UNIVERSITY OF SOUTHAMPTON

FACULTY OF ENGINEERING AND THE ENVIRONMENT

The Improvement of Bus Networks Based on Geographical Information Systems

by

Yuji Shi

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ABSTRACT

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The current regulatory and planning environment means that road-based public transport in UK urban areas (with the exception of London) tends to be planned on a piecemeal basis, and there are often conflicts between the needs and priorities of operators, passengers and planners. In consequence, several local authorities are considering adopting an alternative regulatory environment using quality contracts, with a consequent shift towards centralised service planning. There are though no tools readily available to ensure this centralised service planning will lead to a situation which provides a better balance between the interests of the different stakeholders. This thesis describes the development of a methodology to fill this gap, using Southampton as a case study to diagnose issues with its current bus network, and to explore the corresponding improvement methods which could be applied based on the alternative regulatory environment. Gravity-based accessibility levels from population-weighted centroids of postcodes to key services were calculated as an indicator to measure the performance of the current bus network in Southampton. Based on the accessibility analysis, service improvements, including both route planning and frequency setting, can be developed for the Southampton bus system under the alternative regulatory environment. This service improvement problem is then solved by making use of an optimisation technique, the tabu search algorithm, developed under the environment of ArcObjects for Java. The methodology described above has been shown to work well for the Southampton case study, and the outputs from the optimisation model indicate that the model can deliver a bus network which provides a higher level of accessibility under the alternative regulatory environment. While the methodology is developed in the UK context, the general principles used could be applied more widely to improve transit network planning.

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DECLARATION OF AUTHORSHIP

I, Yuji Shi

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.

The Improvement Of Bus Networks Based On Geographic Information Systems

I confirm that:

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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;
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Signed: ....

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Definitions and Abbreviations

ATOS	Access to Opportunities and Services
AWT	Average Waiting Time
BBAF	Better Bus Area Fund
BQPs	Bus Quality Partnerships
BRES	Business Register and Employment Survey
BSOG	Bus Service Operators Grant
CBTF	Clean Bus Technology Fund
CFR	Concessionary Fare Rebates
CSV	Comma-Separated Values
DCLG	Department for Communities and Local Government
DfT	Department for Transport
EDF	Equivalent Doorstep Frequency
GA	Genetic Algorithm
GIS	Geographic Information System
GP	General Practitioner
ITN	Integrated Transport Network
IVT	In-Vehicle Time
LNS	Large Neighbourhood Search
LSTF	Local Sustainable Travel fund
LTP	Local Transport Plan
NaPTAN	National Public Transport Access Nodes
NOC	National Oceanography Centre

NPTDR	National Public Transport Data Repository
NPPF	National Planning Policy Framework
NP-Hard	Non-Deterministic Polynomial-Time Hard
NS	Neighbourhood Search
OA	Output Area
O-D	Origin-Destination
OS	Ordnance Survey
POI	Points of Interest
PPG13	Planning Policy Guidance Note 13
PT	Public Transport
PTS	Public Transport Support
PTALs	Public Transport Accessibility Levels
QCS	Quality Contract Scheme
SA	Simulated Annealing
SAPs	Service Access Points
SWT	Scheduled Waiting Time
TAT	Total Access Time
TEC	Total External Cost
TfGM	Transport for Greater Manchester
TfL	Transport for London
TFP	Total Factor Productivity
TfSH	Transport for South Hampshire
TNDP	Transit Network Design Problem
TNDS	Traveline National Dataset

TNP	Transit Network Planning
TOC	Total Operator Cost
TSC	Total Social Cost
TS	Tabu Search
TUC	Total User Cost
TXC	TransXChange
WebTAG	Web Transport Analysis Guidance
WKT	Walking Time
WTT	Waiting Time

Chapter 1: Introduction

1.1 Introduction and Motivation

Urban growth is driving continued demand for transport within many cities, and the consequent growth in congestion together with environmental and fiscal pressures means that the provision of effective and efficient public transport services is of crucial importance in supporting urban economies and societies. While rail-based metro systems are often seen as being a first choice option to enable such provision, the high cost of constructing and operating such systems mean that in the majority of cities there will be a continued role for extensive bus networks. Such networks can, in the right circumstances, be extremely effective in moving large numbers of people efficiently from one place to another. However, public perception of bus travel tends to be rather mixed, with buses perceived as being an 'inferior' mode of transport in some areas and amongst certain social groups. This problem is exacerbated in some contexts by a lack of regulation or coordinated planning, with bus routes planned and timetabled on a piecemeal basis with little consultation between different service providers. This can be compounded by the conflicting motivations for operating bus services which exist in unregulated environments, with profit-making not always well-aligned with optimal service provision. Recognition of these issues has led to a renewed interest in integrated planning for public transport services in a number of areas around the world. However, methodologies to determine what a well-integrated customer-focused public transport network in a given area would look like are in short supply. This thesis describes the development of a methodology to help fill this gap by optimising bus network structure to provide maximum accessibility to key services. While the application described here focuses on the British context, the general principles could be applied equally well in other contexts around the world.

