be considered as demand that is fixed which generates the WTT and IVT and hence the endogenous demand level. At low demand levels, PRT stands out because of its higher frequency (due to small vehicle) and faster speeds (due to segregated right of way and low stopping time), and in this case, endogenous demand is greater than exogenous. At high exogenous demand levels, most of the 16 public transport technologies have endogenous demand that is less than exogenous levels. This is because the high demand level would cause congestions which lower the operating speed and eventually make the IVT higher. Passenger WTT would also be effected in this case, as the vehicles have to spend more time at stops for boarding/alighting passengers, who may also experience extra WTT due to the boarding congestion.

The graph also demonstrates the attractiveness for these 16 public transport technologies in different demand levels. For example, the Suburban Heavy Rail has a higher percentage of the fixed passenger demand than other transport modes in the demand level from 38,000 to 89,000. PRT and Minibus have a very high endogenous demand level compared to other public transport modes especially before the exogenous demand reaches 31,000, as the service intervals are much lower than other technologies and thus much more attractive for passengers that value their waiting time highly. The endogenous demand growth of underground is relatively stable compared with other public transport technologies and shows its advantages especially at high exogenous demand levels. This is because the underground provide fewer services at low passenger demand level; at high demand level (from around 80,000 passengers a day onwards), the high capacity and high operational speed feature is able to provide a lower generalised journey time service to users, which result in a greater endogenous demand.

For all public transport technologies, the curves in Figure 5-3 exhibit some parabolic features, as a result of the changing WTT and IVT at different demand levels. The WTT falls with the increasing passenger numbers at the start of the curve, due to the shortened service interval. However, the increasing passenger demand would also cause more boarding/alighting time and thus greater passenger WTT. Therefore a rising trend of WTT is shown, until positive effects of more services are overtaken by the negative effects of congestion. IVT for all passengers is increased with demand levels because the speed is getting lower when more vehicles are on the road. As a result of the changing passenger waiting time and in-vehicle time, the curves in Figure 5-3 gradually grow until the increasing passenger waiting time causes negative effects on the endogenous demand level.

5.4 Endogenous Demand Effects on Average Social Cost

The results of this demand and supply relationship analysis show how the actual public transport performance would affect the passenger demand level by using the DSM. The actual passenger demand can then be substituted back to the SCM to evaluate the average costs after applying endogenous demand. To demonstrate the effects of applying endogenous demand to the SCM, an example is given in this section. The example calculates the average social cost of single-decker bus in mixed traffic by using both the SCM and the DSM, and the results are shown in Figure 5-4.

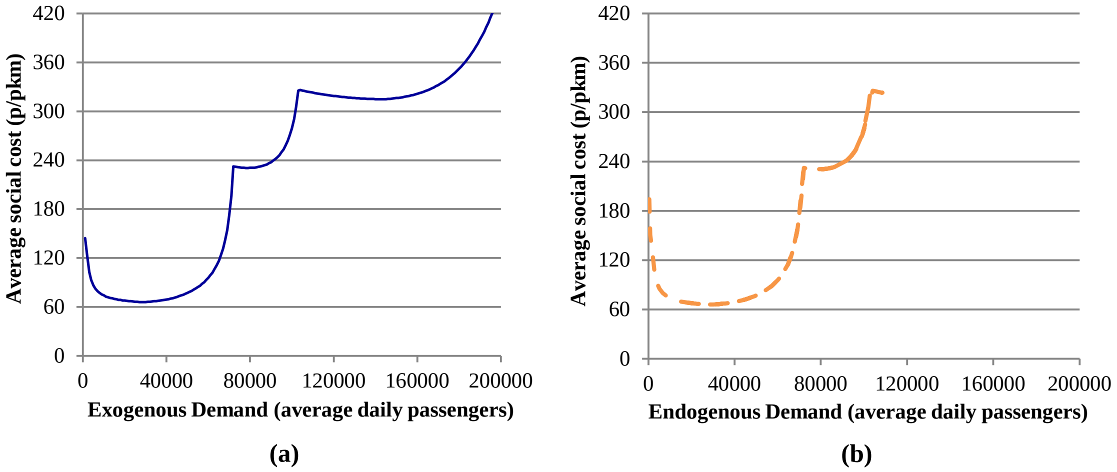


Figure 5-4 Average social cost of single-decker bus in exogenous and endogenous demand

In Figure 5-4, the average social cost of single-decker bus after applying the endogenous demand analysis is shown as the dotted line on the right hand side, and the blue solid line indicates the average social cost of single-decker bus before applying the endogenous demand calculation.

The endogenous demand curve stops at the daily demand level of approximately 104,000 per day, which means passenger are willing to use that public transport service until the endogenous demand level reaches 100% of the exogenous demand (in Figure 5-3). When the maximum point has been reached, any increase in demand will lead to a deterioration service which will bring the level of demand back to the maximum level. This effect will also be shown in the case study in Chapter 7, which compares the performance of conventional single-decker bus and the Straddle Bus technology. As a result of the endogenous demand analysis, with the limited quality of service for the single-deck bus in mixed traffic, the actual level of demand cannot accumulate up to 200,000 passengers per day.

5.5 Conclusion

This chapter discusses how the performance of the public transport service would impact the willingness of public transport passengers to use the service for their journeys by detailing the specifications of the Demand Supply Model.

In order to reflect the changes of public transport passenger demand due to the changes of service performance, the DSM evaluates the demand and supply relationship by using demand elasticities with respect to passenger waiting time and passenger in-vehicle time in a constant elasticity demand function. By using the elasticity values for different public transport technologies and in different network condition, the model and the comparative assessment is able to treat passenger demand level as endogenous rather than exogenous, and the level of demand will not accumulate up to infinity if the public transport system cannot provide sufficient quality of the service to users.

CHAPTER 6 MICROSCOPIC SIMULATION MODEL

6.1 Introduction

In the comparative assessment, the SCM is able to analyse the performances of different public transport modes in terms of average social and operator cost in the given transport network condition, and the DSM evaluates the endogenous demand by using demand elasticities with respect to generalised journey time. As a result of the strategic nature of the SCM, a simulation model is required in the comparative assessment in order to upgrade the assessment to deal with real world transport network rather than in a hypothetical stand-alone corridor.

This chapter is going to describe the Microscopic Simulation Model (MSM) of the comparative assessment, which is also the model used for the application of the comparative assessment in Chapter 7. The reason of selecting Minzu Avenue, Nanning, China is going to be explained in the first place, followed by the data collected from the field survey data collection. The model was developed in VISSIM, and the modelling details are given, including the model infrastructure, control data, traffic data and the simulation of Straddle Bus. To ensure the credibility of the MSM, model calibration and model validation were conducted. The detailed model calibration and validation process is also presented in this chapter.

6.2 Simulation Network Selection

The MSM would make use of traffic data of a city that is suitable for operating all public transport technologies in the assessment. The city Nanning, China was chosen to be the target city of the model, and its main corridor – Minzu Avenue was chosen to be the simulated corridor.

6.2.1 General Information

Nanning is located in southern China as the capital city of Guangxi Province. Due to the location advantage, Nanning has been holding the CHINA-ASEAN Exposition since 2003 and has a large amount of co-operation and trading activities with Southeast Asian countries. It is a middle size city in China compared to metropolises like Beijing and Shanghai, but is still a relatively large city on a global scale. It has a 7.07 million total population among which 2.71 million are urban residents and more than 2 million people are living in the urban built up area in 2010 (Guangxi Hualan Design & Consulting Group, 2011). The city is located in south China as shown in Figure 6-1 and the urban area of Nanning is shown in Figure 6-2 as the areas with colours.

Figure 6-1 The location of Nanning, China

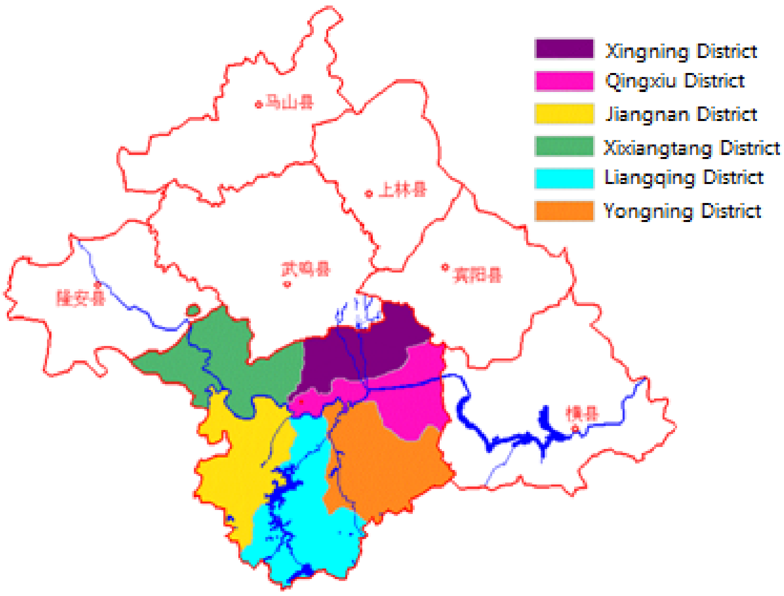


Figure 6-2 The urban area of Nanning

Nanning was developed along the Yongjiang River across the city. The main residential area is located in the north and west part of the city and the main business district is in the city centre. Due to the recent development of the city as well as the investments and trading activities from Southeast Asian countries, the main business activities are moving now to the Langdong area in the east.

According to the investigation at some main junctions in the central district of Nanning, the traffic compositions of Nanning are reported in the Nanning Comprehensive Transport Annual Report – 2010 (NCTAR2010) by Guangxi Hualan Design & Consulting Group (2011). Details are shown in Table 6-1.

Table 6-1 Traffic composition of Nanning (2010)

Vehicle Type	Bus/Coach	HGV	Car	Taxi	Other*	Total
Vehicle number proportion (%)	8.57	2.9	48.28	10.86	28.99	100

*Including bicycle, electrical bicycle, and motorcycle.

Source: Nanning Traffic Police Detachment, adapted from Nanning Comprehensive Transport Annual Report – 2010 (Guangxi Hualan Design & Consulting Group, 2011)

According to the analysis of NCTAR2010, the city central district has more buses and coaches compared to other areas, which is because of the overlapping of bus routes and the traffic congestion affects the route choice of private cars. The heavy congested traffic situation in the city centre also makes other modes of transport such as walking or electric bicycle more preferable.

6.2.2 Corridor Information and Public Transport Data

The Minzu Avenue is the longest corridor in Nanning that has a total length of 12 km. The corridor links the central district of Nanning to the motorway entrance and the main coach station in the east boundary of the city via the recently developed new economic district, Langdong area. The location of Minzu Avenue is shown in Figure 6-3 as the corridor that coloured in red.

Figure 6-3 The location of Minzu Avenue in Nanning

Due to the large traffic volumes on the Minzu Avenue and the rapid development of Nanning, the corridor was reconstructed in 2002. It is now a dual carriageway with at least three lanes for automobiles and a separate lane for cyclists and motorcyclists on each direction, as shown in Figure 6-4.

Figure 6-4 An image of Minzu Avenue, Nanning, China

In the Nanning City of 6,693 km^2 urban area, there are 137 bus routes in total with a total network mileage of 2,336 km on and average 17.05 km per route in 2010 according to NCTAR2010. Public transport passenger demand level is very high in Nanning. From the report, the annual passenger demand by bus in 2010 is 635.98 million people, with a daily passenger demand level of 1.7424 million.

The bus fleet number of all 6 main bus companies in Nanning is 2,601 in total and the distribution and the main operating area of those 6 bus companies are shown in Table 6-2.

Table 6-2 Overview of the operation of each bus company in Nanning (2010)

Bus Companies	Operating Bus Routes	Route Mileages (km)	Number of Buses	Main Operating Area
Nanning Public Transport Company	77	1227	1307	Serving the urban built-up area
Nanning Baima Public Transport Ltd.	37	574	780	Serving the urban built-up area
Nanning Chengyunxin Passenger Transport Ltd.	10	224	203	Serving the outer circle of Nanning and coach stations
Nanning Zhongba Public Transport Co. Ltd.	1	27	20	Linking Dashatian area to the central city area
Nanning Chaoda Public Transport Co. Ltd.	5	107	92	Linking the coach stations in the outer circle of Nanning
Nanning Yongning Public Transport Co.Ltd.	7	177	199	Linking Yongning area to the central city area
Total	137	2336	2601	

Source from: Nanning Bureau of Transportation and Nanning Bus Companies, adapted from Nanning Comprehensive Transport Annual Report – 2010 (Guangxi Hualan Design & Consulting Group, 2011)

As shown in Table 6-2, most of the bus services in Nanning are for the urban built-up area and linked with the coach station. This means most of the bus services in Nanning have connection with Minzu Avenue, which is because of the high public transport demand on that corridor. As a result of the high passenger demand level and the rapid growth of the population of Nanning, underground service has been planned and the construction was started in 2011. The first underground line was expected to finish in 2016, which has approximately half of the stations on Minzu Avenue.

Minzu Avenue has a total length of 12 km, which is a long corridor in microscopic simulation, and it is difficult to calibrate and validate such a large microscopic simulation model. To simplify the simulation, the area simulated in this thesis is part of the Minzu Avenue as shown in Figure 6-5.

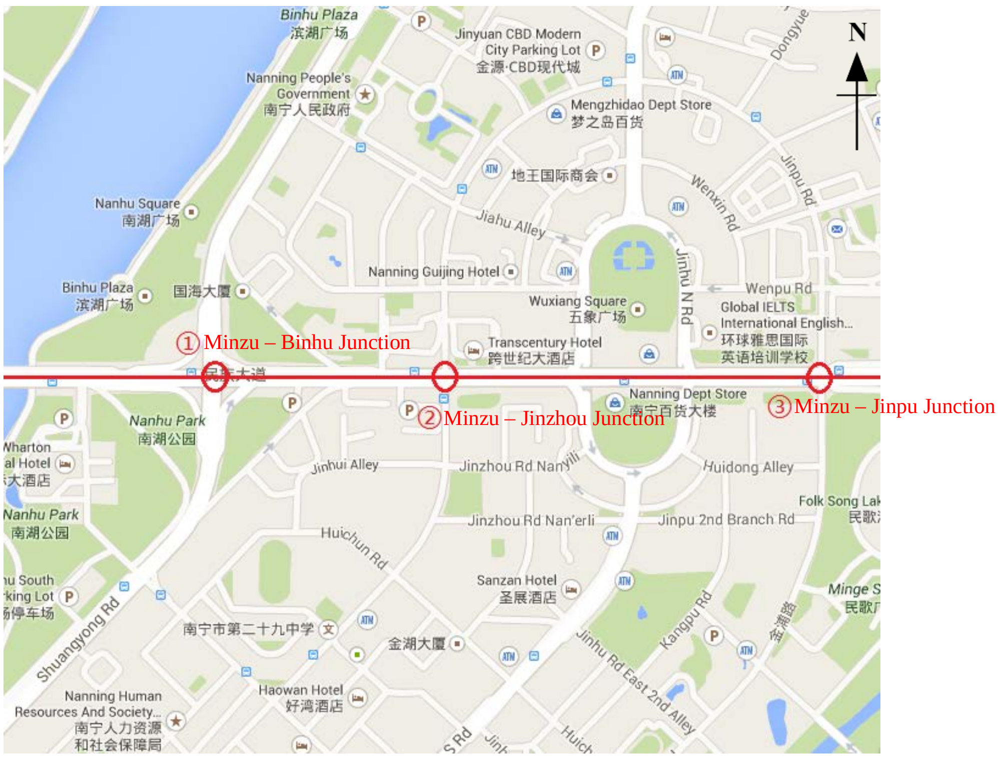


Figure 6-5 Simulation area in the VISSIM model

This area is located in the middle of the Minzu Avenue, which includes three junctions and there are three bus stops for each direction. It is at the boundary of the central district of Nanning and the new economic district, Langdong area.

Within the three bus stops on the Minzu Avenue, the westernmost bus stop has relatively low passenger demand level, and the other two are closed to shopping malls, the largest leisure park in Nanning – Nanhu Park and the tallest buiding – Diwang International Commerce Center where a number of business companies are located. The traffic flows in some major junctions on Minzu Avenue in Nanning are shown in Figure 6-6.

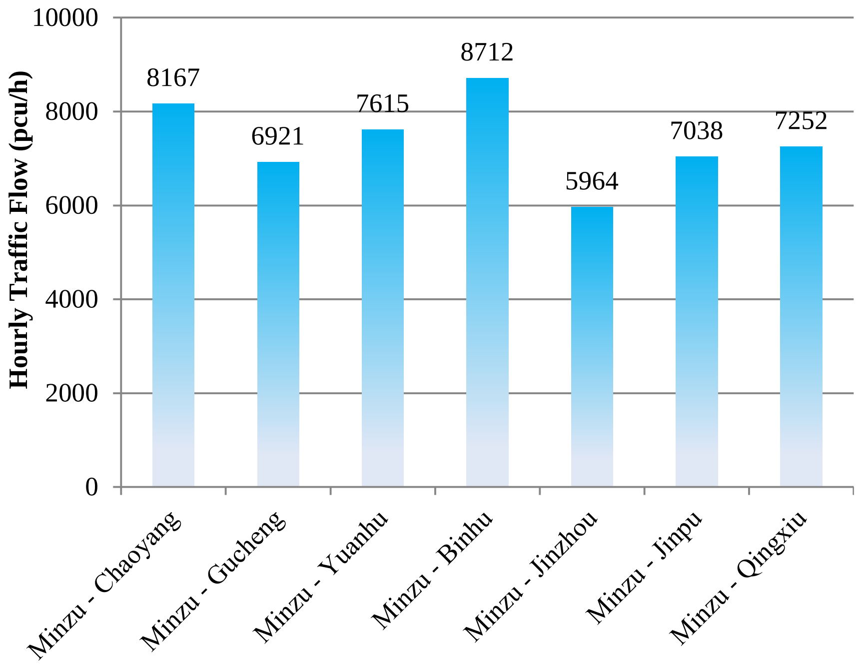


Figure 6-6 Traffic flow in some major junctions on Minzu Avenue

Source from: Nanning Traffic Police Detachment, adapted from Nanning Comprehensive Transport Annual Report – 2010 (Guangxi Hualan Design & Consulting Group, 2011)

According to NCTAR2010, Minzu – Binhu junction has a traffic volume of 8712 pcu/h in peak period, and the traffic volumes of Minzu – Jinzhou junction and Minzu – Jinpu junction are 5964 pcu/h and 7038 pcu/h in peak time, respectively. This is because the Minzu – Binhu junction is at the boundary of the central district and the Langdong area and Minzu – Jinpu junction is connected to the outer ring motorway of the city, and thus they both have extremely high levels of traffic volume. The average traffic flow volume of the three junctions is close to the average traffic flow volume of all junctions on Minzu Avenue that has data available in the report.

Therefore, this simulated area is able to represent the average traffic volume and the average passenger demand level of the entire corridor, and the simulation model can focus on this area with a length of 1.34 km rather than the entire 12 km Minzu Avenue.

6.2.3 Summary

There are three main reasons for choosing Nanning city as the simulation model network which are listed as follows.

1. The availability of the traffic data.
2. The possibility of applying innovative public transport technologies such as Straddle Bus.
3. Large enough passenger demand level for employing various forms of public transport.

For the first reason of the availability of the traffic network data, the local transportation research authority, Guangxi Hualan Design & Consulting Group conducted an annual report for the general traffic information in Nanning every year. They have agreed to provide those traffic data for this research and hence reduce a large amount of data collection work. Although the Intelligent Transportation Systems (ITS) development in Nanning is not as fast as other metropolitan areas in China and other western developed cities, the first phase of the ITS has been finished in recent years. The aim of the first phase was to install cameras in main urban areas for better control of the traffic by the traffic control centre.

As the comparative assessment should be able to take innovative public transport technology such as Straddle Bus into account, the simulation network should have suitable infrastructure. For the Straddle Bus technology, the bus would straddle two lanes on each direction as proposed by the inventor. For the main corridor Minzu Avenue in Nanning, there are 3 or 4 lanes on each direction which is possible for the operation of Straddle Bus. There are also segregated infrastructures for cyclists and motorcyclists and enough distances between two junctions to implement the Straddle Bus stations.

As a developing city, the bus passenger demand for the corridor is very high in peak and off peak periods, and the bus passenger demand of Nanning is increasing every year according to the 2010 data.

Table 6-3 Bus passenger volume of Nanning (2006 – 2010)

Year	2006	2007	2008	2009	2010
Total Passenger Volume (10,000 passenger)	45614.74	48662.7	54109.76	56803.94	63598
Increase Rate (%)	1.78%	6.68%	11.19%	4.98%	11.96%
Dailly Passenger Volume (10,000 passenger)	124.97	133.32	148.25	155.63	174.24
Increase Rate (%)	1.78%	6.68%	11.19%	4.98%	11.96%

Source from: Nanning Bureau of Transportation and Nanning Bus Companies, adapted from Nanning Comprehensive Transport Annual Report – 2010 (Guangxi Hualan Design & Consulting Group, 2011)

The underground project for Nanning was approved in July 2010 and the construction of the underground is on-going. This means Nanning is a developing city with huge public transport passenger demands and is capable of applying both conventional and innovative public transport forms in this research.

However, it is worth pointing out that the simulation of the corridor is limited to public transport systems that have a fixed route, and hence the traffic outside the corridor can be neglected. If those public transport services without a fixed line (such as DRT) were one of the options in the comparative assessment, a transport network for the wider area served is necessary. A dynamic assignment model is needed for evaluating the traffic of the wider network if the public transport technology (e.g. Straddle Bus) changes the capacity of the road and hence the changes the choice of route of other road users.

Those non-fixed line public transport systems have not been included in this thesis, as a result of the PhD study time constraint, and only a public transport corridor is considered, but it is worthwhile to be involved in future research of this topic to improve the comprehensiveness of this model.

6.3 Data Collection

This section of the thesis details the data collected from Nanning City for model development, calibration and validation of the simulation model. The traffic volume data and the passenger demand data were collected on two normal weekdays and the signal data for the three junctions were provided by the Nanning Traffic Police Detachment.

6.3.1 Traffic Data

In order to collect the traffic flow data of the area of interest, field survey was conducted in the off-peak period on three normal weekdays and five sets of data were collected. Due to some technical issues (cameras malfunction, cameras out of battery or videos discontinuous etc.), two data sets were chosen, which are the data collected between 14:30 p.m. to 16:30 p.m. on Thursday September 12, 2013 and Friday September 13, 2013. The dynamics of all vehicles were collected by using video camera recording, and the traffic data were extracted from the videos manually.

In the traffic data collection, two main measurements were required by the MSM. The first measurement is the traffic flow volume of the area, including both cars and buses. Note that there are no heavy good vehicles (HGVs) on the Minzu Avenue as HGVs are restricted on Minzu Avenue, and cyclists and motorcyclists have a separated lane and therefore has very low impacts on the operation of public transport services. The second measurement is the travel time of buses, which is also the performance measurement of the model calibration and validation.

To collect both targeted measurements while avoiding intrusions to drivers, three video cameras were installed in two tall buildings nearby the junctions. The locations of three cameras are shown in Figure 6-7.

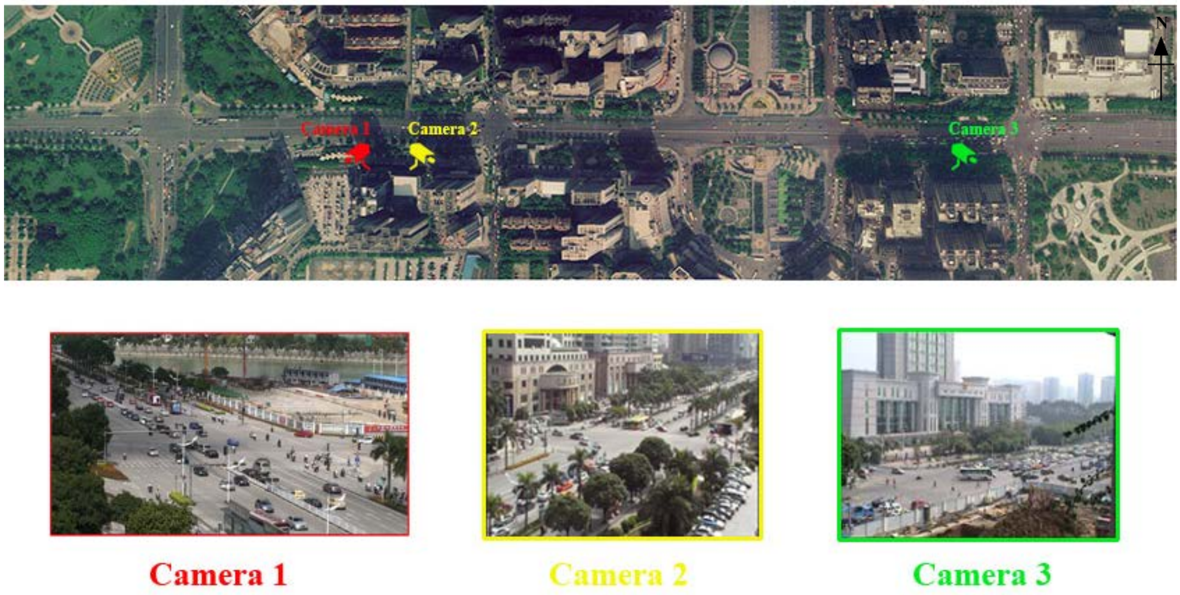


Figure 6-7 Locations of the recording cameras

The length of the traffic flow recording was set to 2 hours for all three cameras in order to obtain large enough sample size for the model calibration and validation, and all cameras were synchronised for collecting bus travel time data. Although the recording cameras were far away from the three junctions, the number of cars and buses passed through the junctions can be counted from the videos, as shown in Figure 6-7.

For building up the simulation model in VISSIM, the vehicle numbers are required for both cars and buses. The number of cars is required for the vehicle inputs and the number of buses is needed for the public transport line inputs in VISSIM. By extracting the traffic flow volume data from the videos manually, the number of vehicles in the simulated area on Minzu Avenue were obtained and shown in Table 6-4 and Table 6-5.