1.2 Structure of British Bus Operations

Based on the *Transport Act 1985*, the previously road service licensing system which imposed quantity control on bus service supply was replaced by a route registration system from 26th October 1986, known as the 'D-Day' within the industry (Preston and Mackie, 2003). According to the new registration system, operators merely had to register their plans to operate a route 42 days (subsequently increased to 56 days) before operations commenced. This ended a regulatory system of quantity control that had been in existence since the *Road Traffic Act* in 1930, and meant that the quantity supply of bus services in Great Britain outside London was deregulated.

The legislation enabling deregulation also made provision for the privatisation of publicly owned bus companies, although this was implemented over a longer time period (Hibbs and Higginson, 2013).

Instead of deregulation, the London bus market retained its regulated system with competitive tendering gradually introduced from 1985 to 1994 (Preston and Mackie, 2003). According to the *London Regional Transport Act* passed in 1984, tendering was organised by the Tendered Bus Division of London Transport and the Group Planning Department of London Transport. Both of them decided which set of routes to put out to tender and service specification for each tender, which includes vehicle capacity, the minimum number of departures per time period, and the streets and bus stops to be used on the services (Kennedy, 1995). Compared with the rest of Great Britain, the bus services in London therefore were not deregulated to the same extent. Instead, the Act created a system of franchised routes operated by private companies but managed by London Transport. The first run of bus tendering started in 1985, with only 1.2% of the London bus network. During the next nine years, the remaining network was totally sold off, and the competitive tendering process of London bus network completed (Kennedy, 1995).

As a result, current London's bus network is unique in the mainland United Kingdom in that it is operated under a fully regulated environment. London Bus Services Limited (London Buses) is part of Transport for London (TfL), and manages bus services in London. It plans routes, specifies service levels and ensures services quality. It is also responsible for bus stations, bus stops and other support services. The bus services are operated by privately owned operating companies, which work under quality incentive contracts to London Buses by tendering process (Transport for London, 2008). In contrast, the bus networks of the areas outside London are operated under the deregulated environment. Local authorities only provide infrastructure (such as bus stops, bus lanes and so on) and underwrite supported services (such as early morning and late evening services, and services which serve less accessible parts of the country and are not capable of being operated commercially). Operators have freedom to plan routes and set timetables by themselves although they need to register services with local authorities.

The idea behind the deregulation process was that competition, or the threat of competition, could provide a more efficient service and a lower cost for both operators and users (Davison and Knowles, 2006). Almost thirty years have passed after the 'D-Day' in 1986, and performances in both London and the areas outside London after the reforms have been traced and analysed by many research papers, such as Kennedy (1995), Mackie et al. (1995), White (1995), Preston and Mackie (2003), Almutairi (2013), and Preston and Almutairi (2013). Results output from these research have demonstrated that although deregulation increased local bus supply, drove some reductions in operating costs, and helped to cut subsidies, it has not delivered all the predicted benefits. For example, the competitive market produced by deregulation was assumed to be more customer-attractive, through more services available in the network and lower fares, but it continues to lose customers after deregulation in reality. According to the data from *Bus Statistics* (Department for Transport, 2016b), the bus market outside London in total lost 35% of journeys during the past three decades, while the usage of the London bus market has doubled (see Figure 1-1). More detailed comparisons of bus market performances in both London and areas outside London after the mid-1980s reforms could be found in section 2.2.