Table 6-4 Traffic flow data collected on Thursday, September 12, 2013

Time Period (minutes) : 117 Start Time: 14:31 p.m. Date: Thursday, September 12, 2013

Junction	**Minzu – Binhu**				**Minzu – Jinzhou**				**Minzu – Jinpu**			
	Bus		**Car**		**Bus**		**Car**		**Bus**		**Car**	
Direction	Total (veh)	Hourly (veh/h)	Total (veh)	Hourly (veh/h)	Total (veh)	Hourly (veh/h)	Total (veh)	Hourly (veh/h)	Total (veh)	Hourly (veh/h)	Total (veh)	Hourly (veh/h)
	19	9.74	549	281.54	44	22.56	412	211.28	0	0.00	230	117.95
	165	84.62	2060	1056.41	173	88.72	2045	1048.72	219	112.31	2627	1347.18
	-	-	-	-	8	4.10	391	200.51	-	-	-	-
	0	0	32	16.41	40	20.51	101	51.79	-	-	-	-
	123	63.08	1780	912.82	133	68.21	1928	988.72	192	98.46	2582	1324.10
	12	6.15	376	192.82	28	14.36	343	175.90	-	-	-	-
	23	11.79	100	51.28	20	10.26	109	55.90	0	0.00	608	311.79
	0	0	740	379.49	24	12.31	222	113.85	0	0.00	230	117.95
	31	15.90	606	310.77	12	6.15	282	144.62	0	0.00	136	69.74
	4	2.05	130	66.67	40	20.51	258	132.31	0	0.00		0.00
	0	0	690	353.85	40	20.51	395	202.56	-	-	-	-
	0	0	78	40.00	8	4.10	157	80.51	0	0.00	75	38.46

Table 6-5 Traffic flow data collected on Friday, September 13, 2013

Time Period (minutes) : 118 Start Time: 14:30 p.m. Date: Friday, September 13, 2013

Junction	**Minzu – Binhu**				**Minzu – Jinzhou**				**Minzu – Jinpu**			
	Bus		**Car**		**Bus**		**Car**		**Bus**		**Car**	
Direction	Total (veh)	Hourly (veh/h)	Total (veh)	Hourly (veh/h)	Total (veh)	Hourly (veh/h)	Total (veh)	Hourly (veh/h)	Total (veh)	Hourly (veh/h)	Total (veh)	Hourly (veh/h)
	13	6.61	613	311.69	8	4.07	419	213.05	0	0.00	255	129.66
	135	68.64	1996	1014.92	138	70.17	2226	1131.86	217	110.34	2665	1355.08
	-	-	-	-	12	6.10	350	177.97	-	-	-	-
	0	0.00	26	13.22	33	16.78	171	86.95	-	-	-	-
	151	76.78	2163	1099.83	142	72.20	2250	1144.07	225	114.41	2737	1391.69
	15	7.63	491	249.66	28	14.24	407	206.95	-	-	-	-
	12	6.10	85	43.22	41	20.85	118	60.00	0	0.00	601	305.59
	0	0.00	867	440.85	23	11.69	241	122.54	0	0.00	228	115.93
	24	12.20	870	442.37	8	4.07	337	171.36	0	0.00	152	77.29
	3	1.53	116	58.98	49	24.92	313	159.15	0	0.00	849	431.69
	0	0.00	894	454.58	37	18.81	297	151.02	-	-	-	-
	0	0.00	66	33.56	8	4.07	114	57.97	0	0.00	167	84.92

Due to the construction of the underground line and station, the south arm of Minzu – Jinpu junction is a one-way lane, and therefore there is no traffic flow volume data available for the vehicles that enter the south arm at Minzu – Jinpu junction. The traffic flow data for the right turning traffics from the west arm of Minzu – Binhu junction and the east arm of Minzu – Jinpu junction are not available because they are blocked either by trees or other traffic in the video. However, the missing traffic flows have very low impacts on other traffic, because there are segregated right turning lanes for right turning vehicles on Minzu Avenue, and they have no interactions with the bus stops on Minzu Avenue.

The simulated corridor also has various bus routes from both north and south arm of the three junctions. As the model only evaluates the public transport services on the Minzu Avenue, the buses that enter the network from either the north or south arm of the junctions were counted as part of the general traffic vehicle input, and the buses from the Minzu Avenue were counted as the input servicing vehicles of the bus route defined in VISSIM. The times the buses entered the simulation area were also extracted from the videos for the buses on the bus route of Minzu Avenue, which were used as the starting time input data of the bus route in the simulation model.

6.3.2 Passenger Demand Data

Data collection for the bus passenger demand was conducted on two normal weekday afternoons, which were the next Thursday and Friday (September 19, 2013 and September 20, 2013) after the traffic flow volume data collection, in the off-peak period between 14:30 a.m. and 16:30 a.m. The locations of the bus stops are illustrated in Figure 6-8.

Figure 6-8 Locations of bus stops in the Microscopic Simulation Model

Six undergraduate and postgraduate students from Guangxi University provided great assistance during the bus passenger demand data collection. For the simulated area, there are six bus stops in total, three on each direction of the corridor. Three teams with two people each were divided, and two bus stops were assigned to each team for collecting the number of boarding and alighting passengers manually. The number of the passengers on board was also collected, in order to compute the occupancy rate and alighting rate for VISSIM input.

The bus services from/to other part of the network (e.g. passenger demand to the north and south arm of each junction from Minzu Avenue) may also stop at the six bus stops. Therefore, these bus passenger numbers were excluded from the total passenger number, and the passenger demand for the bus services on Minzu Avenue are shown in Table 6-6 and Table 6-7.

Table 6-6 Bus passenger demand data collected on Thursday, September 19, 2013

Time Period (minutes) : 120 Start Time: 14:30 p.m. Date: Thursday, September 19, 2013

Data Type	Bus Stop No.	Eastbound			Westbound		
		1	2	3	1	2	3
Raw Data	Total Boarding Passengers (pax)	96	174	762	84	184	708
	Total Alighting Passengers (pax)	134	240	594	262	158	388
	Total Initial Passengers On Board (pax)	1920	1909	1946	1917	1943	1852
	Total Bus Number (veh)	115	117	121	97	97	99
VISSIM Input	Boarding Passenger Number per hour (pax/h)	48	87	381	42	92	354
	Average Alighting Rate	6.98%	12.57%	30.52%	13.67%	8.13%	20.95%

Table 6-7 Bus passenger demand data collected on Friday, September 20, 2013

Time Period (minutes) : 120 Start Time: 14:30 p.m. Date: Friday, September 20, 2013

Data Type	Bus Stop No.	Eastbound			Westbound		
		1	2	3	1	2	3
Raw Data	Total Boarding Passengers (pax)	104	200	744	90	174	720
	Total Alighting Passengers (pax)	212	334	568	342	157	467
	Total Initial Passengers On Board (pax)	2006	1981	1969	2052	2088	1924
	Total Bus Number (veh)	107	108	105	102	101	103
VISSIM Input	Boarding Passenger Number per hour (pax/h)	52	100	372	45	87	360
	Average Alighting Rate	10.57%	16.86%	28.84%	16.67%	7.52%	24.27%

Note that the alighting rate is defined as the percentage of passengers on board that are alighting in VISSIM. This parameter is an input variable in VISSIM to calculate the dwell time. The average alighting rate of each bus stop presented in Table 6-6 and Table 6-7 was computed by dividing the total number of alighting passengers by the total passengers on board initially before boarding and alighting.

6.3.3 Signal Data

As there are 3 signal controlled junctions in the simulated area on the Minzu Avenue, the signal data is one of the most important data to be collected. Nanning Traffic Police Detachment is the local authority who is in charge of all traffic signals in Nanning. Great support was provided, and the relevant signal time data were supplied.

According to the provided signal time data, all signal timings are fixed and there is no difference between peak period and off-peak period due to the early stage of ITS in Nanning. All three junctions in the simulated area have four entrances and four stages for a complete cycle in total, and the traffic signal phases of the three junctions are the traditional “Red – Green – Amber” phase. The stage diagrams and the signal time data for each junction are given in Table 6-8, Table 6-9 and Table 6-10. As a reminder that the Minzu – Binhu junction is the junction on the west end of the simulation area and the Minzu – Jinpu junction is at the east end of the simulated link.

Table 6-8 Traffic signal timing of Minzu – Binhu junction in Nanning

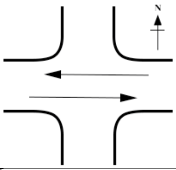
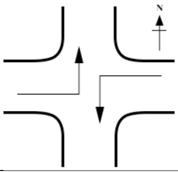
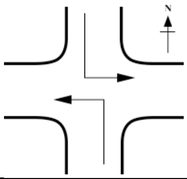
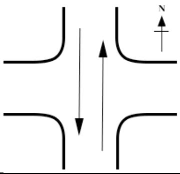
Stage			**Green Time (s)**	**Intergreen Time (s)**
1	West – East Straight		61	5
2	West – East Left Turning		41	5
3	North – South Left Turning		30	5
4	North – South Straight		30	5
Total Cycle Time (s)			182	

Table 6-9 Traffic signal timing of Minzu – Jinzhou junction in Nanning

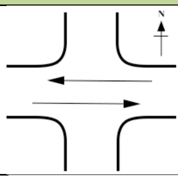
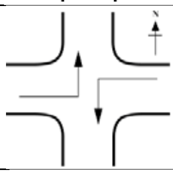
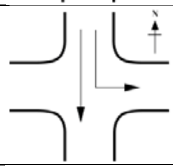
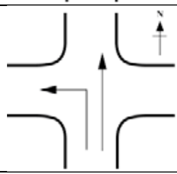
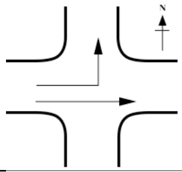
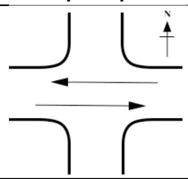
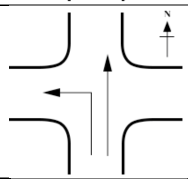
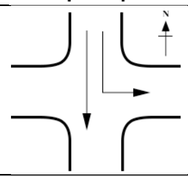
Stage			**Green Time (s)**	**Intergreen Time (s)**
1	West – East Straight		68	6
2	West – East Left Turning		28	6
3	North Arm		30	6
4	South Arm		24	6
Total Cycle Time (s)			174	

Table 6-10 Traffic signal timing of Minzu – Jinpu junction in Nanning

Stage			Green Time (s)	Intergreen Time (s)
1	West Arm		29	6
2	West – East Straight		58	6
3	South Arm		34	6
4	North Arm		40	6
Total Cycle Time (s)			185	

The traffic signal data were provided on Tuesday September 10, 2013 by Nanning Traffic Police Detachment. It has been confirmed by the provider that the signal timing data cover the period of the traffic data collection on Thursday September 12, 2013 and Friday September 13, 2013.

It is worth noting that the right turning traffic on Minzu Avenue is not controlled by the traffic signal. Right turning traffic will have to enter a separated lane before approaching the junction entry. However, due to the construction of the underground project, the right turning lanes were closed for the north arm of Minzu – Binhu junction, where the right turning traffic shares the same lane with the go-straight traffic.

6.4 Simulation Model

As mentioned in previous sections, the MSM would be based on VISSIM to develop an urban corridor traffic network with public transport modes operating on it. This model is going to cooperate with the SCM and the DSM to form the comparative assessment to investigate the performance of the target public transport technology on the selected route.

The model simulates a part of the traffic network in Nanning, and the architecture of the VISSIM model is made up of three components in order to obtain outputs, which are infrastructure, control data and traffic data. Straddle Bus was also simulated in the MSM for the case study. As an innovative and conceptual public transport technology, there is no built-in setting for Straddle Bus in VISSIM. Therefore the simulation of Straddle Bus in VISSIM is also detailed in this section.

6.4.1 Infrastructure

The VISSIM network contains the details of all the roads on Minzu Avenue and the tracks that connecting each road as well as any existing sign posts on the real network. For the simulated area on Minzu Avenue, there are three junctions on the corridor.

The model is built according to the geographic data of Nanning in Google Earth, which is a built-in function in VISSIM 6.0 (PTV AG, 2013). The whole length of Minzu Avenue is 12 km in total, and the simulation area in the VISSIM model is 1.34 km which includes three junctions and six bus stops in total. As a result of the ongoing underground construction on the Minzu Avenue, there are some differences between the geographic data from Google Earth and the corridor condition (lane closure, one-way lane, etc.) on the data collection date, which were collected by observation during the field survey.

The simulated corridor in VISSIM is shown in Figure 6-9.

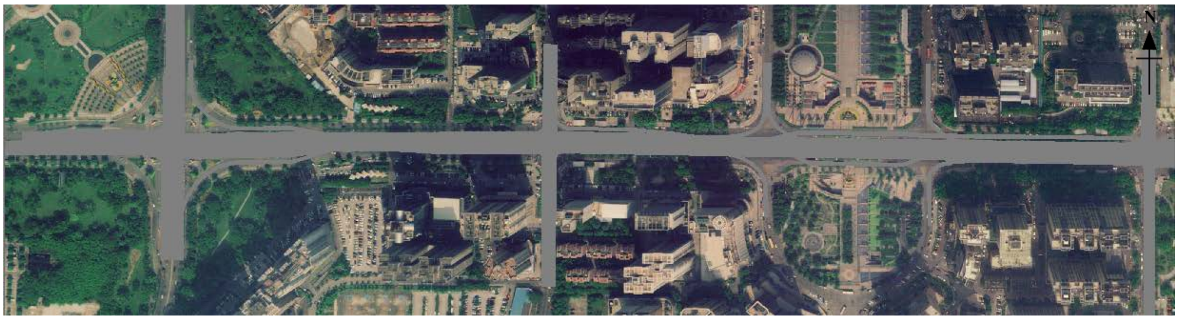


Figure 6-9 Simulated traffic network of Minzu Avenue in VISSIM

The speed limit is 40 km/h in the simulated urban area according to NCTAR2010 (Guangxi Hualan Design & Consulting Group, 2011), and lanes were all built based on the Chinese highway standard with a lane width of 3.5 m for each lane.

For right turn vehicles, an extra separated lane is provided at the entrance of the junction very close to the main road in order to reduce the delay for right turn vehicles and offer more spaces for the vehicles to go straight and left turn. This feature of the road is also described in the simulation model except the north and south entrances of the last two junctions where the right turning vehicles have to wait for green indication. A typical separated right turn road in China is shown in Figure 6-10 as follows.

Figure 6-10 A typical separated right turning lane in China

Minzu Avenue has four lanes on each direction with a barrier in the middle. An extra lane for cyclist is also provided and separated by a green belt for each direction. Note that the public transport technologies simulated in this model are running straight on the corridor without direct interaction with the cyclist on the segregated cycle lane. As a result of that, cyclists were not modelled, and the segregated cycle lane is possible to be neglected. For the roads connected with Minzu Avenue, most of them are three lanes in each direction, and some of them are expanded to four lanes at the junction entry.

6.4.2 Control Data

As mentioned before, due to the early stage of ITS in Nanning, the priority for public transport vehicles has not been set up yet, and therefore the signal phases are fixed without any priority. The collected control data were inputted into the simulation model for the three junctions by using the signal control input interface in VISSIM, as shown in Figure 6-11, Figure 6-12 and Figure 6-13.

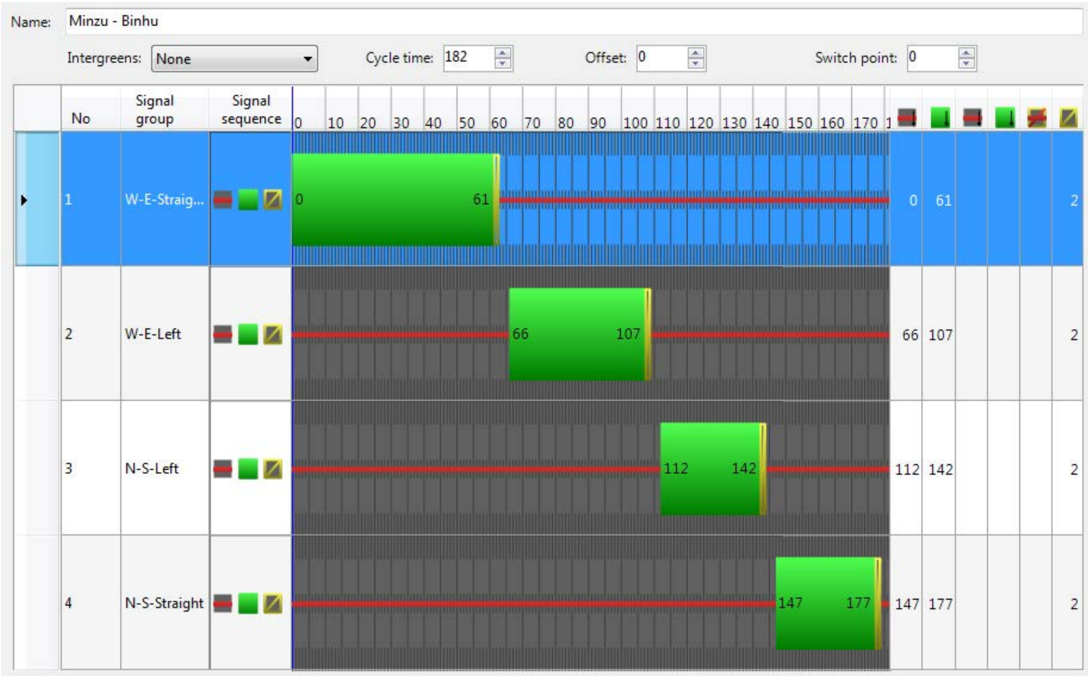


Figure 6-11 Control data for Minzu – Binhu junction

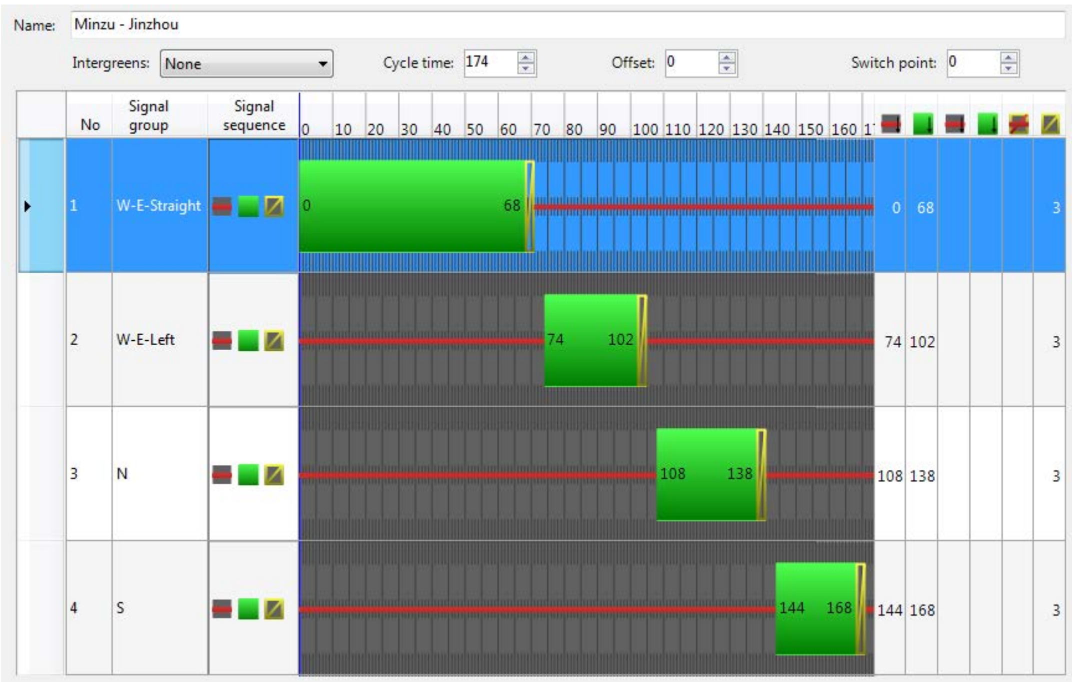


Figure 6-12 Control data for Minzu – Jinzhou junction

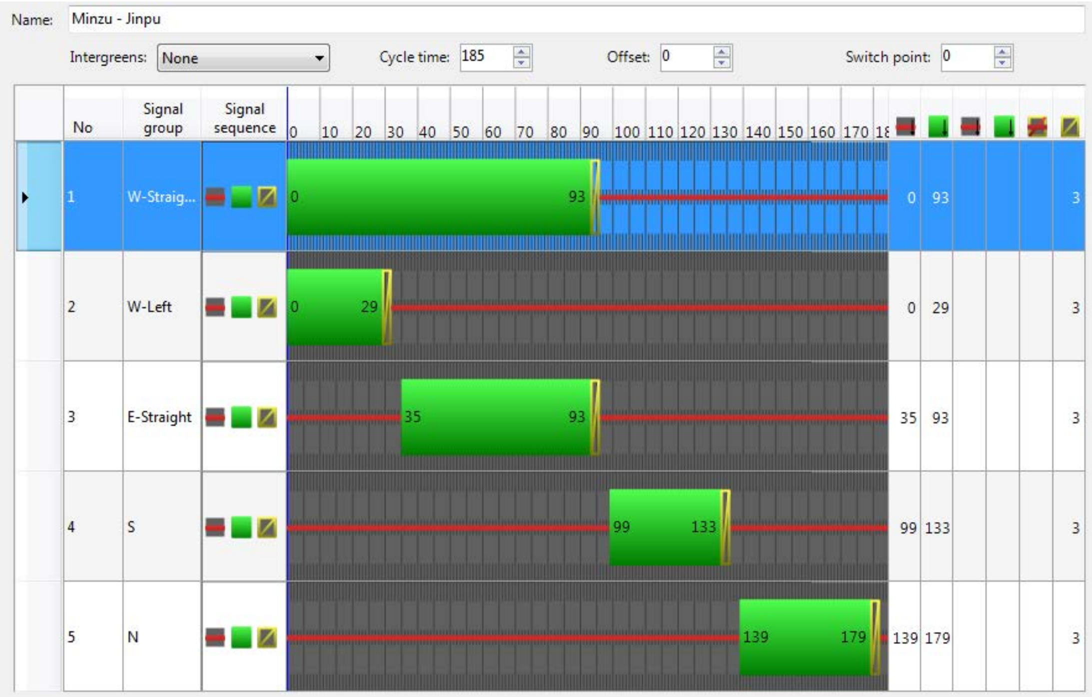


Figure 6-13 Control data for Minzu – Jinpu junction

Note that in Figure 6-13, the "W-Left" stage starts at the same time as the "W-Straight" stage and ends early to allow the traffic flow that goes straight from the east arm. These control data for the three junctions were obtained from Nanning Traffic Police Detachment as mentioned in Section 6.3.3. Data were inputted into the simulation model using the signal control user interface as shown in the figures above. Pedestrian stages are not considered in the control data for each junction, as the traffic signals for pedestrian follow the four stages for the general traffic.

The signal sequence in each cycle for the three junctions is "Red – Green – Amber" for each phase, and the duration for each sequence has to be adjusted based on the data collected from the field survey, and the VISSIM signal control program interface is shown in Figure 6-14.

Figure 6-14 Signal sequence setting in VISSIM

Note that the total cycle time is set up manually as well as the green time, red/amber time and amber time for each junction signal program, and the red time duration for each phase is default to be 1. The actual red time would then be automatically filling the rest of the cycle time for the selected phase. The red/amber time and amber time is 5 second in total, which includes 2 seconds of amber time and 3 seconds of all-red indication for all phases of each junction in the network. For all of the phases, the intergreen time would then be 5 seconds as it counts both the amber time and the all-red indication between two stages.

6.4.3 Traffic Input Data

Traffic input data are required to represent the traffic network of Minzu Avenue in Nanning in the simulation model. The traffic data comprises the information for both private transport vehicles and public transport vehicles, which are going to be demonstrated in this section. The input data include the characteristics of all private and public transport vehicles, the origin-destination of all vehicles, fixed bus routes and the public transport passenger demand, which are also shown in this section.

General Vehicle Input

General vehicle inputs in the VISSIM model include input vehicle volumes, traffic composition and origin information. For each vehicle input data, the origin of the vehicles, the volumes of the input vehicles and the composition category are required, as shown in Figure 6-15.

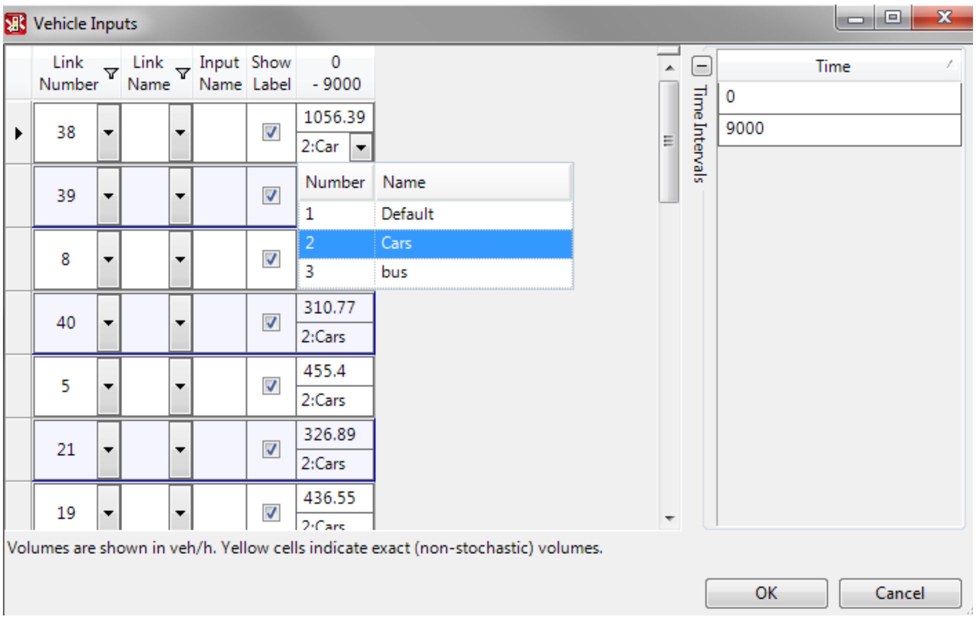


Figure 6-15 VISSIM vehicle input user interface

As shown in Figure 6-15, the origin of the vehicle flow is required for each vehicle input data as the "Link number", the volumes of the input vehicles for the selected time interval are required as vehicle per hour, and the traffic composition category is also needed for each input.

The destination of each vehicle is determined by using Static Routing Decision in VISSIM. Static Routing Decision points were placed at each arm of the three junctions to specify the route choices of each individual vehicle by using user defined proportions. When there is a vehicle that passes the routing decision point during the simulation, a specific route will be assigned unless it already has a route assigned to it (PTV AG, 2011). The proportion of the routes in each Static Routing Decision is defined by the relative flow volume, as shown in Figure 6-16.

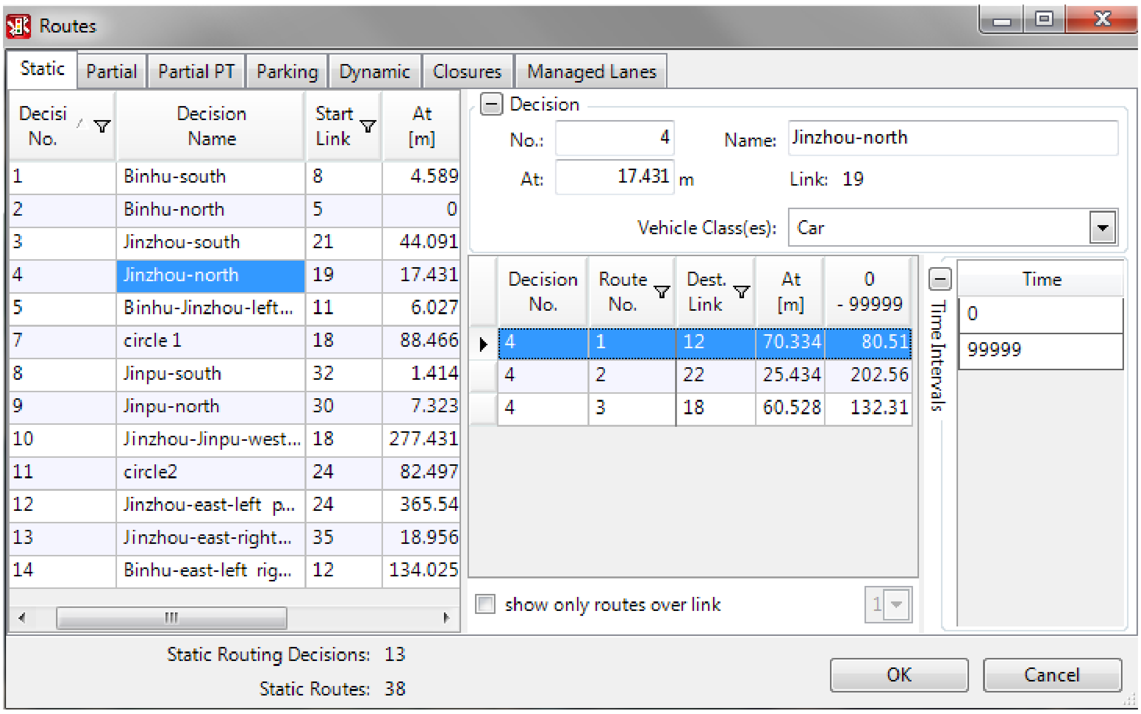


Figure 6-16 Static routing decision settings in VISSIM

In the Static Routing Decision interface as shown in Figure 6-16, user can create additional routes for each routing decision and specify the relative flow volume. In order to follow the traffic data obtained from the data collection, the relative flow volume for each route at each junction were setup based on the traffic data in Section 6.3.1 to define the turning proportion.

The traffic flow simulated in the VISSIM model is made of cars and buses only, without HGVs, bicycles and motorcycles. Therefore in the simulation model, there are only two vehicle composition categories defined: Cars and Buses. Note that the Buses category is defined as the buses that enter the simulated area from other network (north and south arms of each junction), and the buses on the bus route on Minzu Avenue are counted in the Public Transport Input, which are discussed in the next section. For both vehicle types, the desired speed was set to 40 km/h as default value in the first place, based on the speed limit of Minzu Avenue.

Public Transport Input

The public transport input is another primary traffic input in the MSM, as the model was constructed to evaluate the performance of public transport technologies. In VISSIM, public transport operations are defined by using Public Transport Lines, Public Transport Stops and Public Transport Parameters.

For the Public Transport Line in VISSIM, each line has to define the origin, destination, bus route and the activated public transport stops on the route. The starting time of each public transport vehicle on the public transport route needs to be defined in the Public Transport Line as well, which can be set either by service frequency or by entering the exact starting time in terms of the simulation time in VISSIM. The bus travel time would have less variation for a small network with only three junctions and a total length of 1.34 km, if the starting time of the bus service is determined by a fixed service frequency. This is because the dwell time is calculated by using the maximum passenger boarding or alighting time, and a fixed service frequency would lead to a more evenly distributed boarding passenger number per vehicle and hence the bus travel time would have less variation in the simulation model than the data collected from real world transport network. As a result of that, the starting time of each bus in the VISSIM model used the data extracted from the traffic flow video rather than a fixed service frequency.

The occupancy of each public transport vehicle is also required, which is the number of passengers that are in the vehicle when entering the VISSIM network. This parameter is evaluated by using the total initial passengers on board divided by the total bus number at the first stop for each direction. By using the data in Table 6-6, the occupancies can be acquired, and the simulation model uses 17 passengers/veh and 19 passengers/veh as the initial occupancy for the eastbound service and westbound service respectively.

The Public Transport Stops setting in VISSIM is required for each public transport stop in the network. The locations of each bus stop were determined by using the geographic data from the built-in Google Earth function and confirmed during the data collection field survey. Public transport passenger demand levels of the bus stop are in passengers/hour, and the passenger demand for each bus route that uses the bus stop is also identified in the Public Transport Stops setting. The dwell time data at each bus stop is calculated either by user defined distributions or by calculating maximum boarding or alighting time. As the boarding passenger number and the alighting percentages are available through the data collection, the dwell time calculations were based on the passenger boarding and alighting time, and the input data are from the data collection as described in Section 6.3.2.

The Public Transport Parameter setting in VISSIM includes total dwell time calculation and the capacity of the public transport vehicle. The total dwell time calculation was set to the maximum time of passenger boarding and alighting, as the buses in Nanning are all with exclusive doors for alighting passengers at the rear of the vehicle. Vehicle capacity has been set to 75 passengers per vehicle for all buses in the simulation model, which is consistent with the capacity value in the SCM.

6.4.4 Straddle Bus Simulation

In order to compare the performance of conventional bus system and Straddle Bus technology in Nanning in the case study, the simulation model has also been developed to simulate the operation of Straddle Bus on Minzu Avenue as a replacement of the conventional bus services. However, as an innovative and conceptual public transport, there is no default setting in VISSIM to simulate Straddle Bus technology. Hence the simulation of Straddle Bus require further development of the MSM by using the COM Interface in VISSIM to simulate the features of Straddle Bus that are distinct from conventional bus service.

As the MSM is developed for identifying the performance of public transport technology, the simulation of Straddle Bus is emphasised on replicating the feature of the technology, as well as the impacts to the general traffic. The conceptual design of Straddle Bus is to operate above the general traffic by straddling two nearside lanes to avoid congestion. According to the design, the entrance and exit are at the rear end and the front end of the vehicle, it is impossible to move in/out of the Straddle Bus by lane changing, as shown in Figure 6-17.

Figure 6-17 Front view of a Straddle Bus model

Therefore, the requirements of the Straddle Bus simulation are:

- Straddle Bus should be able to operate on the existing road infrastructure without being blocked by the general traffic.
- The lane change behaviours of general traffic are affected by the Straddle Bus vehicle. The vehicles that are under the Straddle Bus would not be able to change to the lanes outside the Straddle Bus, and the vehicles on other lanes cannot move to the lanes where there is Straddle Bus on it.
- Straddle Bus would block the turning traffic (right turning traffic in the Nanning case), and the turning vehicles have to give priority to the operation of Straddle Bus.
- The behaviour of the drivers that are under the Straddle Bus would be affected and the speed of the vehicles might be reduced.

To fulfil the requirements of the Straddle Bus simulation, four modifications to the simulation model were made.

Solution to Requirement 1

For the first requirement, the Straddle Bus technology is believed to be able to run above the traffic to avoid congestions and hence the Straddle Bus in the simulation model should have no collision with the traffic on the road.

To avoid collisions with the general traffic while running on the existing road infrastructure, an extra lane for Straddle Bus route has been created for each direction above the original lanes in the MSM. As the Straddle Bus is believed to operate on the two nearside lanes, the new Straddle Bus lanes were created with a lane width of 7 m (twice of the single lane on Minzu Avenue), and overlapped with the two nearside lanes for each direction on Minzu Avenue. As the Straddle Bus lane is above the original lanes in the model, the collisions between Straddle Bus and the general traffic can be avoided during the simulation.

As the Straddle Buses are also controlled by traffic signals, the signal control for each junction were also installed on the Straddle Bus route, which follow the go-straight signal control for each junction on the existing road infrastructures. Note that there is no bus priority system on Minzu Avenue, and the traffic signal control will use the same cycle time as shown in Section 6.3.3.

Bus stops on the Straddle Bus route were built at the same location of the conventional bus stops, and the existing bus routes were removed and the passenger demands were moved to the Straddle Bus stops to simulate the Straddle Bus replacement.

With an additional Straddle Bus lane that includes Straddle Bus route and Straddle Bus stops for each direction, the operation of Straddle Bus will not be effected by general traffic in terms of speed, and the first requirement can be met.

Solution to Requirement 2

For the second requirement, constraints on the lane change behaviour of general traffic should be set according to the location of Straddle Buses, in order to mimic the Straddle Bus impacts in the simulation model.

In this case, 34 detectors have been installed on the Straddle Bus lane for each direction to detect the movements and locations of the Straddle Bus vehicle. The detectors are "Presence" type detectors to detect the presence of Straddle Bus. The maximum distance between the front ends of two detectors was set to 45 metres, as the vehicle length of Straddle Bus was assumed to be 40 metres in the SCM and the default length of the detector is 5 metres. To increase the accuracy of locating Straddle Bus by using detectors, the distance between two detectors should be as small as possible. However, smaller distances will make it much more difficult to build the model infrastructure, as the behaviours of each lane are different. Therefore the maximum headway between detectors was set to 45 metres to prevent the situation that the Straddle Bus cannot be located by the detectors when it is running between two detectors.

To control the lane change behaviour of each lane according to the location of each Straddle Bus vehicle, a control program was coded in Visual Basic and linked to the simulation model via the VISSIM COM Interface (PTV AG, 2012). The control program was coded to run the VISSIM model with different input data in multiply times and with different random seeds. The format of the output files can also be set by the control program in order to identify the parameter values used in the simulation model for the calibration and validation process as well as the data analysis of the case study.

The control program is able to run the simulation model either by continuing or by single time step for the entire pre-set simulation period. For the conventional bus simulation without detector controlled, the model runs continuous for the entire simulation period. For the Straddle Bus simulation, the control program runs the simulation model by single time step (default value as 5 time steps per simulation second, and each time step is 0.2 simulation seconds) and determines the location of the Straddle Bus according to the states of the 34 detectors. Once the detector has detected that there is Straddle Bus passing through the location of the detector, the lane change options for general traffic between the next detector and the activated detector will be closed for the vehicles move in or out of the two most nearside lanes. Lane changes for general traffic to move in or out of the two nearside lanes will be available again, once the Straddle Bus has been detected by the next detector. An example is given with the help of Figure 6-18 to explain the lane change behaviour modification according to Straddle Bus location.

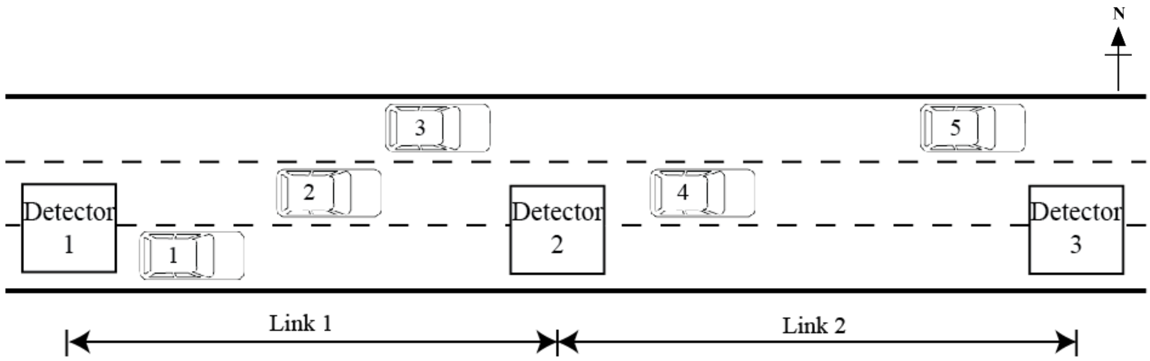


Figure 6-18 Detector control example for lane change behaviour (eastbound traffic)

In Figure 6-18, if a Straddle Bus is detected by Detector 1, the parameters of Link 1 will be changed to restrict the lane changes between the offside lane and the centre lane. Therefore Car 2 cannot make lane changes to the offside lane and Car 3 cannot change to the centre lane. However, there is no restrain on the lane changing between the two nearside lanes that the Straddle Bus straddles. Car 1 is free to make lane change to the centre lane and Car 2 can also change to the nearside lane when Detector 1 is activated. Car 4 and Car 5 have no restriction on lane changes in this case, as Straddle Bus has not arrived Link 2 yet.

If the Straddle Bus vehicle has moved and been detected by Detector 2, the lane changes parameters of Link 2 will be changed as well. In this case, the lane change between the centre lane and the offside lane on Link 2 will no longer be possible. The lane change restriction on Link 1 will be restored once Detector 3 detects the Straddle Bus. As Straddle Bus could be on Link 1 and Link 2 once it has been detected by Detector 2, this control logic will ensure that there is no collision between general traffic and Straddle Bus by controlling the lane change behaviour on certain links.

Note that the control priority of the detectors is descending with ascending detector numbers to deal with the scenario that multiply Straddle Bus vehicles are on the lane. For example, if both Detector 1 and Detector 3 have passed the information to the control program that there is a Straddle Bus passing the detector location, the control program will change the parameter of Link 1 according to the state of Detector 1 rather than the state of Detector 3. Therefore the lane change options between the centre lane and the offside lane are closed both for Link 1 and Link 2, and the lane change parameter of Link 1 will not be restored until the Straddle Bus at Detector 1 reaches Detector 3.

Solution to Requirement 3

For the third requirement, all right turning traffic on Minzu Avenue in the simulation model were investigated and modified in the Straddle Bus simulation to simulate the blocking effects by Straddle Bus.

As a result of the separated lane for right turning traffic on the Minzu Avenue for both westbound and eastbound direction, the vehicles that are planning to turn right will enter another lane before approaching the junctions. To prevent the collision of the right turning traffic and the Straddle Bus and hence to simulate the delays caused by the Straddle Bus technology, an extra signal head with all-red indication was installed on the Minzu Avenue in front of the connecting lane to the right turning lane, as shown in Figure 6-19.

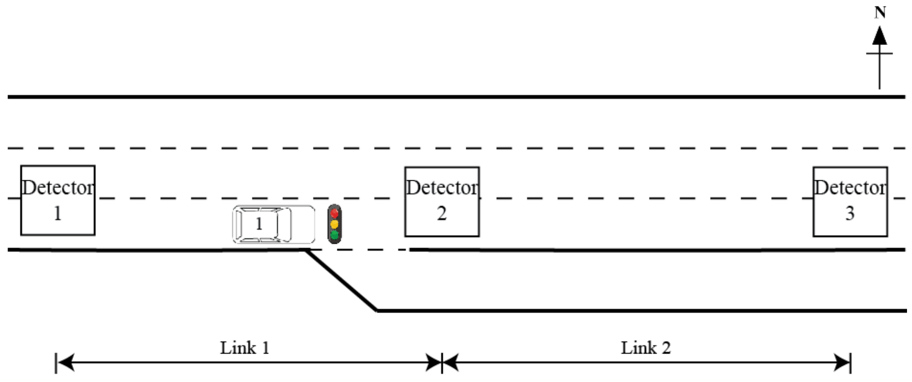


Figure 6-19 Detector control example for right turning traffic (eastbound traffic)

Similar to the lane change behaviour control by using the detector, the signal heads for the right turning lane are also triggered by the states of the detectors on the Minzu Avenue. If a Straddle Bus has been detected by Detector 1, the signal head for the right turning lane will be activated, and therefore Car 1 will have to wait in front of the connector to the right turning lane. The signal head will stay activated until the Straddle Bus reaches Detector 3, and hence the right turning traffic cannot enter the separated lane unless there is no Straddle Bus on Link 1 or Link 2.

To achieve this control in VISSIM, a Vehicle Actuated Programming (VAP) was created. VAP is an optional add-on of VISSIM to simulate a programmable, phase or stage based traffic actuated signal controls (PTV AG, 2012). Control logic can be created in programming language to achieve user defined signal controls. By following the control logic as described before, logic file (*.VAP) and interstage definitions (*.PUA) were created, and then the VISSIM model is able to simulate the impact of the Straddle Bus to the turning vehicles.

Solution to Requirement 4

For the fourth requirement of the Straddle Bus simulation, 34 sets of Desired Speed Decision Controller were installed on the Minzu Avenue for each direction. Those speed controllers were placed at the 34 detectors to change and restore the speed of the general traffic on Minzu Avenue according to the location and presence of Straddle Bus vehicles, as shown in Figure 6-20.

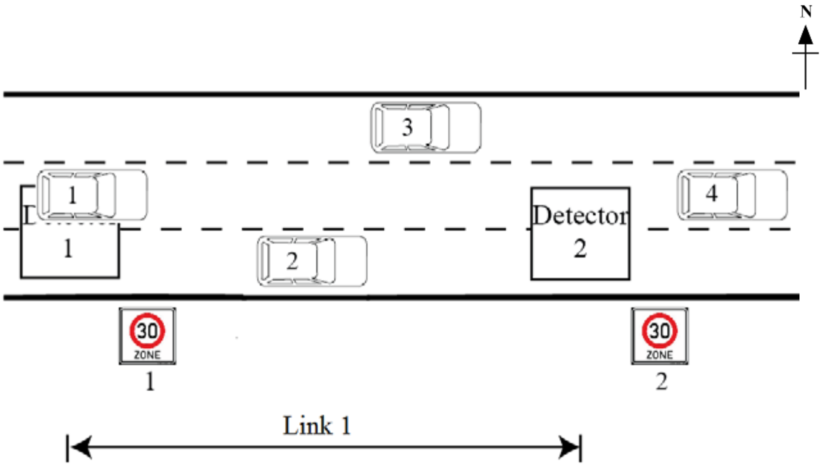


Figure 6-20 Detector control example for Desired Speed Decision Controller (eastbound traffic)

If there is a Straddle Bus vehicle detected by Detector 1, the information will be passed to the control program and the Desired Speed Decision Controller 1 will change the desired speed of the vehicles that pass the controller point. It is worth noting that the Desired Speed Decision Controller does not affect the parameter of the link but the decision of the vehicle passing the controller point. Therefore when Car 1 reaches Desired Speed Decision Controller 1, the speed of Car 1 will be changed based on the pre-set desired speed distribution. However, as Car 2, Car 3 and Car 4 have already passed Desired Speed Decision Controller 1, their speed will not be affected. If Straddle Bus has left Detector 1 and reached Detector 2, the desired speed distribution controlled by Desired Speed Decision Controller 1 will restore while Desired Speed Decision Controller 2 will receive the information of the presence of the Straddle Bus and start to control the speed of the general traffic.

The default desired speed distributions of all controllers were set to 40 km/h according to the speed limit of the simulated area on Minzu Avenue. As the Straddle Bus technology is still a conceptual technology, there is no research for the impacts of the Straddle Bus vehicle on the general traffic. However, the difference of driver's behaviour when following a passenger car and a heavy vehicle, especially the headway difference has been investigated by a number of previous studies (McDonald et al., 1997; Yoo and Green, 1999; Aghabayk et al., 2011). The design of the Straddle Bus technology is to allow vehicles running underneath the vehicle rather than keeping distance and following the Straddle Bus. Therefore the Straddle Bus has been assumed to have impacts on driver's behaviour in terms of vehicle speed rather than headway in the VISSIM model when the driver is driving underneath the Straddle Bus vehicle. Yoo and Green (1999) found that the behaviour of drivers following a passenger car will have 10% lower headway than following a heavy vehicle. The vehicle acceleration distribution results from Aghabayk et al. (2011) show that the maximum acceleration/deceleration in a passenger car-following a passenger car scenario is about 10% lower than a passenger car-following a heavy vehicle scenario. Consequently, the desired speed of general traffic was assumed to a have a 10% reduction due to the appearance of Straddle Bus, and Desired Speed Decision Controllers placed in the simulation model will reduce the desired speed by 10% when control program received the presence information of Straddle Bus from corresponding detectors.

6.5 Model Calibration and Validation

The MSM was developed as part of the comparative assessment to investigate the performance of different public transport technology. To compare the performance of conventional bus service and Straddle Bus on Minzu Avenue in Nanning as a case study of the comparative assessment, the MSM was built based on the data collected from the Nanning network. To ensure the output of the simulation model truly represents the real world transport network, it is necessary to conduct a calibration and validation of the model, which is a process to adjust the parameters and test the accuracy of the simulation model compare with the data collected from the real world.

As it has been discussed in Chapter 3, the model calibration and validation process followed the suggested nine-step procedure by Park and Schneeberger (2003), which is a very comprehensive and standardised calibration and validation procedure for microscopic simulation model and widely accepted by other researches. These nine steps are: 1. measure of effectiveness selection; 2. data collection; 3. calibration parameter identification; 4. experimental design; 5. run simulation; 6. surface function development; 7. candidate parameter set generation; 8. evaluation; 9. validation through new data collection. This section is going to describe the model calibration and validation process in details, by following the nine-step procedure.

6.5.1 Measure of Effectiveness

The MSM was built to evaluate the indicators that are required for solving the concerning problem, and it is rather difficult and unnecessary to create a model that completely replicating every aspects as the actual transport network. Therefore, the first step of the model calibration and validation process is to identify the key performance indicators as the measure of effectiveness, which is the required information from the simulation model for the comparative assessment.

The selected key performance indicators must be able to be collected from both the simulation model and from the actual transport system in order to compare the differences. As the SCM assesses the social and operator cost for a single direction on the corridor, the key performance indicators were chosen for the eastbound traffic on Minzu Avenue rather than both directions. In this case, the travel time of the conventional bus service on eastbound of Minzu Avenue was selected, as the travel time of public transport service is the key variable that is required by the DSM to evaluate the generalised passenger journey time and hence the endogenous demand level.

Therefore, two travel time evaluation points were placed on the eastbound of Minzu Avenue in the model to evaluate the travel time of each bus. Other performance indicators include average private vehicle speed, public transport speed, queue length and delays are available in the VISSIM output file, but they are either difficult to be collected from the real network or less relevant to the SCM and the DSM.

6.5.2 Data Collection

To calibrate and validate the simulation model and hence ensures the accuracy of the model output, input data and output performance indicators are necessary to be collected from the real transport network. For the calibration and the validation, it would be necessary to use different field data under untried condition, and the validation data should be collected in a different time periods or condition compared with the calibration data (Park and Schneeberger, 2003). Hence, two different sets of field data are required to perform the model calibration and validation.

In the data collection field survey in Nanning, China, five sets of data have been collected and two of them were extracted from the recording videos. The calibration data was collected between 14:30 p.m. to 16:30 p.m. on Thursday September 12, 2013 and the validation data was collected between 14:30 p.m. to 16:30 p.m. on Friday September 13, 2013. In the two sets of data collected from field survey, the input data for the model calibration and validation has been shown in Section 6.3, and the output data, which is the bus travel time in this case, was also extracted from the recording videos as all three cameras were synchronised. The bus travel time distribution extracted from the recording videos are shown in Figure 6-21 and Figure 6-22.

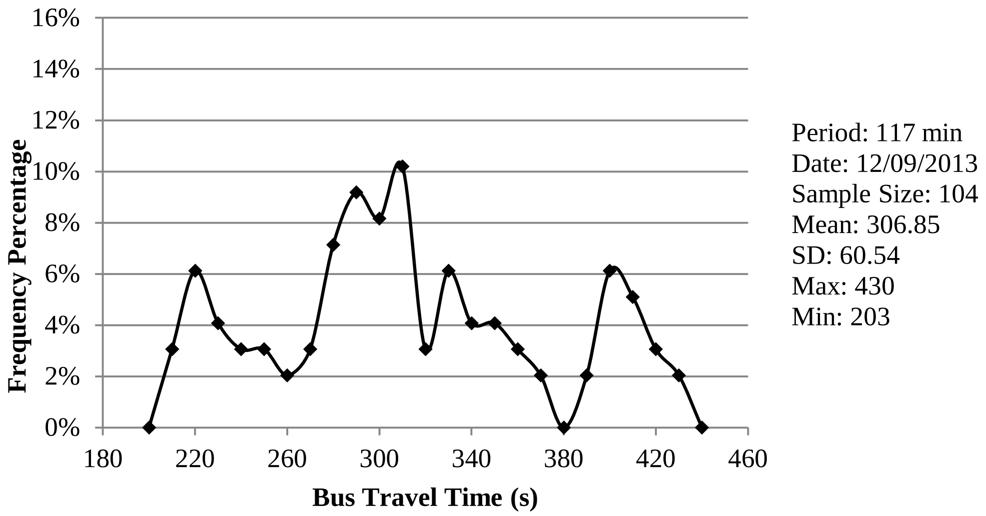


Figure 6-21 Bus travel time distribution for eastbound traffic on Minzu Avenue collected on Thursday, September 12, 2013

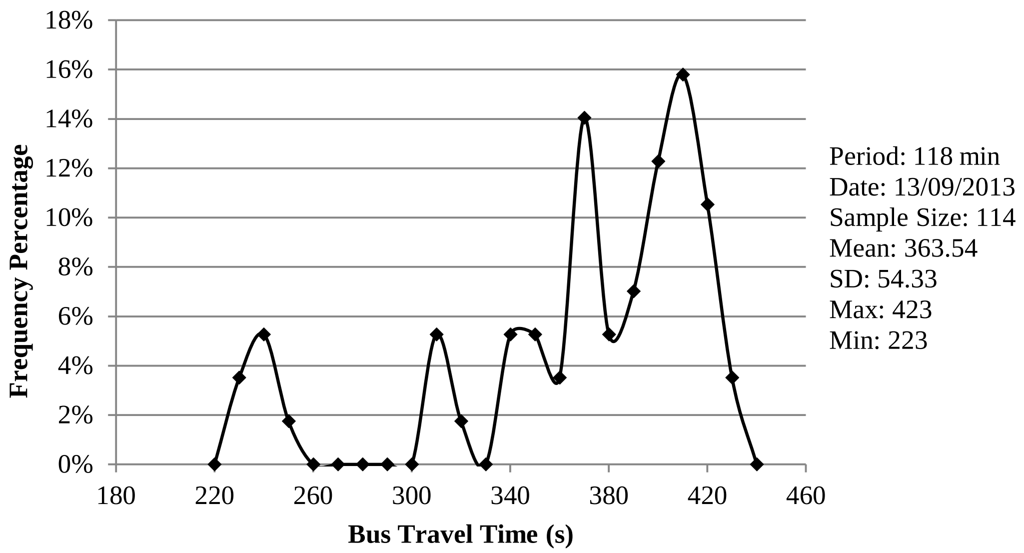


Figure 6-22 Bus travel time distribution for eastbound traffic on Minzu Avenue collected on Friday, September 13, 2013

In order to ensure the credibility of the model, the parameters of the simulation model in VISSIM should be calibrated and validated to produce outputs that match the bus travel time shown in Figure 6-21 and Figure 6-22 by using the same set of data collected from field survey.

6.5.3 Calibration Parameters

In the simulation model, there are various parameters that control the behaviour of the vehicles. To calibrate the model in VISSIM, the values of all relevant parameters have to be adjusted to find out the parameter set that produces the output that matches the field data. As the MSM is aiming to obtain the public transport travel time, public transport parameters such as bus speed, bus acceleration and bus deceleration were selected as the calibration parameters.

Other calibration parameters for general traffic include: emergency stop distance, lane change distance, desired speed distribution of the traffic, safety distance factor of the conflict area, headway time, average boarding/alighting time per passenger and standstill distance, which are the basic parameters in VISSIM. However, the initial calibration test results shows that the p values of the calibration parameters for general traffic are greater than 0.05 in the linear regression model of the parameters and the key performance indicator, which means they are less relevant to the key performance indicator. Moreover, nine calibration parameters will require large number of combinations and hence large amount of time to run the simulation model. Therefore, these parameters for the general traffic were not used in the model calibration and validation.

Ranges of the three public transport parameters are listed in Table 6-11.

Table 6-11 Model calibration parameters

Parameters	Default Value	Other Possible Values	
Bus Desired Speed Distribution (km/h)	25	15	35
Bus Desired Acceleration (m/s^2)	1.24*	1.04	1.44
Bus Desired Deceleration (m/s^2)	-0.85*	-0.65	-1.05

*The desired acceleration and deceleration parameters in VISSIM are functions of current speed. Modifications of other possible values were shifting the curve up or down.

It is worth noting that the bus desired speed distribution is not the actual speed in the simulation, but the speed that drivers are trying to attain on public transport lines. Possible nearby speed distributions set by VISSIM were used, as shown in Table 6-11.

Bus desired acceleration and deceleration are defined as functions of current speed in VISSIM. The variations between different driver's behaviour are also considered by using maximum and minimum curves. The default maximum and minimum desired acceleration/deceleration curves were validated by PTV AG and can be changed by users. As there is no information on the bus acceleration/deceleration in Nanning, possible values will be shifting a unit amount upwards or downwards, as shown in Figure 6-23.

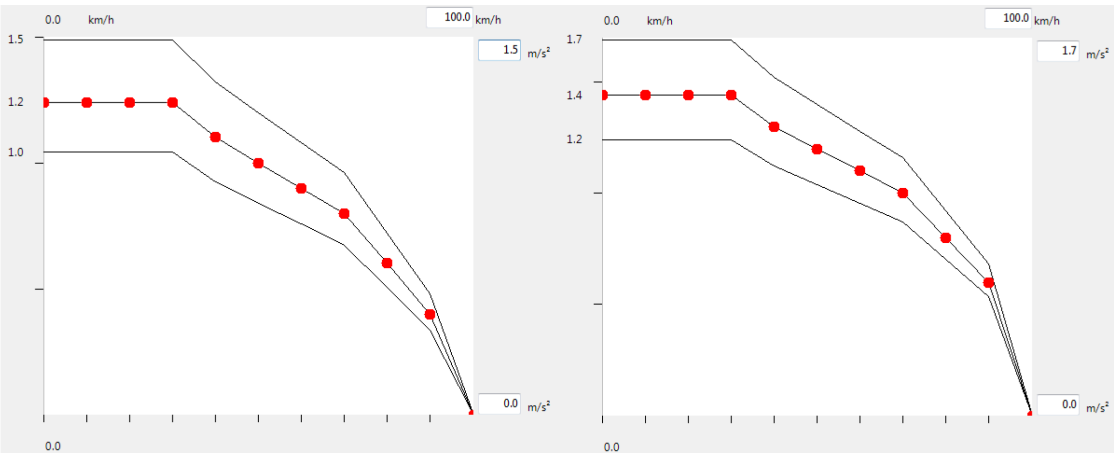


Figure 6-23 Default bus desired acceleration curve (Left) and shifted bus desired acceleration curve (Right)

Note that Figure 6-23 shows the given default acceleration/deceleration equation of buses in VISSIM. The x axis is the current speed of the vehicle in km/h and the y axis is the desired acceleration/deceleration of the vehicle in m/s^2. The desired acceleration/deceleration only defines the acceleration/deceleration that the vehicle intends to achieve, and the actual speed will still be restricted to the parameter of the link in VISSIM. For example, if the speed limit of the link has been set to 40 km/h, the actual acceleration of the bus will be zero once its speed has reached 40 km/h, even though the desired acceleration/deceleration is not zero according to the equation.

6.5.4 Experimental Design

In order to obtain the parameter set that produces the bus travel time values that match the data collected from field survey, different combinations of parameter were tested. There are 27 possible combinations for the three public transport parameters, which were all tested by using a VISSIM control program coded in VB. The control program connects to VISSIM via the COM interface and automatically runs all combinations of the three public transport parameters in the simulation model, and then it generates output files with the value of the parameters used in each run.

Note that the possible combinations will be too high and the simulation process will take a huge amount of time, if nine calibration parameters were used. In that case, a Latin Hypercube Sampling method can be adopted to reduce the sample size while maintaining the range of possible combinations. The Latin Hypercube method is a stratified Monte Carlo sampling method which divides the possible range of each parameter into equal-probability regions and randomly picks an unpicked region for each parameter to form a parameter set. This picking process is repeated to generate parameter sets to an acceptable number while both the wide range of possible combinations and the total simulation time are ensured. However, as the initial calibration test results show that the three public transport parameters are the most relevant parameters and the combinations have been reduced to 27, and the Latin Hypercube method is unnecessary in this case.

6.5.5 Run Simulation

Simulation runs were performed by using the control program mentioned in previous step. To ensure the variability of the simulation result and to reduce the randomness, each parameter combination case has been run five times with different random seeds. Therefore, a total of 135 runs were performed in VISSIM to obtain the bus travel times of the eastbound traffic. The total simulation time in VISSIM has been set to 9000 seconds, which include 0.5 hour system warming up period and 2 hours of travel time collecting period.

6.5.6 Surface Function Development

Surface function was created to estimate the relationships between the bus travel time obtained from the simulation model and the calibration parameter. A linear regression model was built with the three calibration parameters as the independent variables X and the bus travel time as the dependent variable Y. The regression result is shown in Table 6-12 and Table 6-13, and the linear regression model is:

$$y = 514.59 - 7.75x_1 - 10.02x_2 + 9.79x_3$$

Table 6-12 Model calibration regression results

Linear Regression Model

	Coefficients	Standard Error	t Stat	p-value
Intercept	514.5882	10.6474	48.3302	<0.001
Bus Speed Distribution (x_1)	-7.7533	0.2494	-31.0907	<0.001
Bus Acceleration (x_2)	-10.0161	6.2345	-16.0658	0.001
Bus Deceleration (x_3)	9.7878	6.2345	15.6995	0.002

Table 6-13 Model calibration regression statistics

Regression Statistics	
Multiple R	0.988
R Square	0.977
Adjusted R^2	0.974
Standard Error	5.290
Observations	27

The p-value of each term tests the null hypothesis that the coefficient is equal to zero (no effect). As the p-values of the parameters are all under 0.05, it indicates that the parameter has significant impact on the average travel time based on a significance level of 5%.

6.5.7 Candidate Parameter Set Generation

The estimated travel time for each parameter set can be generated by using the developed linear regression function. The candidate parameter sets should be the one with an estimated travel time close to the observation value from field are selected for the evaluation step. To allow the randomness of the simulation, a 5% residual is accepted. The data set for the calibration has an average travel time of 306.85 s with a standard deviation of 60.54. Therefore the parameter sets that produce estimated travel time between 291.51 s and 322.19 s are selected.

6.5.8 Candidate Parameter Set Evaluation

To evaluate the candidate parameter set that produces bus travel time that matches the data collected from field survey, two statistical tests were conducted at a 5% level of significance. The first test is a two-tailed Student's t-test to test if the means of bus travel time distribution obtained from the field observation and the simulation are equal. The second test is a two-sample Kolmogorov-Smirnov test (K-S test) to evaluate the goodness-of-fit of the two probability distributions of bus travel time. The candidate parameter set that passes both tests were then be selected for the model validation.

The two-tailed Student's t test is to determine if the mean of bus travel time distributions from field data and the simulation model are the same, and hence the relevant hypotheses are:

H_0: the mean of bus travel time distributions from field survey and the simulation model are the same.
H_1: the mean of bus travel time distributions from field survey and the simulation model are not the same.

The two-sample K-S test was conducted to find out the goodness of fit between the simulation model result and the field observation, and the test hypotheses are:

H_0: the bus travel time distributions from field survey and the simulation model are the same.
H_1: the bus travel time distributions from field survey and the simulation model are not the same.

The two-tailed Student's t test is just to find out if we should reject the hypothesis that the parameter set produces a similar average travel time to the field data, which does not look at the whole bus travel time distribution of the result while the two-sample K-S test evaluates the goodness-of-fit. Therefore, it is necessary to ensure the candidate parameter set that has passed both tests before the model validation process.

For the two-sample K-S test, the critical d-value was calculated as:

$$D_{crit} = c(\alpha) * \sqrt{\frac{n + n'}{nn'}}$$

where,

$c(\alpha)$ = factors for the selected level of significance, which is equal to 1.36 for the 5% significance level;

n = sample size of the field observation data;

n' = sample size of the simulation model results.

The critical d-value can be computed from the equation, and the parameter set that generates the travel time distribution with a t test result higher than 0.05 and a K – S test result lower than critical d-value were selected to be the candidate parameter set. It is worth to note that there is another key performance measurement should be paid attention to during the simulation model runs, which is the visualisation of the model. Visualisation is a powerful tool for validating microscopic simulation models, as errors will be produced during the simulation (either in the error output file or from the visualisation) if the values of the parameters are unrealistic. Therefore the error files are checked as well as the visualisation to make sure the parameter values are realistic. The parameter sets that pass both tests are listed in Table 6-14, along with the uncalibrated model.

Table 6-14 Candidate parameter sets from model calibration

Case Number		17	18	1 (Uncalibrated)
Bus Parameters	Bus Desired Speed Distribution (km/h)	35	35	25
	Bus Desired Acceleration (m/s^2)	1.0	1.0	1.2
	Bus Desired Deceleration (m/s^2)	-0.7	-1.1	-0.9
Student's t test	Mean Travel Time (s)	303.45	306.91	331.90
	Sample p value	0.608	0.993	<0.001
Kolmogorov – Smirnov test	Critical d value (5% significance level)	0.152	0.153	0.152
	Sample d value	0.079	0.097	0.220

Based on the results shown in Table 6-14, Case 17 and Case 18 have both passed the two statistical tests. The comparisons of the calibrated model, uncalibrated model and the field data are shown in Figure 6-24.

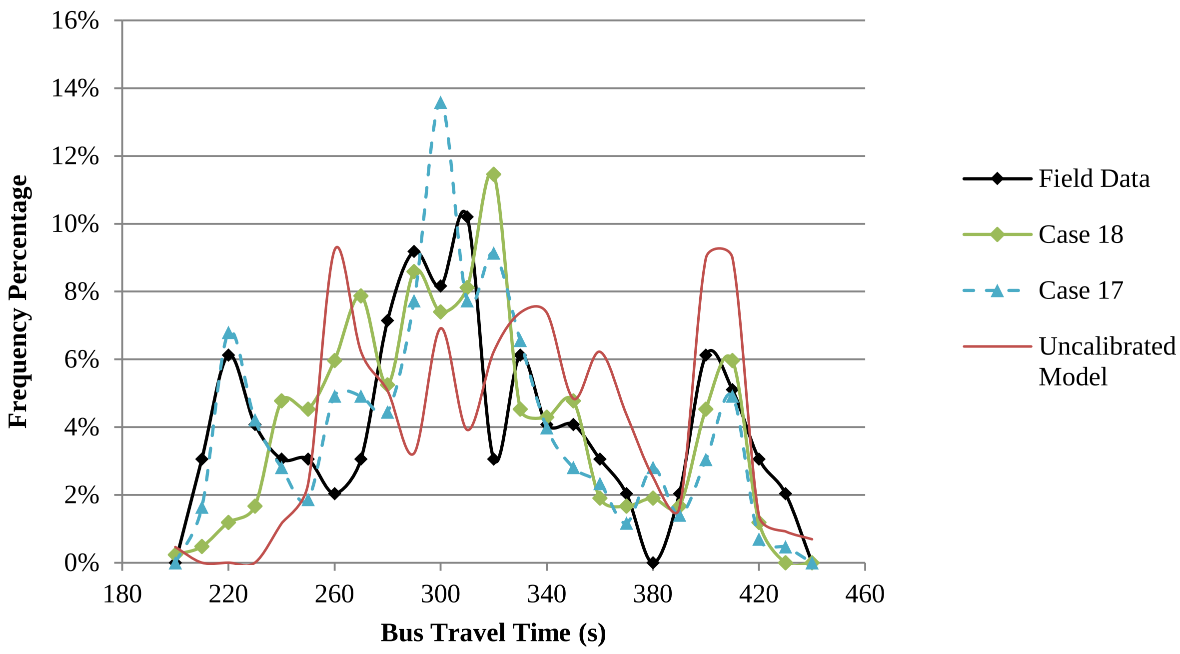


Figure 6-24 Comparisons of the distribution of model calibration results and field data

Although Case 18 performed better in the Student's t test than Case 17, Case 17 has a better K-S result. Figure 6-24 also shows that the travel time distribution of Case 17 fits slightly better in the low range which can reflect the behaviour that the public transport vehicles skip the bus stop due to bus bunching. A root-mean-square error (RMSE) test was also conducted, and the results show that Case 17 (RMSE result 0.022) fits slightly better than Case 18 (RMSE result 0.027). Based on the K-S test and the RMSE test results, Case 17 was selected as the parameter set for the model validation process. To make sure the simulated result also reflects the field observations at different times of the day, Figure 6-25 was produced to compare Case 17 with the field data. Although the bus travel time at any particular time of day does not match the field data perfectly, the Case 17 simulation result lies in the same range as the field data collected in Nanning, and it does not show any significant difference compared with the field observations. Therefore, the parameter set of Case 17 can be used for the validation of the simulation model.

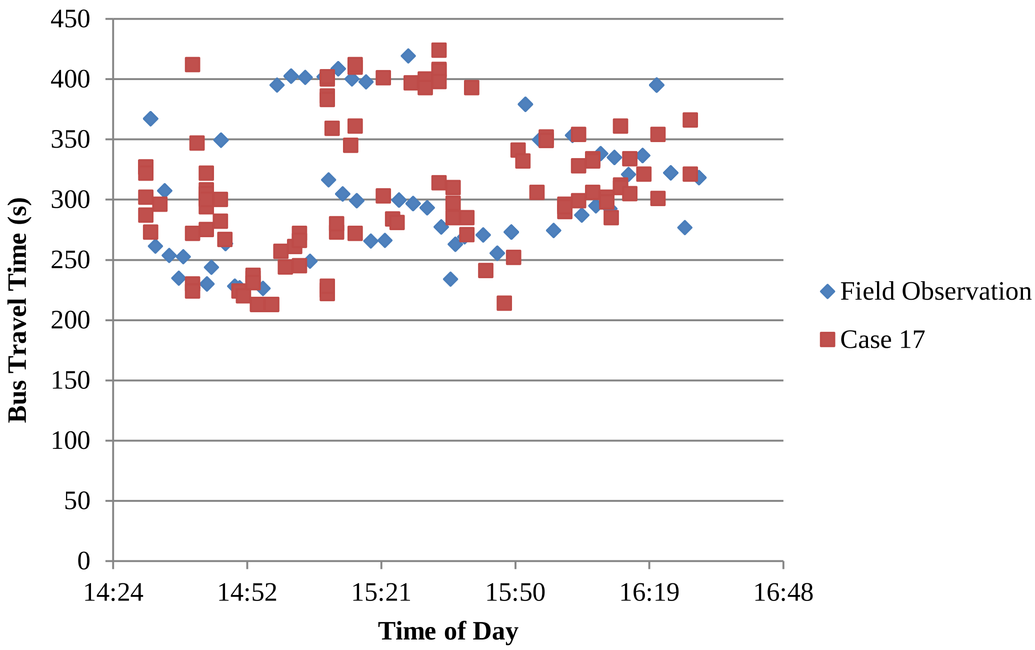


Figure 6-25 Comparisons of model calibration results and field data based on time of day

In conclusion, compared with the field data, the bus travel time distribution of the uncalibrated model has a higher mean and it does not cover the low bus travel time range, as shown in Figure 6-24. The model calibration has a significant improvement on the model results, as both calibrated parameter sets generate as the calibrated models capture both high and low range of the bus travel time distribution. Although the bus travel time distribution from the calibrated model does not match the distribution from field data perfectly, the traffic flow also varies day to day and the statistics tests show the results are still in the acceptable range.

6.5.9 Model Validation

Model validation uses another set of data as shown in Section 6.5.2 to test the accuracy of the model after the model calibration. Another five runs with different random seeds were performed for the Case 17 parameter sets from model calibration. The model run results from the simulation model with the calibrated parameter sets of the two cases were examined against the field data. The field data set for model validation has an average bus travel time of 363.54 seconds with a standard deviation of 54.33. Two-tailed Student's t test and two-sample K-S test were conducted for the model validation process, and the results are shown in Table 6-15.

Table 6-15 Statistical tests for model validation

Case Number		17	1 (Uncalibrated)
Student's t test	Mean Travel Time (s)	370.27	350.79
	Sample p value	0.404	0.06
Kolmogorov – Smirnov test	Critical d value (5% significance level)	0.152	0.144
	Sample d value	0.100	0.171

At a 5% significance level, Case 17 passed both the two-tailed Student's t test for the average bus travel time and the two-sample K-S test for the goodness-of-fit of the bus travel time distribution, while the uncalibrated model failed to pass either statistical test. Therefore, the validated model is sufficiently reliable to produce similar bus travel time result compared with the real transport network in Nanning. As a result of that, the public transport parameters in Case 17 were used in the simulation model for the case study.

6.5.10 Summary

Section 6.5 discusses and shows the model calibration and validation of the simulation model of the comparative assessment, by following the nine-step calibration and validation procedure for microscopic simulation model proposed by Park and Schneeberger (2003). In order to conduct the case study of the comparative assessment in Nanning, China, the model calibration and validation process used two sets of data collected in Nanning from two different days.

Model calibration was conducted to find out the candidate parameter set for the simulation model that is able to produce similar bus travel time distribution to the real transport network. Model validation examined the credibility of the candidate parameter set from model calibration with a different data set. Statistical tests were performed for both calibration and validation, which are the two-tailed Student's t test and the two-sample K-S test at a 5% significance level. The two-tailed Student's t test examined the average bus travel time and the two-sample K-S test examined the goodness-of-fit of the bus travel time distribution from the simulation model. The parameter set that successfully passed the two statistical tests in both model calibration and model validation was chosen for the simulation model for the case study of the thesis.

Although the simulation model did not match the travel time distribution perfectly in every aspect, the statistical tests show that simulation model results are acceptable. Comparisons of the field data, uncalibrated model and calibrated model are demonstrated in Section 6.5 as well, where the improvements after the model calibration and validation are obvious. Hence the simulation model is sufficiently reliable for the case study of the comparative assessment.

6.6 Conclusion

This chapter emphasised the development, calibration and validation of the simulation model of the thesis. The simulation model was built in order to provide accurate traffic data of the public transport service operating on the corridor. Results can be in the DSM to evaluate the endogenous demand level and hence the social and operator cost can be calculated in the SCM. Real network data were collected for the development, calibration and validation of the simulation model, and the reasons of choosing Minzu

Avenue as the simulated corridor were outlined in this chapter. Traffic data were collected by using three synchronised cameras and public transport demand data were collected manually.

A case study to compare the conceptual Straddle Bus technology with the existing conventional bus service on Minzu Avenue was conducted in this research. As there is no default setting in VISSIM for Straddle Bus, the methodology of simulating Straddle Bus by using COM Interface was explained in this chapter. By considering the feature of Straddle Bus along with the impacts to the general traffic, the MSM can then be used in the case study to simulate the operation of Straddle Bus on Minzu Avenue.

The simulation model was calibrated and validated by using the nine-step microscopic simulation model calibration and validation method by Park and Schneeberger (2003). The model calibration and the model validation used two sets of data collected in two different weekdays. The model calibration was conducted in the first place to find out the best parameter set by using one of the field data, and then the model validation was performed to test the accuracy of the parameter set with the another field data collected on a different date. To prove the calibration and validation results are statistically acceptable, two-tailed Student's t test and two-sample Kolmogorov-Smirnov test were performed in both model calibration and model validation process. The simulation model results and the data collected from field survey were compared by using both statistical tests in model calibration and validation to justify the credibility of the model, and the parameter set that passes both statistical tests was chosen for the simulation model. By conducting model calibration and validation, the simulation model was proved sufficiently reliable to represent the simulated area in real world, and it can be applied to the case study of the comparative assessment.

CHAPTER 7 COMPARATIVE ASSESSMENT APPLICATION

7.1 Introduction

Previous chapters describe the three-model structure of the comparative assessment. This comparative assessment can be used to justify the performance of either the existing public transport route or innovative public transport technologies at strategic level in terms of average social cost.

This chapter demonstrates the process of using the comparative assessment to identify the cost and benefit differences between existing conventional bus route and a conceptual public transport technology, Straddle Bus on the main corridor, Minzu Avenue in Nanning, China. The impacts of replacing the conventional bus service with Straddle Bus are quantified into various cost components, including operator cost, users cost and external costs.

7.2 Methodology

This case study is to create a link between the SCM, the DSM and the MSM to compare the users' and non-users' costs and benefits of replacing the conventional bus service on Minzu Avenue, Nanning with the Straddle Bus.

The current public transport passenger demand is 524 passengers boarding per hour on the Binhu Plaza – Zhuxi Motorway Interchange section of the Minzu Avenue according to the field data collection as described in Chapter 7, which is equivalent to a daily passenger demand of 59,713 on a 12 km corridor in the SCM. The daily public transport passenger demand of the Minzu Avenue was estimated to grow by 50% when the current construction of underground line is finished in NCTAR2010, due to the rapid development of the new economic district as well as being the hosting city of the annual China-ASEAN EXPO. Therefore, the future public transport passenger demand of the Minzu Avenue is assumed to be 90,000 per day in this case study.

The comparative assessment includes an iteration process to calculate the endogenous demand of the public transport technology, and there are three variables that need to be changed, which are the general traffic volume input, public transport passenger demand level and the service frequency.

The validated traffic simulation model of the Minzu Avenue was used as a base condition of the network. A daily demand of 90,000 was used as the initial condition, and then replaced by the calculated endogenous demand from the DSM in each iteration steps. The general traffic volumes may change with the public transport passenger demand level. The real proportionate changes of the general traffic volume as a result of the changes in public transport passenger demand level is unknown, and therefore the proportions of car traffic volume and public transport passenger demand were evaluated by using a mode choice logit model. The operator of the public transport service may not be able to react as fast as the changes in the endogenous passenger demand to increase/decrease the vehicle supply, therefore the analysis is also divided into two scenarios: short term scenario and long term scenario. These assumptions and scenarios are explained in this section as well as an eight-step procedure for the calculation of each scenario for both conventional bus service and the Straddle Bus technology.

7.2.1 General Traffic Volume Evaluation

The travel time of the conventional bus service can be obtained from the MSM, which is strongly related to the general traffic volume. Consequently it is essential to determine the current general traffic volume, which is defined as the sum of the car traffic volume and the public transport passenger demand. As the choice is between two modes, a binary mode choice logit model was adopted to evaluate the competition between travelling by private vehicles and public transport service.

To compare the existing conventional bus service and the Straddle Bus technology, the structure of the choice model is shown in Figure 7-1. The binary choice model structure for the existing conventional bus service is shown on the left and the binary choice model structure for the Straddle Bus technology as a replacement of the existing bus service is shown on the right.

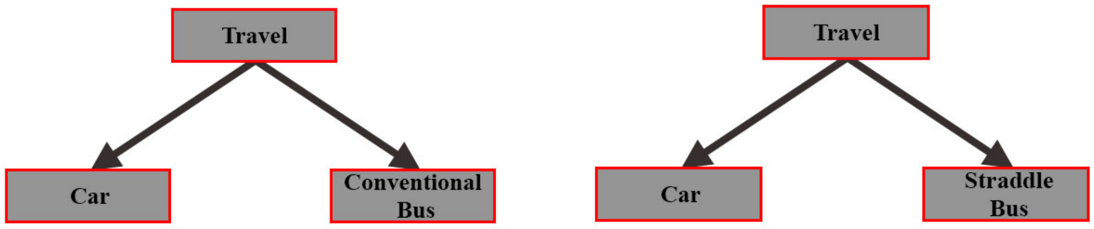


Figure 7-1 Binary choice model structure

To evaluate the choices of passengers, the utilities of travelling by both modes need to be determined in the first place. Utility theory is the most common theoretical framework for generating discrete-choice models (Ortúzar and Willumsen, 2011), which is used to measure the benefits of an individual from performing the activities, and activity A will be more preferable than activity B if A has a higher utility value by assuming a rational behaviour of consumers. This concept was also explained in Chapter 5. By adopting this concept, the utility of travelling by either private vehicle or public transport service can be obtained by using the generalised time costs in a linear-additive utility function as:

$$U_C = a_C + b_C \cdot t_{IV}^{C}$$

$$U_{PT} = a_{PT} + b_{PT} \cdot t_{IV}^{PT} + c \cdot t_{WT}^{PT} + d \cdot t_{WK}^{PT}$$

where,

U_C is the utility of travelling by private vehicle;

U_{PT} is the utility of travelling by public transport service;

a_C is the mode specific constant (MSC) for car which specified in favour of car for the choice model;

a_{PT} is the MSC for public transport service which specified in favour of public transport service for the choice model;

b_C is the utility coefficient of in-vehicle time of travelling by private vehicle;

t_{IV}^{C} is time spent travelling in the private vehicle;

b_{PT} is the utility coefficient of in-vehicle time of travelling by public transport service;

t_{IV}^{PT} is time spent travelling in the public transport vehicle;

c is the utility coefficient of waiting time of travelling by public transport service;

t_{WT}^{PT} is time spent waiting for the public transport vehicle;

d is the utility coefficient of walking time of travelling by public transport service;

t_{WK}^{PT} is time spent walking from/to the public transport stops/stations.

After reviewing the disaggregate mode choice models developed in the UK, Wardman (1997) gives the coefficients for passengers' generalised journey time relate to a linear-additive utility function in car and bus binary choice logit model for both peak and off peak period in pence and minutes, which are summarised in Table 7-1.

Table 7-1 Utility coefficients of car and bus binary choice logit model

	MSC	Waiting	Walking	In-vehicle	Observation Number	Context
Car	0.3518	-	-	-0.0372	4795	Off Peak
	0.4666	-	-	-0.0418	4067	Peak
Bus	0.3518	-0.0554	-0.0601	-0.0372	4795	Off Peak
	0.4666	-0.0583	-0.0663	-0.0418	4067	Peak

(source: adapted from Wardman, 1997)

Travelling by either mode will generate disutility to the users, as they have to spend time in the vehicle, waiting for the vehicle and walking from/to the station (ATOC, 2009). To express this travelling disutility in monetary terms, the users' generalised journey time cost is defined as the total time values that passenger spent in the journey. Therefore the utility coefficient for the users' time spent has a negative sign, and any increase in the generalised journey time while using the mode indicates a lower utility value. With the utility coefficients provided in Table 7-1 and the generalised journey time obtained from the models, the utility of travelling by either private vehicle or public transport service can be obtained.

To calculate the probability of choosing one of the modes in a binary mode choice logit model, an equation was used based on the multinomial model equation provided in PDFH (ATOC, 2009). The equation for the binary mode choice model is:

$$P_1 = \frac{e^{U_1}}{\sum_{i=1}^{n} e^{U_i}} = \frac{e^{U_1}}{e^{U_1} + e^{U_2}}$$

where,

1 and 2 indicate different modes in the binary mode choice model;

P_1 is the probability of choosing mode 1;

U_i is the utility of using mode i.

This equation describes the relationship between the utility of different mode and the probability of being chosen. For example, if the passenger spends less generalised journey time by choosing mode 1 compared to rest of the available modes, the probability of passengers choosing mode 1 is greater, and vice versa.

With the evidence available on current market shares in the base condition, the calculation of the probability in the logit model can be replaced by the incremental form:

$$P_{1f} = \frac{P_{1b} e^{\Delta U_1}}{P_{1b} e^{\Delta U_1} + P_{2b} e^{\Delta U_2}}$$

where,

P_{1b} is the probability of travelling by car in the base situation;

P_{2b} is the probability of travelling by using public transport services in the base situation;

P_{1f} is the probability of travelling by car in the forecast situation;

ΔU_1 and ΔU_2 are the changes in utility of private vehicle and public transport service, respectively.

As the general traffic volume has been defined as the sum of the car traffic volume and the public transport passenger demand, this probability of choosing either private vehicle or public transport service can also be calculated as the current market shares. By denoting the car traffic as 1 and the public transport service as 2, the equation is expressed as:

$$P_{1b} = \frac{Q_{1b}}{\sum_{i=1}^{n} Q_{ib}} = \frac{Q_{1b}}{Q_{1b} + Q_{2b}}$$

where,

Q_{1b} is the car traffic volume in the base situation;

Q_{2b} is the public transport demand level in the base situation.

Along with the changes in utility, the probabilities of travelling by private vehicles or public transport in base situation can then be used in forecasting probabilities of choosing either mode. Note that each car accounts for 1.6 passenger trips, according to the UK average car occupancy rate given by the National Travel Survey 2013 (DfT, 2014). With the new endogenous public transport demand level and the updated generalised time results, the binary logit model is able to provide the forecasted car traffic volume. As the endogenous public transport demand level is obtained from DSM, the changes in the car traffic volume will also have impacts on the generalised journey time of the conventional bus service users and hence the endogenous demand. Therefore the evaluation of the car traffic volume is required in the iteration of the endogenous demand calculation, and the logical procedure will be described in Section 7.2.3.

7.2.2 Short Term and Long Term Scenarios

Service frequency of the public transport technology has a great impact on the passenger WTT and passenger IVT. If the service frequency is lowered, passengers would have to wait longer at the stop/station and the total waiting time is increased. A lower service frequency will also lead to a higher dwell time, as more passengers are waiting to board/alight the vehicle. This increased dwell time will result in an increase in the passenger in-vehicle time as well, due to the lowered operating speed.

However, the operator may have delays in recognising the changes of the new endogenous passenger demand and therefore the change of the vehicle supply (service frequency) may also be delayed. The current supply of the public transport service impacts the generalised journey time of the passengers, and it more directly affects users rather than operator. Due to the lack of dynamic data collection and evaluation procedure in the public transport service companies in developing cities, the service frequencies are fixed rather than flexible based on current passenger demand level. In these public transport service companies, the service frequency may depend more on the availability of either their vehicle fleets or the drivers, and they normally revise the service frequency of the public transport according to the company's seasonal financial report. As a result of that, the comparative assessment was divided into two scenarios: short term and long term.

The short term scenario is defined as the operators have no awareness of the changes in the passenger demand level yet and the vehicle supply is unchanged. Therefore the service frequency of the public transport service in the comparative assessment is fixed at the initial condition.

The long term scenario is defined as the operators have noticed the changes in the passenger demand level in a longer time period. In this scenario, the vehicle supply is changed in the MSM based on the endogenous demand level, and hence the results in the DSM and the SCM are also affected by this change.

7.2.3 Operating Procedure

The comparative assessment application contains eight steps to obtain the average costs of the public transport technology operating on the corridor:

1. The first step was to setup the base condition of the model, which is the validated simulation model by using the real network data in Chapter 7. As the MSM simulates only a part of the corridor (1.34 km), the passenger demand in the SCM is equivalent to 8.96 (12 km / 1.34 km) times the passenger demand in the MSM by assuming the passengers are uniformly distributed along the corridor.

2. The second step was to modify the public transport passenger demand level in the MSM to the initial condition, which is 90,000 (passenger/day) for a 12 km corridor. The service frequency of the public transport mode was also changed according to the passenger demand level as well.

3. The third step was to run the traffic simulation model with different random seeds to obtain the average travel time for both peak and off-peak period for both the car traffic and the public transport service. This average travel time is then converted into average operating speed of the public transport service.

4. The fourth step was to evaluate the new car traffic volume by using the binary logit model. The generalised journey time from the MSM and the SCM was used as the input of the binary logit model.

5. The fifth step was to run the simulation model again with the new car traffic volume to obtain the generalised journey time of the public transport passenger.

6. The sixth step was to calculate the endogenous demand level in the DSM by using the new generalised passenger journey time from step 5. Note that the service frequency of the public transport mode will also be changed based on the endogenous demand level, if it is the long term scenario.

7. The seventh step was to repeat step 3 to 6 until convergence – the difference between the previous demand and the endogenous demand is less than 1%.

8. The eighth step was to use the endogenous demand obtained in the previous step to evaluate the users' and non-users' costs and benefits of different modes by using the SCM.

This eight-step procedure was applied to both short term and long term scenarios for the conventional bus service and the alternative Straddle Bus service in the simulated network to obtain the average costs for comparison. The logical operating procedure of the model application on Minzu Avenue is shown as a flow chart in Figure 7-2.

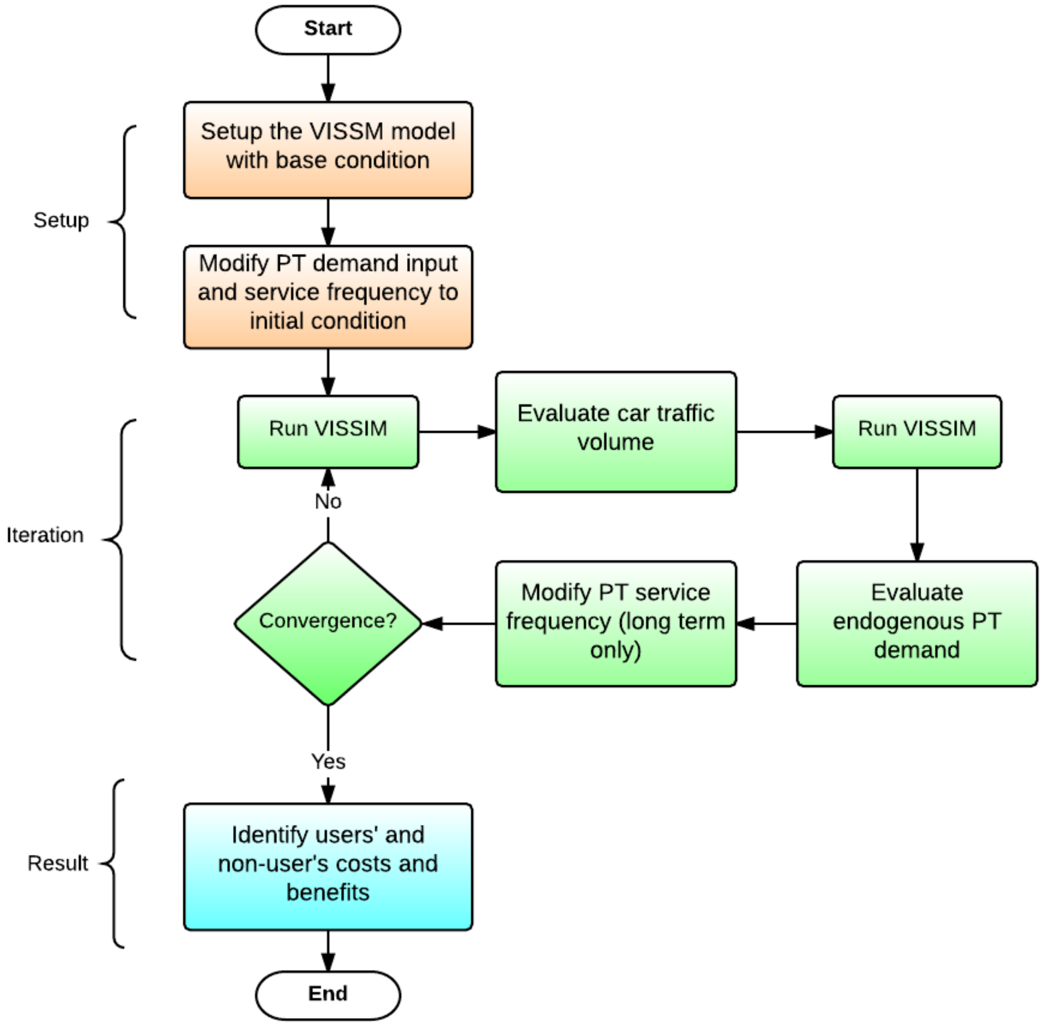


Figure 7-2 Model application procedure for each case and scenario

7.3 Results and Discussions

In this section, the results from the comparative assessment of operating conventional bus service and Straddle Bus technology are shown, in terms of average operator cost, average user cost, average external cost and the forecasted endogenous demand levels for both short term and long term scenario. All comparison results are then summarised and discussed for each scenario to justify the benefits and impacts of replacing the existing conventional bus routes by Straddle Bus technology on the Minzu Avenue.

7.3.1 Short Term Scenario

In the short term scenario, the operator's supply of public transport service is assumed to be unchanged. Therefore the service frequency is fixed at the initial condition in all three models in the comparative assessment.

After the calculation of the endogenous demand from the iteration process, the average operator cost (AOC), average user cost (AUC), average external cost (AEC) and average social cost (ASC) are obtained from the SCM for both conventional bus and Straddle Bus. With the initial exogenous demand of 90,000 passengers per day on a 12 km corridor, endogenous demand results and the average costs for both the conventional bus service and the Straddle Bus technology are discussed in this section. In order to compare the average costs and endogenous demand levels of both public transport modes, Table 7-2 was produced to summarise all average costs and the final endogenous demand levels for the short term scenario.

Table 7-2 Cost and demand results of short term scenario

	AOC (£ / pkm)	AUC (£ / pkm)	AEC (£ / pkm)	ASC (£ / pkm)	Endogenous Demand (pax / day)
Conventional Bus	0.172	0.494	0.0191	0.685	85,905
Straddle Bus	0.245	0.420	0.0056	0.671	96,030

Started from an exogenous demand of 90,000 per day, the endogenous demand of Straddle Bus increased to 96,030 per day while conventional bus service fell to 85,905 per day. The ASC of Straddle Bus is slightly lower, which is mainly contributed by the lower AUC, even though the AOC of Straddle Bus is higher. Detailed results and interpretations of each sector are given in the following sections.

General Traffic Volume and Performance

The boarding passenger numbers and the car traffic volumes of conventional bus service and the Straddle Bus technology in the short term scenario were calculated by using the binary logit model and the DSM. The performance variables were generated in the SCM according to the endogenous public transport demand level in both peak and off peak period, as shown in Table 7-3.

Table 7-3 General traffic volume and performance of short term scenario

Indicator	Period	Conventional Bus Service	Straddle Bus Technology	% Change
Boarding passengers (pax/h)	Off Peak	6,750	7,545	+11.8%
	Peak	9,664	10,803	+11.8%
Car traffic volume (car/h)*	Off Peak	5916.93	5858.66	-0.98%
	Peak	8465.99	8390.08	-0.90%
Service frequency (veh/h)	Off Peak	98.78	31.43	-68.2%
	Peak	141.43	45.00	-68.2%
Car average speed (km/h)	Off Peak	19.16	18.78	-2.0%
	Peak	13.66	17.20	+25.9%
PT average operating speed (km/h)	Off Peak	11.03	17.94	+62.6%
	Peak	8.32	14.69	+76.6%
Vehicle-kilometres (millions)		3.94	1.25	-68.3%
Passenger-kilometres (millions)		89.66	100.23	+11.8%
Mean passenger loading (pax/veh)		22.78	80.02	+251.3%

* The car traffic volumes account for the simulated link only, rather than the entire 12 km corridor.

Note that the model assumes 2 hours for each peak time and 7 hours for the off peak and 11 hours of steady operating period in total, and the values in Table 7-3 are for the whole 12 km long Minzu Avenue, except the car traffic volumes.

For the public transport passengers, the Straddle Bus technology is more attractive than the conventional bus service in the short term scenario, which is shown as 11.8% higher boardings for peak and off peak period. The special vehicle feature of Straddle Bus leads to a higher vehicle capacity and average operating speed service, which reduces the probability of waiting longer due to vehicles being full and hence less generalised time cost. Therefore the attractiveness of the Straddle Bus is greater because of the better service performance as evidenced in Table 7-3, even though the service frequency is much lower than the conventional bus service.

The car traffic volumes shown in Table 7-3 were calculated from the binary mode choice model, of which the Straddle Bus has a slightly lower value than the conventional bus service. This is because in the binary mode choice model, the utility of car is higher than the conventional bus due to the low operating speed of bus in high demand level. Hence the probability of people travelling by car was increased in the conventional bus case. However, the difference in car traffic volume is not significant. This is because the car average speed and hence the utility of travelling by car is able to be maintained in peak period by implementing Straddle Bus to free the spaces taken by the conventional buses.

The average PT operating speed was calculated by using the route/track length (1.34km in this case) divided by the travel time obtained from the simulation model. As shown in Table 7-3, there is a large improvement in the public transport service operating speed by replacing the conventional bus with Straddle Bus. This is because the straddling feature of this innovative public transport technology is able to avoid congestion, especially in the peak period, and the advantages of this technology would be more obvious when the general traffic is more congested. Although the reduced service frequency leads to a higher stopping time for each bus stop due to more boarding passengers, the Straddle Bus feature of being able to run above the car traffic to avoid congestion makes Straddle Bus run 62.6% and 72.6% faster in off-peak and peak period. Note that the average speed of the car traffic was reduced by 2% rather than being increased in the off-peak period after the replacement of Straddle Bus. This is because of the impacts on the lane changing behaviour, turning traffic and desired speeds of other vehicles on the road, by the presence of the Straddle Bus (as discussed in Chapter 6).

Operator Costs

The operator costs were calculated in the SCM based on the current level of endogenous public transport passenger demand, which includes both capital investment costs and daily operating and maintenance costs, as shown in Table 7-4.

Table 7-4 Capital investment, operating and maintenance costs of short term scenario

Indicator	Conventional Bus Service	Straddle Bus Technology	% Change
Total capital investment costs (£millions)	40.61	213.94	+426.8%
- Capital investment for vehicles (£millions)	32.69	113.74	+247.9%
- Capital investment for infrastructures (£millions)	7.92	100.20	+1,165.2%
- Annual capital charge (£millions/year)	4.38	15.79	+260.5%
Total operating costs (£millions/year)	10.52	8.38	-20.3%
- time-related operating costs (£millions/year)	5.42	4.78	-11.8%
- distance-related operating costs (£millions/year)	1.20	0.91	-24.2%
- vehicle-related operating costs (£millions/year)	3.86	2.54	-34.2%
- route-maintenance-related operating costs (£millions/year)	0.03	0.15	+400.0%
Total operator costs (£millions/year)	15.42	24.58	+59.4%
Average operator costs (£/pkm)	0.172	0.245	+42.4%

Because of the greater costs of the infrastructures and the vehicles, the Straddle Bus technology requires much higher total capital investment compared to providing a conventional bus service. By breaking down the capital investments to each of the expected economic life, the annual capital charges for both public transport modes are shown in Table 7-4.

In Table 7-4, the total operating costs of the Straddle Bus technology are lower than the conventional bus service, although the total passenger demand is higher. With a lower service frequency and fleet size requirement and hence lower vehicle-kilometres and vehicle-hours, the Straddle Bus technology is able to offer an operating saving of 11.8%, 24.2% and 34.2% for the total operating costs with respect to time-related, distance-related and vehicle-related.

Overall, the operator of the Straddle Bus technology required to spend more than the conventional bus service provider, by 59.4% higher in total and by 42.4% per passenger-kilometres, mainly because of the capital investment cost. The difference between TOC and AOC resulted from the higher endogenous demand level of the Straddle Bus technology. This extra operator costs can be transferred to the public transport users by charging higher fare prices if the technology is able to perform better than the conventional bus service and provide a lower time costs to the users. It is also possible for the operator to receive subsidies from the local government, if the Straddle Bus have a higher passenger-kilometres value and provide a higher level of service to the public transport passengers to reduce the users generalised costs.

User's Generalised Time Costs

The public transport users' generalised time costs were calculated in the SCM by converting the users' generalised time to monetary costs by using the value of time. The monetary value of passenger in-vehicle time used in this calculation was computed from the values of travel time of the British passenger study by Abrantes and Wardman (2011). To account for the different perceptions of WKT and WTT compared with IVT, a value of 2 was used. The user's generalised costs of travelling by conventional bus service and Straddle Bus are summarised in Table 7-5.

Table 7-5 User's generalised costs indicators of short term scenario

Indicator	Conventional Bus Service	Straddle Bus Technology	% Change
Total Annual walking time (hour/year) (million)	2.80	3.13	+11.8%
Mean walking time (min/pax)	7.50	7.50	-
Annual walking time cost (£millions/year)	14.51	16.22	+11.8%
Total Annual waiting time (hour/year) (million)	1.09	1.92	+76.1%
Mean waiting time (min/pax)	2.97	4.71	+58.6%
Annual waiting time cost (£millions/year)	5.66	9.94	+75.6%
Total Annual in-vehicle time (hour/year) (million)	9.32	6.14	-34.1%
Mean in-vehicle time (min/pax)	24.95	14.71	-41.0%
Annual in-vehicle time cost (£millions/year)	24.14	15.91	-34.1%
Total user costs (£millions/year)	44.32	42.08	-5.1%
Average user costs (£/pkm)	0.494	0.420	-15.0%

The total annual user costs of travelling by Straddle Bus on the Minzu Avenue are lower than conventional bus, which is mainly because of the saving of IVT costs. Straddle Bus also provided a 15.0% generalised time savings to individual passenger, as shown in Table 7-5.

In the short term scenario, the service frequency is fixed at the initial condition level. Therefore the capacity advantage of Straddle Bus cannot be shown when the passenger demand level increased. As a result of that, the mean waiting time per passenger of the Straddle Bus technology is 58.6% higher than the conventional bus user. However, the specific straddling feature of Straddle Bus has contributed to a 41.0% reduction of the passenger in-vehicle time, even though each individual Straddle Bus has a higher dwell time per bus stop.

External environment impacts

To comprehensively consider the costs of operating public transport service, the impacts to the external environment were also taken into account. Table 7-6 presents the costs of externalities of both public transport technologies on Minzu Avenue.

Table 7-6 External environmental impacts of short term scenario

Indicator	**Conventional Bus Service**	**Straddle Bus Technology**	**% Change**
Total air pollution cost (£million/year)	1.09	0.17	-84.4%
Total noise pollution cost (£million/year)	0.46	0.27	-41.3%
Total climate change cost (£million/year)	0.09	0.09	0.0%
Total external accident cost (£million/year)	0.07	0.03	-57.1%
Total external costs (£millions/year)	1.71	0.56	-67.3%
Average external costs (£/pkm)	0.0191	0.0056	-70.7%

The external costs were calculated by using the unit cost of air pollution, noise pollution, climate change and external accident cost to multiply by the vehicle-kilometre. In the conceptual design of the Straddle Bus, the vehicles are powered by electricity, and the unit cost of air pollution of the Straddle Bus technology was believed to be lower than the conventional diesel engine buses. Although the unit external accident cost of Straddle Bus was assumed to be 50% higher than other modes, the low vehicle-kilometre reduced the total external accident cost to 57.1% lower than the conventional bus service. With a much lower service frequency, the total and average external environment costs of the Straddle Bus are 67.3% and 70.7% lower than the conventional bus service.

Total Social Costs

The total social cost is calculated as the total costs for operator, users and the environments, and it varies based on the characteristics of the operating public transport technology on the corridor as well as the passenger demand level. The higher the passenger demand level may lead to greater total social costs, and therefore it is necessary to evaluate the average social cost to compare the options of operating different public transport technology on the corridor. Figure 7-3 and Figure 7-4 show the percentage of average social cost and Figure 7-5 compares the average cost of conventional bus and Straddle Bus on the Minzu Avenue.

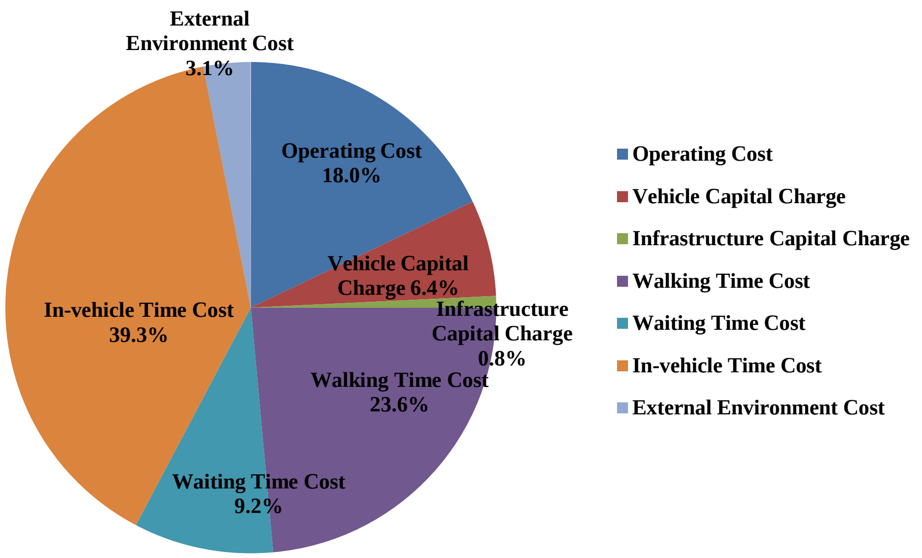


Figure 7-3 Percentage of average social cost of conventional bus in short term scenario

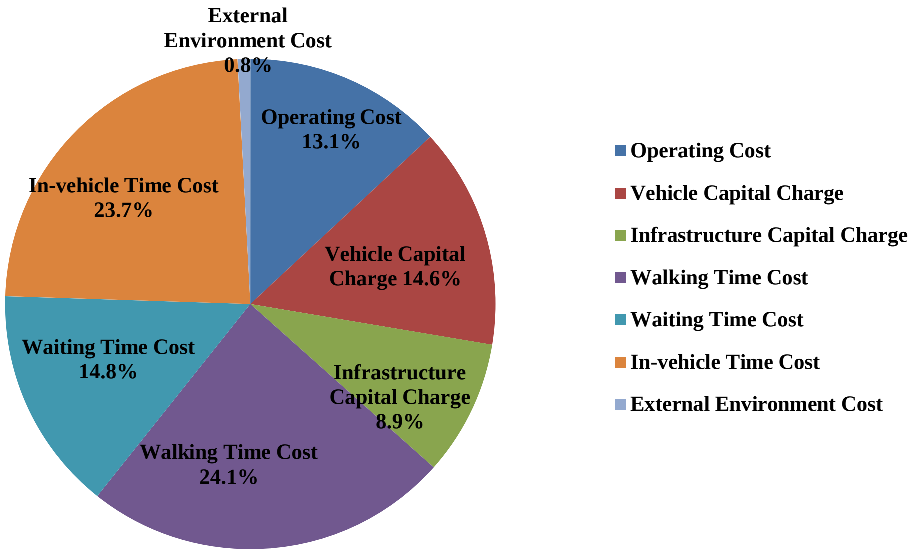


Figure 7-4 Percentage of average social cost of Straddle Bus in short term scenario

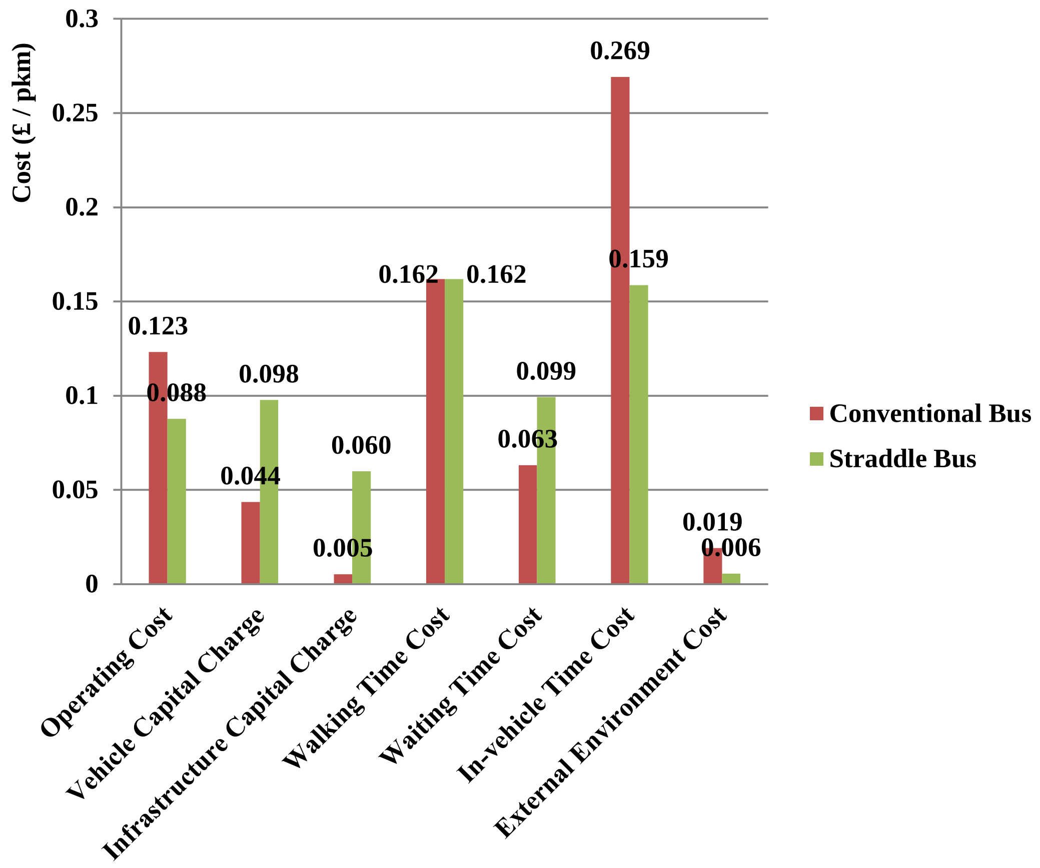


Figure 7-5 Comparison of average cost of conventional bus and Straddle Bus in short term scenario

From Figure 7-5, the operating costs of Straddle Bus were down from £0.123/pkm to £0.088/pkm, compared with conventional bus service. This was contributed by the lower vehicle-kilometres and vehicle-hours of the Straddle Bus technology, due to its high capacity characteristics. However, the percentages of the average operator cost of the Straddle Bus technology are still higher than the conventional bus service because of the capital investment requirements of both the vehicle and infrastructure construction, which are 14.6% and 8.9% of the total ASC, respectively.

For the AUC, the WKT cost is unchanged, as the stops of Straddle Bus were assumed to be in the same place as the conventional bus service. With an average social cost of £0.671/pkm, the percentage of the WKT is 24.1% in the Straddle Bus technology case. Although the higher capacity of the Straddle Bus reduces the probability of boarding congestion, the percentages of the WTT cost rise to 14.8%, up from 9.2%, as a result of the lower service frequency of Straddle Bus. The travel time cost of using Straddle Bus is £0.159/pkm, reduced from £0.269/pkm of using the conventional bus service on the

Minzu Avenue, which is mainly contributed to the straddling feature of the technology to avoid congestion of the general traffic, especially in the peak period.

Although the AEC only takes a small percentage in the social costs of operating the public transport technology, the result shows the advantages of the environmental friendly design of the Straddle Bus. From Figure 7-5, it is able to reduce the AEC from £0.0191/pkm to £0.0056/pkm, which takes 0.8% of the ASC of Straddle Bus, compared with the 3.1% of conventional bus service.

Summary

Overall, in the short term, by replacing the existing conventional bus service on the Minzu Avenue with the Straddle Bus technology, the average social cost can be decreased to £0.670/pkm from £0.685/pkm. Although the service frequency was assumed to be fixed in the short term, the Straddle Bus is able to provide a greater attractiveness to the public transport passengers and serve 96,030 passengers per day on the 12 km corridor, up from the estimated demand level of 90,000 per day while the endogenous demand level of the conventional bus service is 85,905 passengers per day. This endogenous demand is possible to reach a higher level in the long term scenario, as the operator of the Straddle Bus can increase the service frequency because of the high capacity characteristics of the technology, and hence to reduce the generalised time cost, especially the waiting time cost of the public transport users.

7.3.2 Long Term Scenario

In the long term scenario, the service frequency of the public transport service was assumed to be changed based on the endogenous demand level. Therefore in the iteration process of the comparative assessment, the service frequency of the public transport service was updated for every new endogenous public transport passenger demand level.

The endogenous demand and average cost outputs of the long term scenario are summarised in Table 7-7.

Table 7-7 Cost and demand results of long term scenario

	AOC (£ / pkm)	AUC (£ / pkm)	AEC (£ / pkm)	ASC (£ / pkm)	Endogenous Demand (pax / day)
Conventional Bus	0.146	0.483	0.018	0.648	83,023
Straddle Bus	0.246	0.399	0.006	0.651	143,281

The ASC of the Straddle Bus is £0.651/pkm in the long term, which is slightly higher than the £0.648/pkm average social cost of conventional bus. The AOC of Straddle Bus is still higher than the conventional bus, by £0.1/pkm while the AUC is lower by £0.084/pkm. However, compared to the short term scenario, the endogenous demand level of the conventional bus has small change in the long term scenario while the endogenous demand level of the Straddle Bus was dramatically increased to 143,281 passengers per day from the 96,030 passengers per day in the short term. This huge growth in the passenger demand level shows a great improvement in the attractiveness to the passengers by replacing the existing conventional bus service on the Minzu Avenue with the Straddle Bus technology. Although the passenger number of the conventional bus service can reach the same level by using exogenous demand, the ASC will be extremely high due to the boarding congestion and high WTT, and by using the endogenous demand analysis, the deterioration service will eventually bring the demand level down.

General Traffic Volume and Performance

The boarding passenger numbers and the public transport demand share in the long term are shown in the Table 7-8, along with the performance indicators such as the vehicle-kilometres, passenger-kilometres and mean passenger loading. With the remarkable growth of the endogenous demand of Straddle Bus in the long term, there were also significant changes in these performance indicators.

Table 7-8 General traffic volume and performance of long term scenario

Indicator	Period	Conventional Bus Service	Straddle Bus Technology	% Change
Boarding passengers (pax/h)	Off Peak	6,523	11,258	+72.6%
	Peak	9,340	16,119	+72.6%
Car traffic volume (car/h)*	Off Peak	6107.67	5414.22	-11.35%
	Peak	8756.13	7755.01	-11.43%
Service frequency (veh/h)	Off Peak	91.42	50.03	-45.3%
	Peak	130.46	71.64	-45.1%
Car average speed (km/h)	Off Peak	19.20	18.87	-1.7%
	Peak	14.06	17.44	+24.04%
PT average operating speed (km/h)	Off Peak	11.50	17.01	+47.9%
	Peak	9.77	13.91	+42.4%
Vehicle-kilometres (millions)		3.63	1.99	-45.2%
Passenger-kilometres (millions)		86.65	149.54	+72.6%
Mean passenger loading (pax/veh)		24	75	+212.5%

* The car traffic volume accounts for the simulated link only, rather than the entire 12 km corridor.

With the endogenous demand level of 143,281 passengers per day on the 12 km corridor, the boarding passengers per hour for the Straddle Bus technology is 72.6% higher than the conventional bus service in both off peak and peak period. For the public transport passengers, Straddle Bus is more attractive in the long term scenario, as the increased service frequency would reduce the passenger WTT costs when the demand level is higher than the estimated 90,000 passengers per day. However, the car traffic volumes are lower in the Straddle Bus case, which is contributed by the improved operating speed and service frequency and hence higher utilities of the public transport service.

For the performance indicators, the service frequency of the Straddle Bus is still lower than the conventional bus service in the long term scenario. However, compared with the short term scenario, the service frequencies increased from 31.43 veh/h to 50.03

veh/h in off peak period and from 45.00 veh/h to 71.64 veh/h in peak period. This is because the service frequency was adjusted in the long term scenario based on the endogenous demand, and therefore the service frequencies were increased due to the higher endogenous demand level of Straddle Bus. With a lower endogenous demand level than the initial condition of 90,000 passengers per day, the service frequency of the conventional bus service was reduced, which also leads to a small improvement in the average speed of the car traffic compared to the short term.

Among the performance indicators of the long term scenario, vehicle-kilometres and passenger-kilometres were both increased for the Straddle Bus technology while they were both decreased for the conventional bus service compared to the short term scenario. With the creased number of serving vehicles and boarding passengers in the long term scenario for the Straddle Bus, the passenger-kilometres are 72.6% higher while the vehicle-kilometres are still lower by 45.2% compared with conventional bus service.

Operator Costs

The operator costs for the conventional bus service and the Straddle Bus technology in the long term scenario were calculated by using the endogenous demand level, and the results are summarised in Table 7-9.

Table 7-9 Capital investment, operating and maintenance costs of long term scenario

Indicator	Conventional Bus Service	Straddle Bus Technology	% Change
Total capital investment costs (£millions)	33.64	288.84	+758.6%
- Capital investment for vehicles (£millions)	25.72	188.64	+633.4%
- Capital investment for infrastructures (£millions)	7.92	100.20	+1,165.2%
- Annual capital charge (£millions/year)	3.55	22.24	+526.5%
Total operating costs (£millions/year)	8.69	13.83	+59.1%
- time-related operating costs (£millions/year)	4.52	8.03	+77.7%
- distance-related operating costs (£millions/year)	1.11	1.45	+30.6%
- vehicle-related operating costs (£millions/year)	3.04	4.20	+38.2%
- route-maintenance-related operating costs (£millions/year)	0.03	0.15	+400.0%
Total operator costs (£millions/year)	12.68	36.76	+323.0%
Average operator costs (£/pkm)	0.146	0.246	+68.5%

Due to much higher endogenous demand level, greater service frequency and hence larger vehicle fleets must be provided by the Straddle Bus operator in the long term scenario. Therefore, the total costs for the operator, including capital investments and operating costs were increased compared with the short term. However, the AOC of the Straddle Bus technology were not changed significantly, which is from £0.245/pkm in the short term to £0.246/pkm in the long term. For the conventional bus, the reduced number of required vehicles resulted in a lower capital investment and operating costs, as shown in Table 7-9. The TOC of conventional bus fell by £2.74m while the AOC decreased from £0.172/pkm to £0.146/pkm compared with the short term scenario.

Compared with the conventional bus service, the increased service frequency of Straddle Bus in long term scenario requires 323.0% higher total operator costs per year, including 526.5% more annual capital investment charges and 59.1% more operating costs.

User's Generalised Time Costs

The generalised time costs of public transport passengers in the long term for both modes were computed in the SCM, as shown in Table 7-10.

Table 7-10 User's generalised costs indicators of long term scenario

Indicator	Conventional Bus Service	Straddle Bus Technology	% Change
Total Annual walking time (hour/year) (million)	2.71	4.67	+72.3%
Mean walking time (min/pax)	7.50	7.50	-
Annual walking time cost (£millions/year)	14.03	24.21	+72.6%
Total Annual waiting time (hour/year) (million)	1.30	2.01	+54.6%
Mean waiting time (min/pax)	3.65	3.30	-9.6%
Annual waiting time cost (£millions/year)	6.76	10.43	+54.3%
Total Annual in-vehicle time (hour/year) (million)	8.13	9.67	+18.9%
Mean in-vehicle time (min/pax)	22.53	15.53	-31.1%
Annual in-vehicle time cost (£millions/year)	21.07	25.06	+18.9%
Total user costs (£millions/year)	41.85	59.69	+42.6%
Average user costs (£/pkm)	0.483	0.399	-17.4%

From Table 7-10, the total annual user costs of travelling by conventional bus are lower than travelling by Straddle Bus, which is because of the remarkably increase in the endogenous demand level of Straddle Bus in the long term scenario. As a result of the higher endogenous demand level and the shorter service interval, the AUC of Straddle Bus was reduced from £0.420/pkm in the short term scenario to £0.399/pkm in the long term scenario.

With the additional service supplies in the long term, the average WTT per passenger can be reduced by 9.6% by replacing the existing conventional bus service with Straddle

Bus. By avoiding the congestion of the general traffic, the Straddle Bus technology can provide a service with 31.1% lower average IVT per passenger. The time savings made the Straddle Bus option have a 17.4% lower AUC compared with the conventional bus service.

External environment impacts

The external costs of both modes were calculated from the SCM by using the unit environmental cost and the vehicle-kilometre. The cost results are compared and shown in Table 7-11.

Table 7-11 External environmental impacts of long term scenario

Indicator	Conventional Bus Service	Straddle Bus Technology	% Change
Total air pollution cost (£million/year)	1.00	0.34	-66.0%
Total noise pollution cost (£million/year)	0.43	0.56	30.2%
Total climate change cost (£million/year)	0.09	0.19	+111.1%
Total external accident cost (£million/year)	0.06	0.07	+16.7%
Total external costs (£millions/year)	1.58	1.15	-27.2%
Average external costs (£/pkm)	0.0182	0.0090	-50.6%

Due to the increased supplies of the Straddle Bus service, the vehicle-kilometres were also increased. Therefore the total annual external costs of Straddle Bus are higher than the short term, up from £0.56m to £1.15m in the long term scenario. The TEC of the conventional bus service are lower in the long term, as a result of the lower service frequency. However, the AEC of conventional bus is still almost double than the Straddle Bus technology.

Total Social Costs

By adding up the total costs for operator, users and the environments, the total social costs were obtained for both public transport modes. The percentages of each main cost sector in the TSC are shown in Figure 7-6 and Figure 7-7, and the comparison is shown in Figure 7-8.

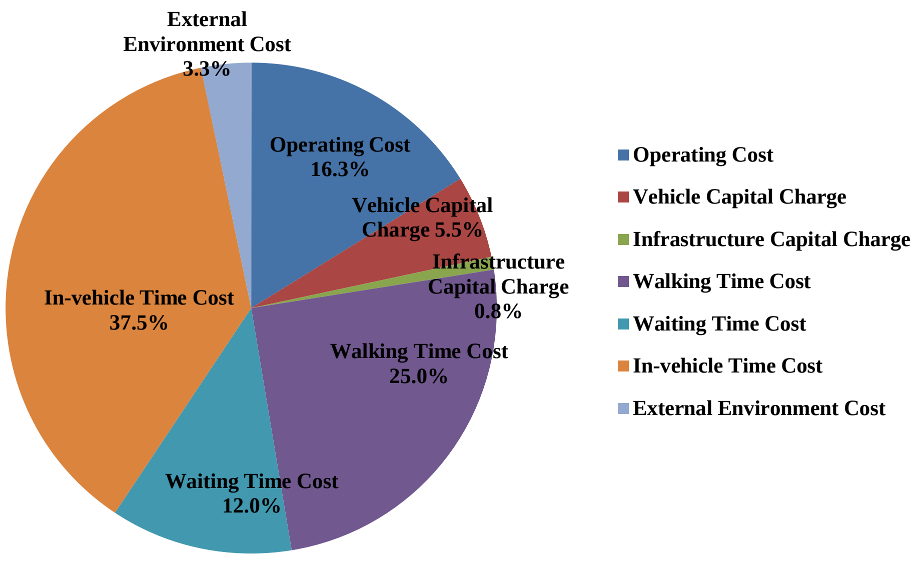


Figure 7-6 Percentage of average social cost of conventional bus in long term scenario

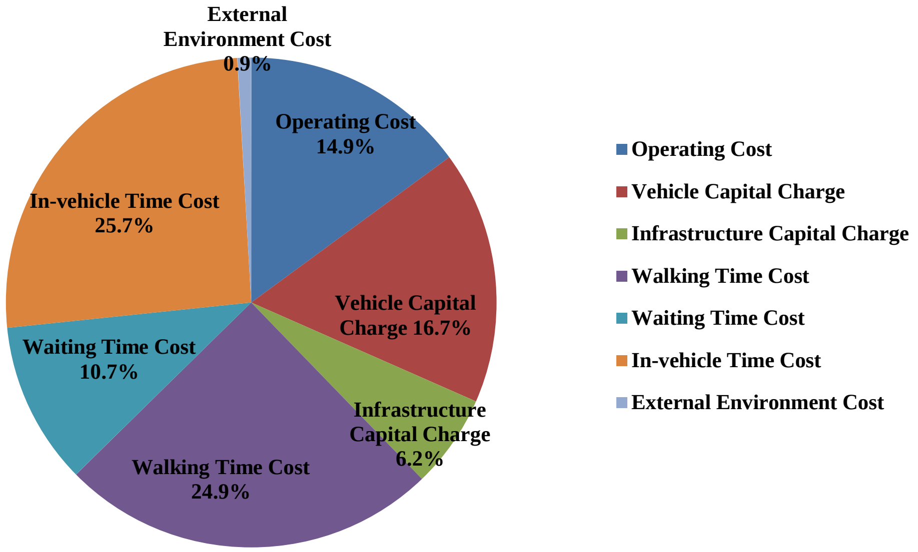


Figure 7-7 Percentage of average social cost of Straddle Bus in long term scenario

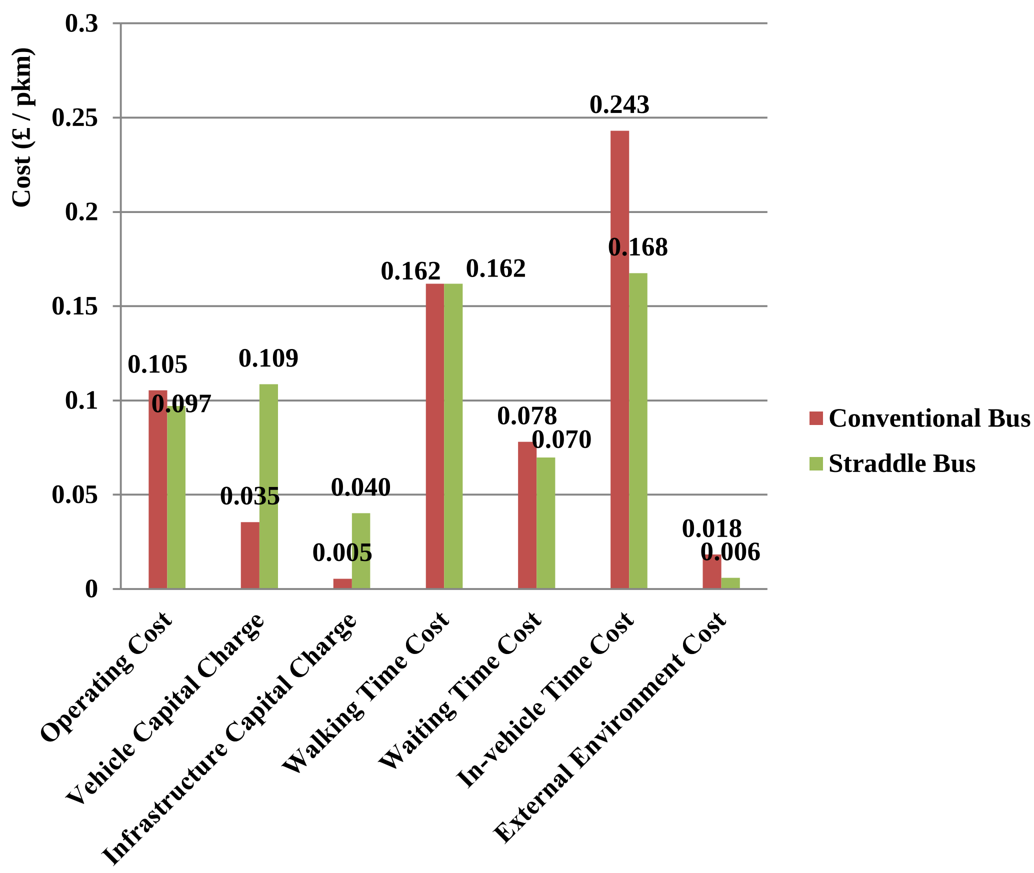


Figure 7-8 Comparison of average cost of conventional bus and Straddle Bus in long term scenario

The percentages of operator cost of Straddle Bus are still higher than the conventional bus operator in the long term. However, compared with the short term scenario, the reduced service frequency of the conventional bus leads to a greater waiting time cost while the increased service frequency of the Straddle Bus leads to a lower passenger waiting time cost. The changes in the operator's supply also affect the operating costs and the capital investment charges, which result in a decrease and an increase in the operator costs of conventional bus and Straddle Bus, respectively.

From Figure 7-6 and Figure 7-7, the percentages taken by the operator costs of the Straddle Bus are 37.8%, including 14.9% for operating cost and 22.9% for investment cost. This percentage is much higher than the 22.6% of operator cost of conventional bus operator in the long term.

From Figure 7-6 and Figure 7-7, the AUC (WKT cost, WTT cost and IVT cost) takes up 74.5% of the ASC of conventional bus, while the AUC of Straddle Bus is 61.3% of the ASC. This result suggests that although the costs of the public transport are still on user's side, Straddle Bus is able to provide benefits to passengers to reduce the AUC, in particular IVT cost.

Overall, the ASC of Straddle Bus is slightly higher than conventional bus. Although Straddle Bus requires a high investment cost, the savings in user cost and external cost are obvious, as shown in Figure 7-8.

Summary

By adjusting the operator's supply of service based on the endogenous demand level in the long term scenario, the ASC of replacing the conventional bus service with the innovative Straddle Bus technology is estimated to be increased slightly from £0.648/pkm to £0.652/pkm. However, due to the lower generalised time cost of the public transport users, the Straddle Bus option is able to attract 53,281 more passengers per day on the 12km corridor than the estimated level of 90,000 per day, while the conventional bus service is less attractive due to the lower operating speed in the congested traffic. This significant boost in endogenous demand level is also 49.2% higher than the demand level of Straddle Bus in short term scenario.

Compared with the conventional bus service, Straddle Bus is able to provide more benefits to the users, and the costs are transferred to the operator costs. The benefits to users were evidenced in the results of 31.1% lower mean IVT and 9.6% lower mean WTT, which are also the main reasons of the additional public transport passengers.

Although the operation of Straddle Bus will reduce the speed of the car traffic, the Straddle Bus option can still provide benefits to the car traffic. As the spaces taken by the conventional buses can be freed, the Straddle Bus technology is able to raise the average speed for car users by 15.8% in the long term scenario.

7.4 Conclusion

This chapter demonstrates the model application on the main corridor, Minzu Avenue in Nanning, China to show how the comparative assessment can be applied to a real network. The performance of the existing conventional bus service and the alternative Straddle Bus technology were evaluated and compared, and the differences were quantified in terms of cost. Endogenous demand levels and the average costs were calculated and presented in both short term where the service frequency was assumed to be fixed and long term scenario where the service frequency was recalculated based on the endogenous demand level. Results from this comparative assessment can be used by transport planners and decision makers to find out the most suitable public transport technologies from different aspects.

As bus operator companies in developing cities and countries may lack of methods for monitoring dynamics passenger demand level, it is worthwhile to consider the cost difference if they do. Hence two scenarios were evaluated in the comparative assessment. The advantages of Straddle Bus were more explicit in the long term scenario where service frequency was assumed to be changed based on endogenous demand levels. The greater capacity and the straddling feature of the Straddle Bus technology make it possible to provide sufficient services to passengers in high demand level. Consequently, the endogenous demand level of Straddle Bus rises dramatically in the long term scenario, because of the lower passenger generalised journey time. The ASCs of both conventional bus service and Straddle Bus technology were reduced, which was mainly contributed by the reductions in user costs. Compared with the short term scenario, the ASCs are lower in the long term scenario. This is because passengers will consider the generalised cost of the trip and balance the utilities of WTT and IVT. Passengers are able to seek lower generalised cost in the long term by affecting the supply, and the affected supply would also influence the demand, as analysed in the DSM. The lowered ASCs suggest that operators should oversee the relationship between demand and supply, in order to minimise the user cost and hence the social cost.

From operator's point of view, compared with the existing conventional bus service, the operators need to pay higher capital investment costs for the infrastructure construction and the vehicle with straddle feature. Straddle Bus can reduce the operating costs in the short term compared with conventional bus, which results from the lower vehicle-kilometres value. However, with the greater endogenous demand in the long term, the additional service supplied brings up the vehicle-kilometres, peak vehicle requirement and vehicle-hours, and therefore the total operating costs become 59.1% greater than the conventional bus service.

From user's point of view, the straddling feature of Straddle Bus is able to reduce the generalised journey time, in particular IVT, by 41.0% in the short term scenario and 31.1% in the long term scenario. In the short term, passengers need to spend 58.6% more time in waiting for the Straddle Bus than the conventional bus, due to the differences in service headway. In the long term, by adjusting the service frequency for the higher endogenous demand level, the average passenger waiting time can be reduced by 9.6% compared with the existing conventional bus service.

For the general public, compared with the conventional bus service, the Straddle Bus technology is able to provide a 70.7% lower average external cost per passenger-kilometre in short term scenario and 50.6% lower in long term scenario.

In conclusion, by replacing the existing conventional bus service on Minzu Avenue with Straddle Bus technology, the "winners" are the local bus users, general traffic in peak period and the general public while the "losers" are the bus operators and the general traffic in off-peak period. The comparative assessment results suggest that the Straddle Bus is a possible option for the Minzu Avenue to resolve the high passenger demand level estimated in the future, while maintaining the level of service in terms of public transport operating speed and car traffic speed. However, due to the extra capital investment cost of the Straddle Bus technology, the increased operator costs should also be recognised by the local government in order to provide subsidies or better policies to support the operation of Straddle Bus. Otherwise the operators may have to increase fares and subsequently reduce public transport passenger demand. The analysis of short term and long term scenario also suggests that the bus operator should pay attention to the changes in passenger demand level if the Straddle Bus was adopted in Nanning. As public transport users are sensitive to the service performance, insufficient operator supply of bus service may not be able to reveal the advantages of the public transport technology. By providing sufficient Straddle Bus service, the ridership can be significantly increased while the car usage could be reduces according to the results from the comparative assessment.

CHAPTER 8 CONCLUSIONS

8.1 Introduction

This chapter concludes the main activities conducted during the PhD study. The achievements of this research project were compared with the objectives of this thesis mentioned in the first chapter. Discussions and recommendations of future work are also given at the end of this chapter.

8.2 Research Summary

This research developed a comparative assessment which aims to provide a comprehensive way to evaluate the operation performance of different public transport technologies on a selected transportation corridor. The main activities conducted during the PhD study have been reported in Chapter 2 to Chapter 7, which include the literature review of public transport cost modelling (Chapter 2), literature review of microscopic traffic simulation (Chapter 3), development of Spreadsheet Cost Model (Chapter 4), development of Demand Supply Model (Chapter 5), development of Microscopic Simulation Model (Chapter 6) and the application of the comparative assessment (Chapter 7).

8.2.1 Research Tasks

To identify the main achievements of this thesis, this section begins with recalling the research objectives raised in Chapter 1 and compared with the tasks completed during the PhD research.

- *Research Objective 1: To investigate the social cost, including operator, user and external costs of the fixed line public transport technologies in different user demand level.*

1) A Spreadsheet Cost Model was developed to evaluate the social cost of different public transport technologies operating on the selected corridor. The social cost is calculated as the sum of operator cost, user cost and external environment cost, which are evaluated based on the characteristics of the transport mode and the operating performance on the corridor.

2) The calculations of operating performance of the public transport service were developed in the thesis, which is based on the previous TEST project work described by Brand and Preston (2006). The operating performance is indicated by the intermediate variables include service frequency, average operating speed, vehicle-kilometre, passenger-kilometre, peak vehicle requirement and vehicle-hour, which are calculated by using the characteristics of the transport mode, based on optional user input data or default values. The default values were given in the SCM, based on previous studies.

3) The calculation of operating speed of different public transport modes in the SCM was revised by considering the infrastructure capacity of the public transport form. The investment costs of extra infrastructure were considered in the operator cost sector while the benefits were not recognised in the user cost sector in the previous work. By introducing the infrastructure capacity differences, the advantages of rail-based transport mode and having a segregated lane for road-based transport modes were clarified.

4) Operator cost of the public transport service calculation was developed, which includes investment cost and operating cost. The investment cost calculation evaluates the annual investment cost for both infrastructure cost and vehicle fleet cost by using the economic life expectancy and the total capital investment. The operating cost is computed by using the operating performance indicators along with the unit operating cost from either user input data or default values in the Spreadsheet Cost Model.

5) The calculation of user cost of the public transport service was developed by considering generalised journey time of passengers, which includes walking time, waiting time and in-vehicle time. Walking time is computed by using the user input data of distance between stops. Passenger in-vehicle time is a function of average journey length and average operating speed of the public transport service. Passenger waiting time is determined by using the service frequency of the public transport service and the average dwell time per stop/station. To estimate the passenger waiting time in the SCM, the calculation also considers the possibility that passengers may find the incoming vehicle is full and hence extra waiting time is arose, by introducing queuing theory.

6) Cost of externalities calculation was also developed. The related external costs are involved in the calculation, including noise pollution cost, air pollution cost, climate change cost and external accident cost. In order to link the externality cost to the passenger demand and the public transport technology, the costs are determined by the vehicle-kilometre and the unit costs of the public transport technology from either user input data or default values of the SCM.

7) In order to conduct a case study of the comparative assessment, a conceptual innovative public transport technology, Straddle Bus was included in the Spreadsheet Cost Model by using public information as well as the data obtained from the inventor.

- *Research Objective 2: To evaluate the interactions between the public transport technologies and the public transport users, in order to find out how the performance of the public transport system would affect the user demand level.*

8) A Demand Supply Model was created to estimate the endogenous demand level under the current operator supply level. The model evaluates the endogenous demand level by using demand elasticity with respect to passenger generalised journey time. As walking time is not changed in different passenger demand level and service level, the model calculations are based on passenger waiting time and passenger in-vehicle time, which can be obtained from the SCM. Therefore, the comparative assessment is able to take the effect of public transport service

performance on passenger demand level into account to reflect the willingness of passengers to use the service.

- *Research Objective 3: To develop a traffic simulation mode of fixed line innovative public transport technologies in, and hence determine how the specific characteristics of fixed line innovative public transport technologies can be shown in such a model.*

9) A Microscopic Simulation Model was developed to assess the performance of public transport service. In order to conduct a case study of the comparative assessment in Nanning, China, the development of the simulation model used the data collected from Nanning.

11) The operation of the conceptual public transport technology, Straddle Bus, was simulated in the MSM. The impacts of the Straddle Bus to the general traffic, including lane changing, average speed and junction blocking were discussed and modelled. In order to simulate these impacts, a control program was coded in Visual Basic, which is connected to VISSIM via the VISSIM COM Interface.

12) Model calibration and model validation were conducted by using the traffic data of Nanning, China in two different days, in order to prove the simulation model results are sufficiently reliable compared with the real transport network. Model calibration and validation followed the proposed nine-step procedure by Park and Schneeberger (2003). As the simulation model is mainly used for evaluating the performance of public transport, bus travel time was chosen as the performance measurement of both model calibration and model validation. The mean and the goodness-of-fit of bus travel time distribution produced by using different parameter sets were examined by conducting two-tailed Student's t test and two-sample Kolmogorov-Smirnov test to ensure the credibility of the MSM.

- *Research Objective 4: Apply the models to a real network to demonstrate the usefulness of the comparative assessment in analysing and quantifying the benefits of different public transport technologies in a given traffic network.*

12) Application of the comparative assessment was conducted to assess the social and operator cost of replacing the conventional bus service with Straddle Bus

technology on Minzu Avenue in Nanning, China. Social and operator cost for short term and long term scenarios were evaluated along with endogenous demand level and the service performance of both conventional bus service and Straddle Bus technology.

13) Detailed interpretations of the model result were given to show the costs and benefits by replacing the existing conventional bus services on Minzu Avenue with Straddle Bus. In conjunction with the model results, recommendation was then provided, as a demonstration of the usefulness of the comparative assessment.

8.2.2 Contribution Summary

By demonstrating the development of a comprehensive comparative assessment for fixed line public transport technologies, the following contributions have been made.

First, a cost model for evaluating the social cost of different public transport was developed based on the approach in the TEST project. This model calculates the social costs, including operator, user and external costs of the public transport technology. With optional user inputs and the flexibility of the cost function, this model is able to be modified to suit various fixed line public transport systems. Different from the previous approach, the model developed in this thesis also considers vehicle to vehicle congestion by taking into account the impacts of the operating environment on the average speed and passenger on passenger congestion by considering the probability of having to wait for an extra service headway due to the incoming vehicle being full. These improvements are essential to the comparative assessment, as the factors affected will have significant impacts on the utility of the public transport users, and then the passenger demand level and the actual social cost of the public transport system might change.

Second, the calculation of the endogenous demand rather than the exogenous demand was undertaken to assess the effects of change in the performance of the public transport technology to the user’s utilities and hence the passenger demand level. The impacts to the public transport user are recursively calculated in the model and the results are based on the updated passenger demand level rather than being externally fixed. The impacts of this endogenous demand calculation was applied to the model as a feedback process to the social cost calculation to refine the actual passenger demand level according to the attractiveness of the service.

Third, the simulation of innovative public transport in a traffic simulation model was discussed and presented. Some innovative public transport technologies may not have existing operating system all around the world, and therefore there is no default setting in the traffic simulation software. The use of the COM Interface of VISSIM has shown that it is able to modify the traffic simulation model according to the requirements of the user by using computer programming. The flexibility of the microscopic simulation package has been well demonstrated to simulate the different operating methodology compared to the conventional public transport technology, which can be further developed to suit various innovative public transport technologies. Although this thesis only conducted a simulation of the Straddle Bus operating on part of a corridor, it has demonstrated a possible way to look at the detailed interactions between innovative public transport vehicles and the existing road users, in order to find out more detailed impacts on ridership and on the social costs of the technology.

Overall, the main achievement of the PhD study is the development of a methodology to evaluate the social cost, including the operator, user and external cost for different fixed line public transport technologies by considering the detailed interactions between public transport vehicles, road users and the public transport passengers. This methodology can be applied and modified to various transport networks to assess the costs and benefits of adopting new fixed line public transport systems to the existing network, and hence to provide information and evidences for decision makers.

8.3 Future Work

This thesis demonstrated the appraisal of different public transport technologies operating on a selected corridor in terms of social and operator cost. The usefulness of the comparative assessment is clearly shown through the case study in Nanning, China. However, some potential future works were recognised during the study, which are discussed in this section.

8.3.1 Combination of Public Transport Service

In the comparative assessment, the comparisons are between each public transport technology in terms of social and operator cost. For each public transport technology, passengers were assumed to access the service by walking. The walking time is calculated by using the distance between stops and the influence width of the corridor. However, it is unrealistic to consider every passenger will walk to the railway station rather than using other transport or feeder services, such as cars, buses and underground. In order to consider all relevant trips and costs raised by the public transport technologies, it is necessary to consider the costs of the combination of different public transport services as well as the feeder services. It is worthwhile to investigate the costs of those extra trips in order to present a comprehensive cost appraisal for different public transport technologies.

The combination of different public transport services and feeder services may also be able to expand the corridor to larger transport areas by providing those extra services in residential areas. For example, by providing demand responsive transport services or other feeder services in various residential areas to link with the public transport services on main corridor, the attractiveness of the service could be increased. Hence the average social and operator costs of the service on the main corridor could be reduced and cancelled out the extra costs for providing the feeder services.

To further assess the costs and to expand the scope of the comparative assessment, more public transport technologies, including taxi, suspended monorail and high-speed rail should be considered in the model. The comparative assessment can also be used to assess the costs of travelling by various public transport systems such as regional travel by air, sea or rail.

8.3.2 A Substantial Database for Public Transport Technologies

In the comparative assessment, the SCM is able to evaluate 16 different public transport technologies. The values of default parameters and default unit costs of the public transport system are from previous studies. In order to allow users to compare a wider range of public transport systems, a substantial database is needed to store the characteristics and information of the existing public transport services in the world. Due to different local network condition of public transport systems, the costs and the characteristics may differ. A substantial database for various public transport technologies is able to provide more options for users to suit their situations. The SCM can then link to the database for users to be able to select the existing public transport system to compare with.

8.3.3 Passenger Demand Level Evaluation

The comparative assessment evaluates the variation of passenger demand level by using demand elasticity with respect to passenger generalised journey time. As the comparative assessment assumes the comparisons are between public transport technologies, the evaluation in the comparative assessment do not cover the costs raised in other transport mode on the corridor. For example, if the service frequency of the public transport service is increased, the operating speed of cars could be reduced and hence leads to extra costs for car users. Replacing or reducing the existing conventional bus services by introducing other public transport systems, for example Straddle Bus and underground, the space taken by conventional buses will be freed. This action may lead to additional cars on the corridor and hence more environmental costs. Therefore it is necessary to consider all transport modes in the corridor including cars, walking and cycle in order to take all interactions between trip modes into account. Hence all related costs borne to the public transport can be evaluated in the comparative assessment.

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APPENDICES

Appendix A: Spreadsheet Cost Model Interface

The Spreadsheet Cost Model developed in this thesis is a mathematical model to evaluate social and operator cost of different public transport technologies. The model is developed in Microsoft Excel, and a screenshot of the user interface is attached in this section.

Public Transport Technology:		Straddle Bus	9
			Click here to update the current table ->	Update

Annulisation Factor:	7	days/week	
	365.3	days/year	
	52.19	weeks/year	
	261	weekdays/year	

(red)	means user input (required)
(yellow)	means user input (optional)
(grey)	means this cell is dependent on others/ is calculated
(green)	means this cell will be changed exclusively during model runs
(blue)	means internal variables should not be changed

Demand: average daily demand	PAX	90000	passengers		
		For AM Period	For PM Period	For OffPeak Period	
Share demand in time period i	ShPAX(i)	22.5%	22.5%	55.0%	%
Duration of time period i	T(i)	2	2	7	hour
Share of daily demand per hour	Sh(i)	11.3%	11.3%	7.9%	%
Average daily demand per hour in time period i	PAX(i)	10125.0	10125.0	7071.4	passengers per hour

Technology Supply:		For AM Period	For PM Period	For OffPeak Period	
Average operational speed incl. all stop density and capacity restraints	V(t,i)ALL	21.67	21.67	21.67	km per hour
Average operational speed incl. stop density restraints (no lane capacity restraints)	V(t,i)NoCap	21.67	21.67	21.67	km per hour
Service level frequency required to meet demand (no lane capacity restraints)	F(t,i)NoCap	45.00	45.00	31.43	vehicle per hour
Average stopping time as the sum of vehicle stopping time and passenger boarding time	T(t,i)Stop	30.00	30.00	30.00	sec
Lane capacity for the public transport per hour	C(t)	129	vehicles per hour	Facility Capacity Percentage	0.68 n/a
Supply/demand factor to allow seasonal changes	α	1.1	n/a		
Total vehicle capacity (seating and standing)	VehCap	330	paseengers per vehicle		
Maximum relative load factor to require a new vehicle	MaxLF	0.5	n/a		
Max. vehicle speed in free-flow conditions	V(t)MAX	60	km per hour		
Acceleration and deceleration	A(t)	1.34	metres per square sec		
Average distance between stops	D(t)stop	0.4	kilometres		
Average vehicle stopping time	T(t)Veh	15	sec		
Average boarding time per passenger	T(t)Pas	4	sec		
Track length (single direction)	L	24	km		
Vehicle length	L(t)Veh	40	metres		
Deceleration in emergency breaking situation	A(MAX)	3	metres per square sec		
Safety headway	H(t)	27.90	sec		

Intermediate Outputs:			
Vehicle-kilometres for the technology t	VKM(t)	2504914	vehicle-km
Passenger-kilometres for technology t	PKM(t)	93934286	passenger-km
Peak vehicle requirement	PVR(t)	55.00	vehicles
Vehicle -hours for technology t	VH(t)	115570	vehicle-hour
Mean passenger loading	LF(t)	38	passengers per vehicle
Factor allowing for spare vehicles	δ	10%	%
Average PT journey length in the corridor	JL	4	km

Extra Waiting Time Calculation:	PEAK	OFFPEAK
mu	45.00	31.43
lambda	33.8	23.6
rho	0.5	0.75
a	1.1	1.1
p (1)	38.94%	62.98%
p (2)	30.33%	52.89%
p (3)	23.62%	44.42%
p (4)	18.39%	37.30%
p (5)	14.33%	31.33%
p (6)	11.16%	26.31%
p (7)	8.69%	22.09%
p (8)	6.77%	18.55%

Parameters | Calculation | ASC Result Graph | Minimum Cost | MSC | Apply Endogenous

	J	K	L
	p (10)	0.34%	1.52%
	p (11)	0.20%	1.07%
	p (12)	0.12%	0.76%

Row	B–D	E	F	G	H	I
49	**Total Operating Cost:**					
50	Unit operating costs, time related	UOC(t)T	62.219	£ per vehicle-hour		
51	Unit operating costs, distance related	UOC(t)D	0.661	£ per vehicle-km		
52	Unit operating costs, vehicle related	UOC(t)V	61834.66667	£ per peak vehicle		
53	Unit operating costs, route-maintenance related	UOC(t)R	12880	£ per route-km		
54	Operating costs, time related	OC(t)T	5154544	£ per year		
55	Operating costs, distance related	OC(t)D	1214215	£ per year		
56	Operating costs, vehicle related	OC(t)V	2473387	£ per year		
57	Operating costs, route-maintenance related	OC(t)R	154560	£ per year		
58	Total operating costs exclude capital investment	TOC(t)	8996706	£ per year		
59	Factor simulating more fuel use due to congestion	β(t)	1.1	n/a		
60	Interest rate for capital investment	IR(t)	3.50%	%		
61	Discount rate for capital investment	DR(t)	3.38%	%		
62	Economic life expectancy for the fleet	EL(t)veh	15	years		
63	Economic life expectancy for infrastructure	EL(t)inf	25	years		
64	Unit capital cost per vehicle	UC(t)veh	2774100	£ per vehicle		
65	Unit cost per km of infrastructure (double track)	UC(t)inf	8350000	£ per km		
66	Total capital investment costs, vehicles	CC(t)tot,veh	110964000	£		
67	Total capital investment costs, infrastructure	CC(t)tot,inf	100200000	£		
68	Total capital investment costs	CC(t)tot	211164000	£		
69	Annual capital charge	CC(t)ann	15549702.37	£ per year		
70	The depot & management costs etc top-up to total cost	λ	5.00%	%		
71	Total operating costs plus financing and other costs	TOC(t)ALL	24996244.19	£ per year		
73	**Total User Cost:**		For AM Period	For PM Period	For OffPeak Period	
74	Mean waiting time for tech. t and time period i	T(t,i)wait	0.0316	0.0316	0.0372	hours
75		T(t,i)wait old	0.0181	0.0181	0.0217	
76	Mean walking distance to/from stop	D(t)walk	0.25	km		
77	Average width of route influence along the corridor	Wroute	0.6	km		
78	Mean walking time	T(t)walk	0.0625	hours		
79	Average walking speed	Vwalk	4	km per hour		
80	Total annual walking time	TT(t)walk	2609285.71	hours per year		
81	Total annual waiting time	TT(t)wait	723508.41	hours per year		
82	Total annual in vehicle time	TT(t)IV	4142259	hours per year		
83	Perception of walking time vs in vehicle time	WTT(t)walk	2	n/a		
84	Perception of waiting time vs in vehicle time	WTT(t)wait	2	n/a		
85	Value of in vehicle time	VoT(t)	4.53	£ per hour		
86	Total user costs	TUC(t)	48959548.51	£ per year		
88	**Total External Cost:**					
89	Air pollution cost per vehicle-km	EC(t)air	0.133	£ per vehicle-km		
90	Noise pollution cost per vehicle-km	EC(t)noise	0.218	£ per vehicle-km		
91	Climate change cost per vehicle-km	EC(t)climate	0.075	£ per vehicle-km		
92	External accident cost per vehicle-km	EC(t)accidents	0.017	£ per vehicle-km		
93	Total external costs	TEC(t)	739784.69	£		
95	**Outputs**					
96	Total social costs	TSC(t)	74695577.39	£		
97	Average social costs	ASC(t)	0.89	£		

Parameters | Calculation | ASC Result Graph | Minimum Cost | MSC | Apply Endogenous

Appendix B: Control Program for Simulating Straddle Bus in VISSIM

As the Straddle Bus technology is a conceptual technology and there is no default setting available in VISSIM, a control program was coded in Visual Basic to simulate the behaviours and impacts of Straddle Bus. The control program was developed based on multiple run file provided by PTV AG, and the control program is able to perform both multiple model runs with different random seeds as well as simulation of Straddle Bus. Part of the control program codes (the main program, not including the functions) are given in this section, followed by a screenshot of the interface in Microsoft Excel.

```
Option Explicit

Private Declare Sub Sleep Lib "kernel32" (ByVal dwMilliseconds As Long)



Dim simPath As String
Dim simPathGlobal As String '(value entered in "Data path" in spreadsheet)
Dim simFileNoExt As String
Dim runIndex As Integer
Dim renamedFilesCount As Integer

Dim dateTimeSimStart As Variant
Dim dateTimeSimEnd As Variant
Dim fs As Object
Dim pos As Integer
Dim randomSeed As Integer

'Definitions of all Desired Speed Decisions
'2 Desired Speed Decisions points for 1 detector, as the Straddle Bus straddles two lanes
'link numbers, detector numbers are ascending from east to west on eastbound direction (1 - 34)
Dim decisions As DesiredSpeedDecisions

Dim decision As DesiredSpeedDecision


'Definition of Links
Dim links As links

Dim link As link

'Define Detectors
Dim dets As Detectors

Dim det As Detector

Const DELIMITER = "."
Const iniName = "multirun_settings.ini"
```

```
Sub RandomSeed2VISSIM()
    'Main program


    'initial setup
    Set decisions = vissim.Net.DesiredSpeedDecisions

    Set links = vissim.Net.links

    Set dets = vissim.Net.SignalControllers(2).Detectors



    'Disable excel alerts (calls to the COM interface are synchronous)
    Application.DisplayAlerts = False

    'Declare VISSIM COM types
    Dim vissim As Object 'for late binding (see chapter 3.6 Advanced issues using Visual Basic)
    Dim Simulation As Object

    'Declare further types
    Dim simFile As String
    Dim iniPath As String
    Dim commentINI As String
    Dim fileIndex As Integer

    'Load a network
    Sheets("VISSIM").Select
    simPathGlobal = Range("SimPath").Value

    If simPathGlobal <> "" Then
        'Check for trailing \ character
        pos = InStrRev(simPathGlobal, "\")
        If pos <> Len(simPathGlobal) Then
            simPathGlobal = simPathGlobal + "\"
        End If
    Else
        simPathGlobal = Application.ThisWorkbook.Path + "\"   ' use same directory as Excel file
    End If

    'Create file system object for file operations
    Set fs = CreateObject("Scripting.FileSystemObject")

    ' - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
    ' Check if all INP & INI files do exist
    Range("SimFile").Select
    If Selection = "" Then
        MsgBox "You need to provide at least one INP file name.", vbInformation
        Exit Sub
    End If

    While Selection <> ""
        simFile = Selection.Value

        'Remove any leading \
        pos = InStr(simFile, "\")
        If pos = 1 Then
            simFile = Mid(simFile, 2)
        End If
```

```
    'Check if filename contains path information
    pos = InStrRev(simFile, "\")
    If pos > 0 Then
        simPath = simPathGlobal + Left(simFile, pos)
        simFile = Mid(simFile, pos + 1)
    Else
        simPath = simPathGlobal
    End If

    'Check if path and file exists
    If Not fs.FileExists(simPath + simFile) Then
        MsgBox "The file '" & simPath & simFile & "' was not found.", vbCritical
        Exit Sub
    End If

    ' Check first if local INI file exists
    iniPath = simPath + iniName
    If Not fs.FileExists(iniPath) Then
         'Check if INI file exists in global path
         If simPathGlobal <> "" Then
             iniPath = simPathGlobal + iniName
         End If

        If Not fs.FileExists(iniPath) Then
            MsgBox "The configuration file '" & iniPath & "' was not found.", vbCritical
            Exit Sub
        End If
    End If

    'Look for more INP file names...
    ActiveCell.Offset(1, 0).Select
Wend

' - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
' Check if any random seeds are defined
Range("RandomSeedStart").Select
If Selection = "" Then
    MsgBox "You need to define at least one random seed value.", vbInformation
    Exit Sub
End If

' - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
' Start Vissim and create an instance of a Vissim object and a simulation object
Set vissim = CreateObject("Vissim.Vissim") 'Create VISSIM instance from system registry
Set Simulation = vissim.Simulation 'Get the simulation interface of Vissim

' - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
' Start the batch run of all INP files
fileIndex = 0
Range("SimFile").Select
While Selection <> ""
    simFile = Selection.Value

    'Remove any leading \
    pos = InStr(simFile, "\")
    If pos = 1 Then
        simFile = Mid(simFile, 2)
    End If

    'Check if Filename contains path information
```

```
pos = InStrRev(simFile, "\")
If pos > 0 Then
   simPath = simPathGlobal + Left(simFile, pos)
   simFile = Mid(simFile, pos + 1)
Else
   simPath = simPathGlobal
End If

'Load VISSIM network and options (e.g. evaluations)
vissim.LoadNet simPath + simFile 'each data directory can have its own multirun_settings.ini file

iniPath = simPath + iniName  ' if exists, open local INI file
If Not fs.FileExists(iniPath) Then
    'Open INI file in global path
   iniPath = simPathGlobal + iniName
End If
vissim.LoadLayout iniPath

'Remove extension
pos = InStrRev(simFile, ".")
If pos > -1 Then
   simFileNoExt = Left(simFile, pos - 1)
End If

'Initialize values
runIndex = 1
Range("RandomSeedStart").Select
commentINI = Simulation.Comment

'Loop of simulation runs
While Selection <> ""
   Simulation.runIndex = runIndex
   randomSeed = Selection.Value
   Simulation.Comment = Simulation.Comment & "; Random Seed = " & randomSeed
   Simulation.randomSeed = randomSeed



   'Run Simulation
   dateTimeSimStart = Date + Time  ' store time & date when simulation started

   Dim i As Long

   For i = 1 To 45000
      Simulation.RunSingleStep


      'modify parameters according to detector status
      'Check all detectors in desceding order
      For j = 34 To 1 Step -1

         'set detector number in the first place
         Set det = det.GetDetectorByNumber(j)

         'check if Straddle Bus is Presence
         If det.AttValue("PRESENCE") = 1 Then

            'modify related Desired Speed Decisions
             'Change Desired Speed when Straddle Bus is detected
            Call SpeedDecisions(j)
```

```
            'modify the lane change behaviour of the related links
            Call LaneChange(j)

          End If

        Next j

      Next i

      dateTimeSimEnd = Date + Time  ' store time & date when simulation stopped

      'Rename evaluations
      renamedFilesCount = 0
      Call RenameEvaluations(simFileNoExt + ".*", False)
      Call RenameEvaluations(simFileNoExt + Format(runIndex) + ".*", True) ' handle those evaluations differently that add the runindex automatically to the filename

      'Get next random seed
      ActiveCell.Offset(1, 0).Select
      runIndex = runIndex + 1
      Simulation.Comment = commentINI
    Wend

    'Look for more INP files...
    Range("SimFile").Select
    fileIndex = fileIndex + 1
    ActiveCell.Offset(fileIndex, 0).Select
  Wend

  ' close VISSIM
  vissim.Exit
  Set vissim = Nothing

 ' MsgBox "Multirun succesfully completed."

End Sub
```

	A	B	C	D	E	F	G	H
2	Start		Prior to **"Start",** the desired evaluation and view settings of the simulations need to be saved to the **"multirun_settings.ini"** file that resides in the the same directory as the corresponding INP file. Only if this directoy does **not** contain a "multirun_settings.ini" file then the "multirun_settings.ini" file found in the Data path is used.					
3								
4	**Random Seeds**		After each run the evaluation files will be copied and the random seed no. be appended to the file names so that they will not be overwritten by subsequent runs that use a different seed.					
5	20							
6	40							
7	60		**Data path** *(optional - if emtpy, the same directory as where this Excel file resides is used)*		Specify the value of parameters used. The model will use default value if leave bla			
8	80							
9	100							
10			**INP file(s)** *(must include extension* ***.inp****, may include path)*		**EmergencyStop (m)**	**LaneChange (m)**	**StandstillDistanceCC0 (m)**	**HeadwayTim**
11			Straddle bus(offpeak).inp					
12			Straddle bus(peak).inp					
13								
14								
15								
16								
17								
18								
19								
20								
21								
22								
23								
24								
25								
26								
27								
28								
29								
30								
31								
32								
33								
34								

VISSIM | Sheet1 | Sheet2

Appendix C: Selected Symbols and Abbreviations for the Speadsheet Cost Model

A	acceleration and deceleration of the public transport vehicle (metre/second^2)
A_{max}	maximum deceleration of the public transport vehicle in emergency breaking situation (metre/second^2)
a	annulisation factor (weekdays/year)
ACC_{inf}	annual capital investment charge for the infrastructure (£/year)
ACC_{veh}	annual capital investment charge for the vehicle fleet (£/year)
ASC	average operator cost (£/passenger kilometre)
ASC	average social cost (£/passenger kilometre)
C_{fac}	critical facility capacity (vehicle/hour)
C_{inf}	infrastructure capacity of the public transport technology (vehicle/hour)
C_{veh}	the total passenger capacity of the vehicle, including seating and standing (passenger/vehicle)
CC_{ann}	total annual capital investment charge of the public transport technology (£/year)
CC_{inf}	total capital investment costs for the infrastructure (£)
CC_{veh}	total capital investment costs for the vehicle fleet (£)
D_{stop}	distance between stops (kilometre)

D_{walk}	average walking distance from/to the public transport stop/station (kilometre)
F_t	service frequency requirement for the passenger demand level in the time period *t* (vehicle/hour)
f	capacity percentages of public transport technologies in different operating environments
H	safety headway (second)
IIA	independence of irrelevant alternatives
JL	average public transport passenger journey length (kilometre)
L_{veh}	the total length of the vehicle (metre)
L_{track}	total track length of the corridor (kilometre)
MNL	multinomial logit
m	economic life expectancy of the infrastructure (years)
NL	nested logit
n	economic life expectancy of the vehicle fleet (years)
OC	annual operating cost (£/year)
OC_{all}	total annual operating cost, including other cost such as depot cost and management cost (£/year)
OC_D	annual distance-related operating costs (£/year)
OC_T	annual time-related operating costs (£/year)
OC_R	annual route/track maintenance costs (£/year)
OC_V	annual vehicle-related operating costs (£/year)
P_0	probability of not having to wait for extra public transport services

P_i	probability of having to wait for the extra ith number of the public transport vehicle
PKM	passenger-kilometres
PVR	peak vehicle requirement
Q	total daily passenger demand (passenger)
Q_t	passenger demand in the time period *t* (passenger/hour)
r	discount rate for capital investment
s	spare capacity percentage, which is the percentage of available spaces left for each vehicle
T_{dwell}	average vehicle dwell time per stop/station, including average fixed vehicle stopping time and passenger boarding/alighting time (second)
T_{fixed}	fixed passenger waiting time (seconds)
T_{pas}	average boarding time per passenger (second)
T_{stop}	average fixed vehicle stopping time per stop/station (second)
T_{wait}	average waiting time per passenger for the time period (hours)
T_{walk}	average walking time per passenger (hours)
T_t	number of hours of the time period (hours)
TT_{IV}	total annual in-vehicle time (hours)
TT_{wait}	total annual waiting time (hours)
TT_{walk}	total annual passenger walking time (hours)
TEC	total annual external cost (£/year)
TOC	total annual operator cost, including operating cost and capital investment charge (£/year)

TSC	total annual social cost (£/year)
TUC	total annual user cost (£/year)
$UEC_{accident}$	unit external accident cost per vehicle-kilometre (£/vkm)
UEC_{air}	unit air pollution cost per vehicle-kilometre (£/vkm)
$UEC_{climate}$	unit climate change cost per vehicle-kilometre (£/vkm)
UEC_{noise}	unit noise pollution cost per vehicle-kilometre (£/vkm)
UC_{inf}	unit cost per kilometre of the public transport infrastructure route/track with double lane/tracks (£/km)
UC_{veh}	unit cost per vehicle of the public transport fleet (£/vehicle)
UOC_D	unit distance-related operating cost (£/vehicle-kilometre)
UOC_T	unit time-related operating cost (£/vehicle-kilometre)
UOC_R	unit route/track maintenance cost (£/vehicle-kilometre)
UOC_V	unit vehicle-related operating cost (£/vehicle-hour)
V	operating speed, including stop density restraints but no capacity restraints (kilometre/hour)
V_{all}	average operating speed, including all stop density and capacity restraints (kilometre/hour)
V_{max}	maximum operating speed of the public transport vehicle (kilometre/hour)
V_{walk}	average walking speed (kilometre/hour)
VH	vehicle-hours
VKM	vehicle-kilometres
VoT	value of in-vehicle time for the public transport technology (£/hour)

W	average influence width of the public transport corridor (kilometre)
w_{wait}	factor to represent the weighting perception of waiting vs. in-vehicle time
w_{walk}	factor to represent the weighting perception of walking vs. in-vehicle time
WT	average waiting time for each passenger before boarding the vehicle (hours)
α	supply/demand factor to allow for seasonal variation in demand
β	factor to account for additional fuel consumption in congested traffic
γ	maximum load factor of the vehicle at which level a new vehicle is required
δ	factor allowing for spare vehicles
λ	passenger arrival rate (passenger/hour)
μ	service frequency of the time period
ρ	utilization rate of the public transport system
η	percentage of other cost factor to be added to the operating cost

Appendix D: Specification of the Unit Costs Used in the Spreadsheet Cost Model

D.1 Unit Operating Costs

The unit operating cost is used in the SCM to calculate the operating cost as part of the operator cost of each public transport technology at the given demand level. The following table is given in Chapter 4 to demonstrate the default value of the unit operating costs of the 16 public transport technologies modelled in the SCM.

Categories	**Cost components**	**Time-related**	**Distance-related**	**Route maintenance**	**Vehicle-related**
	Units	£ per Vehicle-hours	£ per Vehicle-kilometres	£ per Route-kilometres	£ per Peak Vehicle Requirement
Small Vehicle Technology	Minibus	10.600	0.139	2,642	4,292
	Personal Rapid Transit	1.325	0.139	2,642	661
Conventional Bus	Single-decker bus	13.250	0.277	2,642	17,168
	Articulated bus	13.913	0.305	2,642	18,885
	Double-decker bus	13.913	0.333	2,642	20,601
	Single-decker bus on bus lane	13.250	0.264	3,963	17,168
	Single-decker bus on busway	13.250	0.264	3,963	17,168
	Single-decker bus on guideway	13.581	0.264	6,605	18,026
	Double-decker bus on guideway	13.581	0.264	6,605	18,026
Light Rail Transit	Guided Light Transit	13.581	0.366	6,605	22,318
	Straddle Bus	62.219	0.661	12,880	61,835
	Modern light rail	62.219	0.661	12,880	46,376
	LRV tracksharing	62.219	0.661	10,806	90,116
Heavy Rail Transit	Suburban heavy rail	54.954	1.057	19,815	66,050
	Regional heavy rail	123.910	2.153	60,269	292,872
	Underground	84.676	4.597	541,512	106,787

An example of the operating cost breakdown is given in the figure as follow, which shows the operating cost breakdown of South Hampshire Rapid Transit.

Detailed cost	Quantity	Cost/Unit	Total cost	%
Drivers	39	15,900	620,100	14.69
Senior controllers	2	20,140	40,280	.95
Controllers	5	18,020	90,100	2.13
Line supervisors	3	20,140	60,420	1.43
Rostering, train	1	20,140	20,140	.48
Senoir inspectors	1	20,140	20,140	.48
Inspectors	7	16,960	118,720	2.81
Vehicle maintenance supervisors	2	20,140	40,280	.95
Vehicle maintenance technicians	7	15,900	127,200	3.01
Managers (main, ops & mark, fin & pers)	3	31,800	95,400	2.26
Assistants (main, ops & mark, fin & pers)	3	25,970	77,910	1.85
Secretaries, clerks	4	14,310	57,240	1.36
Managing directors	1	47,700	47,700	1.13
TOTAL STAFF	**88**	**17,809**	**1567,210**	**37.12**
Power supply (traction)			300,465	7.12
Other energy (elec, gas, water, etc.)			60,093	1.42
Maintenance materials (track, equip)			526,336	12.47
Subcontracts (clean, rs, maint. Equip)			441,620	10.46
Subcontracts (bus service)			70,000	1.66
Subcontracts (surveys, marketing)			75,000	1.78
Tunnel maint.			80,000	1.89
Insurance			250,000	5.92
Depot security, vandalism			50,000	1.18
Rating			75,000	1.78
Office supply and misc.			75,000	1.78
TOTAL OTHER EXPENSES			**2003,514**	**47.45**
Tech. Assist. Managt fees, profit			357,072	8.46
Contingencies (7.5%)			294,585	6.98
TOTAL OPERATING COSTS			**4222,381**	**100**
Operating costs per veh km			3.48	

(Source: SHRT, 2000)

As the operating cost figures are difficult to obtain due to the commercial confidentiality, some assumptions have to be made, which are explained in this section.

Time-related operating cost

The time-related operating costs of different public transport technologies are measured in £ per vehicle-hours. It includes the operating costs that are related to the number of operating hours of the public transport vehicles (for example, staff wages and vehicle servicing).

Distance-related operating cost

The distance-related operating cost is to measure the cost of the public transport company based on the distances travelled by the public transport vehicle. This includes the cost of fuel, vehicle tyres, vehicle insurance, compensation and the maintenance of the vehicles, and the unit is £ per vehicle-kilometres.

Route maintenance cost

The costs that are included in the route maintenance are the related infrastructure such as stops, stations, tracks and signals. As the route maintenance cost is depending on the length to the route, it is measured in £ per kilometres.

Vehicle-related cost

The total vehicle-related cost of each public transport technology depends on the number of vehicles required by the transport network. The costs include vehicle cleaning cost, vehicle maintenance material and vehicle insurance, and the unit is in £ per vehicles.

Assumptions and Sources

The default values of the operating cost used in the SCM are taken from Brand and Preston (2003) and modified to the price level in 2011 from the price level in 2000. The following assumptions were made in Brand and Preston (2003) for the 15 public transport technologies in TEST project, together with the Straddle Bus assumptions made in this thesis:

- Single-decker bus: The operating costs of the single-decker bus are taken from the CfIT (2002) report for a radial urban route in middle size cities.

- Articulated bus: The unit costs are based on the single-decker bus. The time-related cost is assumed to be 5% higher than the single-decker bus, as a result of the higher servicing staff costs. Because of the higher fuel consumption, insurance and more maintenance material needed of the mode, distance-related costs and the vehicle-related costs are assumed to be 10% higher than the single-decker bus.

- Double-decker bus: The unit costs are based on the single-decker bus. Similar to the articulated bus, the time-related cost is assumed to be 5% greater. With greater fuel consumption rate and a higher insurance cost of the double-decker feature, the distance-related costs and the vehicle-related costs are assumed to be 20% higher than the single-decker bus.

- Single-decker bus on bus lane/busway: The unit costs are based on the single-decker bus. As these two modes are operating with a right-of-way compared to the normal single-decker bus, a 5% cost saving was assumed on the time-related cost to account for the higher fuel efficiency while an additional 50% route maintenance costs were assumed.

- Single-decker/double-decker bus on guideway: The unit costs are based on the single-decker bus. Vehicle-related costs are assumed to be 5% greater than the single-decker bus in mixed traffic, as a result of the requirement of the guidance arm. Due to the higher vehicle servicing costs and the higher route maintenance costs of the guideway, 2.5% additional time-related cost and 150% additional route maintenance costs were assumed.

- Guided light transit: The unit costs are based on the single-decker bus. A 30% greater vehicle-related cost and a 20% greater distance-related cost were assumed due to the higher vehicle insurance and maintenance material costs, and the higher fuel costs (due to larger vehicle), respectively.

- Minibus: The unit costs are based on the single-decker bus. As a result of the smaller vehicle and hence lower insurance, maintenance material and fuel cost, the vehicle-related costs are assumed to be 25% of the single-decker bus and the distance-related costs are assumed to be half.

- PRT: The unit costs are based on the ULTra PRT. The time-related costs were assumed to be 10% of the single-decker bus due to the driverless feature of the technology. Although PRT service can operate without a fixed route, this study is focus on fixed line public transport. Hence the route maintenance cost is still required, which is assumed to be the same as the single-decker bus.

- Straddle Bus: As a conceptual public transport technology, there is no operating cost data available. Therefore, the operating costs are assumed to be based on the operating cost modern light rail as a result of the large vehicle and insurance cost. The vehicle-related cost of Straddle Bus is assumed to be 33% greater than the modern light rail due to the larger size vehicle.

- Modern light rail: The unit costs are all based on the review of the costs and benefits of the Manchester Metrolink scheme by Brand and Preston (2002).

- LRV tracksharing: The unit costs are all based on the review of the costs and benefits of the Karlsruhe tracksharing scheme by Brand and Preston (2002).

- Suburban heavy rail: The unit costs are all based on the review of the costs and benefits of the operation of Robin Hood Line by Brand and Preston (2002).

- Regional heavy rail: The unit costs are adopted from the Public Transport Fact Book (APTA, 1999) by Brand and Preston (2002)[3].

- Underground: The unit costs are all based on the operation cost of London Underground (TfL, 2001)[4].

D.2 Unit Capital Investment Costs

The capital investment cost is considered in the SCM as part of the operator cost of each public transport technology at the given demand level. The capital investment for each public transport technology includes the infrastructure cost and the vehicle cost. The

[3] Updated report can be found at www.apta.com
[4] Updated report can be found at www.tfl.gov.uk/corporate/publications-and-reports/

economic lives for the infrastructure and the vehicle are for calculating the annual capital investment cost. The following table is given in Chapter 4 to demonstrate the default value of the infrastructure costs of the 16 public transport technologies modelled in the SCM.

Categories	**Technologies**	**Infrastructure costs (£m per km)**	**Vehicle costs (£ per vehicle)**	**Economic life, fleet**	**Economic life, infrastructur**
Small Vehicle Technology	Minibus	0.66	79,260	10	25
	Personal Rapid Transit	3.05	33,025	10	25
Conventional Bus	Single-decker	0.66	145,310	10	25
	Articulated Bus	0.66	198,150	10	25
	Double-decker Bus	0.66	198,150	10	25
	Single-decker Bus on bus lane	1.31	145,310	10	25
	Single-decker Bus on busway	6.61	145,310	10	25
	Single-decker Bus (Guided)	4.80	151,915	10	25
	Double-decker Bus (Guided)	4.80	204,755	10	25
Light Rail Transit	"Guided Light Transit"	3.30	1,453,100	15	25
	Straddle Bus	8.15	2,774,100	25	50
	Modern light rail	9.15	1,849,400	25	50
	LRV	5.30	1,981,500	25	50
Heavy Rail Transit	Suburban heavy rail	13.21	2,377,800	25	50
	Regional heavy rail	26.42	3,302,500	25	50
	Underground	105.68	2,642,000	25	50

The infrastructure costs and the economic life expectancies of the 15 different public transport technologies in TEST project were given in the review of the financial characteristics of public transport systems by Brand and Preston (2001). The review involves the light rail systems in Berlin, Croydon, Manchester, Nantes, Paris, Pittsburgh and Sheffield, the guided bus system in Leeds, Edinburgh, Liverpool and Paris, the busways in Ottawa, Paris, Pittsburgh and Quito and the ULTra PRT testing facility in Cardiff.

The vehicle costs and the economic life expectancies of the 15 different public transport technologies in the TEST project are also from the review by Brand and Preston (2001). As the vehicle market is more international and has less local differences compared with the operating costs such as wage rates, insurance and fuel costs, the prices given in the review are the prices of the most common vehicle types provided in the market.

For the Straddle Bus, the infrastructure cost given by the inventor, Youzhou Song is 50 million RMB (year 2000 prices) per km for both directions. This price has been changed to GBP by using the PPP exchange rate between the UK and China as in Chapter 4. As there is no further financial resource available and the feasibility report of the Straddle Bus vehicle is not published, the vehicle cost is assumed to be 50% higher than the modern light rail, mainly due to the larger vehicle and greater capacity of the Straddle Bus.

D.3 Unit External Costs

The external costs of the public transport technology are related to the impacts to the environment (including air pollution, noise pollution and climate change effect) and the road accident. To deal with the uncertainty and the range of the data found in the previous study, three scenarios are given: low, central and high. The following table is shown in Chapter 4, which provides the default external unit costs used in this thesis in the SCM. This table is based on the works by Brand and Preston (2003), who summarised the study of various surface transport systems in Great Britain by Sansom et al (2001).

Categories	Technologies	Air pollution (pence/vkm)			Noise pollution (pence/vkm)			Climate change (pence/vkm)			Accidents (pence/vkm)		
		low	central	high	low	central	high	low	central	high	low	central	high
Small Vehicle Technology	Minibus	8.7[4]	16.5[4]	25.2[4]	1.3[4]	5.8[4]	6.9[4]	1.2[4]	1.5[4]	1.7[4]	0.3	1.7	3.2
	Personal Rapid Transit	0.7[5]	1.3[5]	2.4[5]	0.5[5]	1.1[5]	1.7[5]	0.4[5]	0.8[5]	1.5[5]	-	0.2	-
Conventional Bus	SingleBus	14.5	27.6	42.1	2.8	11.8	13.9	2.1	2.4	2.8	0.3	1.7	3.2
	ArtBus	17.4[1]	33.2[1]	50.6[1]	2.8	11.8	13.9	2.5	2.9	3.3	0.3	1.7	3.2
	DoubleBus	16.0[2]	30.4[2]	46.4[2]	2.8	11.8	13.9	2.2	2.6	3.0	0.3	1.7	3.2
	SingleBus on buslane	14.5	27.6	42.1	2.8	11.8	13.9	1.8[7]	2.1[7]	2.5[7]	0.3	1.7	3.2
	SingleBus on busway	14.5	27.6	42.1	2.8	11.8	13.9	1.8[7]	2.1[7]	2.5[7]	0.3	1.7	3.2
	SingleBus (Guided)	14.5	27.6	42.1	2.8	11.8	13.9	1.8[7]	2.1[7]	2.5[7]	0.3	1.7	3.2
	DoubleBus (Guided)	16.0[2]	30.4[2]	46.4[2]	2.8	11.8	13.9	2.1[8]	2.4[8]	2.8[8]	0.3	1.7	3.2
Light Rail Transit	"Guided Light Transit"	7.3[3]	13.9[3]	21.0[3]	1.8[6]	7.8[6]	9.2[6]	2.1[3]	2.4[3]	2.8[3]	0.3	1.7	3.2
	Straddle Bus	7.1	13.3	21.0	10.0	21.8	33.6	3.7	7.5	14.9	0.5	2.6	4.8
	Modern light rail	7.1	13.3	23.6	10.0	21.8	33.6	3.7	7.5	14.9	-	0.0	-
	LRV tracksharing	7.1	13.3	23.6	10.0	21.8	33.6	3.7	7.5	14.9	-	0.0	-
Heavy Rail Transit	Suburban heavy rail	4.5	12.3	23.2	12.2	26.2	40.2	4.2	8.6	17.0	-	0.0	-
	Regional heavy rail	5.5	14.0	25.8	4.9	10.6	16.2	4.5	8.9	17.7	-	0.0	-
	Underground	-	24.8	-	-	26.3	-	-	8.3	-	-	0.0	-

Note:
1. Assumed 20% higher local air pollution emissions (mainly PM10) than single bus, mainly due to higher weight and larger engines.
2. Assumed 10% higher local air pollution emissions (mainly PM10) than single bus, mainly due to higher weight and larger engines.
3. Assumed 50% lower local air pollution emissions than single bus, mainly due to hybrid-electric propulsion. Climate change impacts similar to articulated bus.
4. Assumed 40% lower local air pollution and climate change emissions than single bus, mainly due to smaller engines and lower weight.
5. Assumed to be 10% of light rail costs.
6. Assumed 33% lower noise emissions than single bus, mainly due to quieter hybrid-electric propulsion.
7. Assumed 10% lower CO_2 emissions per km than single bus due to less congested running and therefore better fuel consumption.
8. Assumed 10% higher CO_2 emissions per km than single bus due to increased weight and engine size but less congested running and therefore better fuel consumption.

(sources: adapted from Brand and Preston, 2003)

Air pollution cost

For the air pollution of buses, the health and non-health effects of the atmospheric emissions, including CO, CO_2, SO_2, NO_X, PM_{10} from the public transport vehicle are considered. The study by Sansom et al (2001) gives the air pollution costs of both petrol bus and diesel coach of 9 different speed band categories from < 10mph to > 61 mph by summarising the air pollution and health/non-health relationship studies of COMEAP (COMEAP, 1998) and ExternE (EC, 1995). The health effect includes the acute outcomes, chronic disease outcomes and reproductive outcomes from air pollution. The non-health effects include building soiling, material corrosion and crop damage.

For the air pollution from rail transport, the method is similar to the bus transport. The emissions of diesel train are considered, and the figures are taken from different train categories such as InterCity, PTE, Rural, Cross-country and London suburban.

These impacts from bus and rail transport to the local and regional health and air quality are then converted into monetary terms to obtain the air pollution cost. As the air pollution cost considers the emissions from the public transport vehicles, the more operating public transport vehicles and the more distance travelled by the vehicle will lead to greater pollution and cost. Therefore the air pollution costs are measured in pence per vehicle-kilometres. However, as the study does not involve all public transport technologies modelled in this thesis, assumptions are made and listed in the note of the above table.

Noise pollution cost

The noise pollution cost figures are taken from Sansom et al, 2001, which calculates the noise impacts of the bus and rail transport by using the recommended methods by Department of Transport/Welsh Office, 1988 and Department of Transport, 1995, respectively. The noise pollution costs are calculated based on the relationship of the average noise level of the public transport technology and the price of the property.

Similar to the air pollution, the noise pollution also considers the effects of the noise from the public transport vehicles only. The costs of the noise pollution are based on the number of operating vehicles and the distance travelled by the vehicle, and hence the unit of the cost is pence per vehicle-kilometres.

Climate change cost

The climate change cost measures damage costs of the amount of CO_2 emission from the public transport vehicle. The sources of the amount of CO_2 emission is the same as the air pollution, and the damage costs by the emission are valued as £7.3/tonne, £14.6/tonne and £29/tonnes, which are given by Sansom, et al (2001).

Note that, as the climate change cost only considers the CO2 emission from the public transport vehicle, excluding the number of passengers on board, the unit costs is related to the fuel type and the size of the vehicle rather than the capacity. As a result of that, the unit of the climate change cost is in pence per vehicle-kilometre.

Accident cost

The accident cost calculated in the SCM values the costs caused by the public transport vehicle which are taken from Brand and Preston (2002, 2003), based on the cost study by Sansom et al (2001). The cost consists of medical treatment cost, human cost (reduced quality of life and fatality) and lost output cost. To value the accident cost of different public transport technologies, Sansom et al (2001) used accident rates per vehicle-kilometres from the Road Accident Statistics (DETR, 1999) and then converted into monetary term by using the average value per casualty.

Note that there is no accident cost provided for the rail transport, which is the result of low accident rates of rail transport compared with conventional buses and there is no evidence that the introduction of rail will increase the accident rate of buses (Brand and Preston, 2002). Together with the demonstrated results in Chapter 7 that the average external cost is much lower than the average operator cost and the average user cost, the unit accident cost of rail transports are neglected.

It is also worth noting that the unit accident cost, as well as other unit costs used in the SCM is an optional parameter which can be changed by the user of the comparative assessment, if there is reliable value for the parameter for the selected public transport technology and transport network.

Straddle Bus assumptions

As there is no existing Straddle Bus system, the unit external costs of the Straddle Bus have to be assumed based on similar public transport technology and the proposed characteristics of Straddle Bus.

Compared with conventional buses, Straddle Bus has much greater capacity, size and it is able to operate above the general traffic to avoid congestion. As the environmental costs (air pollution, noise pollution and climate change) of the public transport are based on the vehicle and the units are pence/vkm, it is therefore assumed that the unit cost of air pollution, noise pollution and climate change of Straddle Bus are the same as the modern light rail technology. Although the assumed size and the capacity of Straddle Bus are greater than the modern light rail in the default value which could lead to higher unit environmental costs, Straddle Bus is proposed to be powered by electricity which reduces the environmental unit cost. Note that it is difficult to estimate the unit environmental cost of the system as there is no available source for the operation of Straddle Bus, and a crude estimation may cause inaccurate results. However, as the external cost only takes a very small percentage in the average social cost (as demonstrated in Chapter 7), and the purpose of this thesis is to develop a methodology to model the social cost of public transport technology, it is therefore assumed that the unit costs of air pollution, noise pollution and climate change of Straddle Bus are the same as the modern light rail.

For the unit accident cost, as the Straddle Bus is also operating on road surface and has interactions with other road users, it is assumed to be based on the cost of single-decker bus. To account for the greater vehicle size and hence greater lost output and human cost arise in an accident, a 50% top-up is assumed compared with single-decker bus.

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