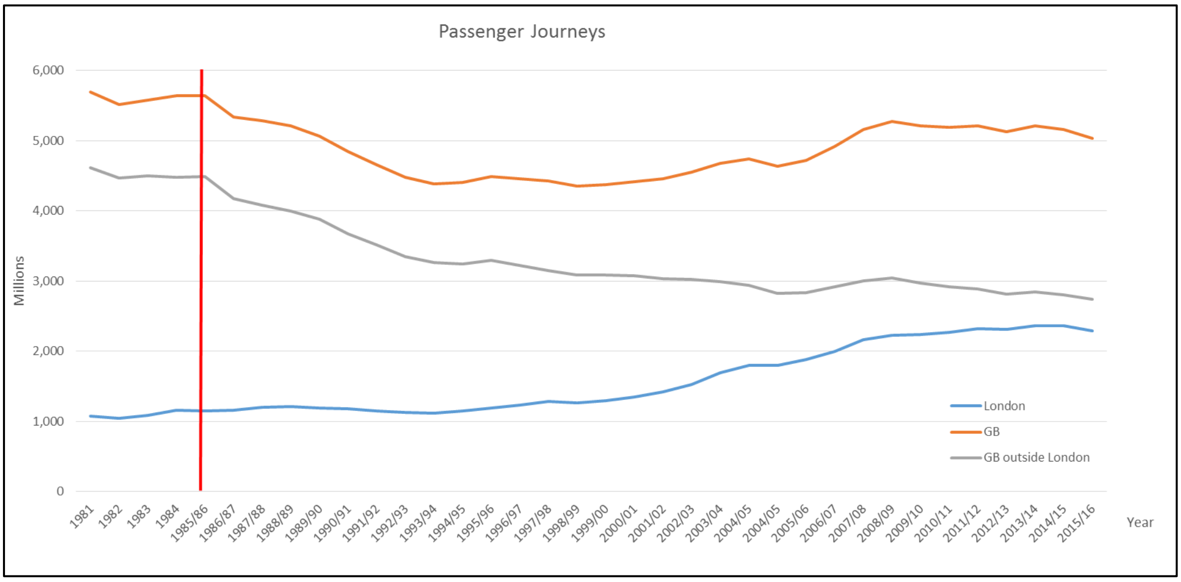

Figure 1-1 Trends in Bus Demand after the Deregulation

Furthermore, deregulation made it very difficult for transport planners to maintain coherent and integrated public transport systems within particular areas, with for example competition legislation limiting the potential for network-wide ticketing structures. The results of welfare analysis by Preston and Almutairi (2013) also provide some relatively strong evidences that deregulation led to a reduction in overall welfare compared to the system of regulation in London (in other words, competition for the market is preferable to competition in the market).

In order to reverse the current shrinking bus markets in areas outside London, the *Transport Act 2000* and *Local Transport Act 2008* have provided some potential solutions, such as Bus Quality Partnerships (BQPs) and Quality Contracts (more detailed information on BQPs and Quality Contracts is available in section 2.4. The idea behind these solutions is to introduce centralised planning for bus services, thus effectively reproduce the structure that exists in London across the rest of country. According to the success achieved by London bus market, BQPs and Quality Contracts are considered as solutions to overcome disadvantages of deregulation, and have been developing widely across the country. Between 2011 and 2015, DfT awarded funding to 96 BQPs from 77 local authorities between 2011 and 2015 (Ricci et al., 2016). Although there are no formal legislative Quality Contract schemes in operation at the time of writing, many local authorities are currently actively pursuing them, such as North East Combined Authority, Greater Manchester Combined Authority, West Yorkshire and Merseyside (pteg, 2014). There are though no tools readily available to ensure this centralised service planning will lead to a situation which provides a better balance between the interests of the different stakeholders. This thesis describes the development of a methodology to fill this gap, using Southampton as a case study to explore what improvements in bus services could be obtained under the alternative regulatory environment, and to compare the performance of bus networks under both regulatory scenarios to evaluate the potential of centralised service planning to improve public transport in UK urban areas outside London.

1.3 Research Objectives

The overall aim of this thesis is to evaluate the potential of centralised service planning to improve the accessibility levels of public transport in UK urban areas outside London. This research aim will be achieved by meeting the following objectives:

1) To develop an evaluation methodology to assess the performance of current bus networks. This is covered in Chapter 5.
2) To generate a practical methodology to explore improvement methods for bus networks, including both bus route design and frequency setting, for current bus networks under a fully regulated environment. This is covered in Chapter 6.
3) To build and test an automated model to assess potential improvements to networks, which is made up of both evaluation model and optimisation model. This is covered in Chapters 5, 6, and 7.

1.4 Methodology

Based on the research aim and objectives listed above, two key components are involved in the process of assessing the potential of centralised planning of bus services in UK urban areas outside London: an evaluation model to evaluate the performances of current bus networks, and an optimisation model to explore the corresponding improvement methods under the alternative regulatory environment (see Figure 1-2). The performance of the current bus network will be measured based on the level of accessibility it provides to a set of key services. For each potential origin point, defined as population-weighted centroids of postcodes, gravity-based accessibility level is calculated to represent its ability to access key services, such as schools, GPs, city/town/district centres, employment centres, and open spaces, through the current public transport network. After that, a practical optimisation model is developed to explore the potential improvements, including both route planning and frequency setting, which could be achieved with centralised planning of bus networks using an adapted tabu search algorithm. The methodology of the improvement approach is to minimise total social cost, which is a combination of operator cost, user cost and external cost, subject to a variety of constraints which reflect system performances and/or resource limitations. The final output of the optimisation model is then a more optimal bus network as measured by total social cost, consisting of a set of bus routes with associated frequencies.

Both the evaluation model and optimisation model have been developed under the environment of ArcObjects for Java based on the methodology described above. An real-world city-scale public transport network, the Southampton case study, was chosen to test the performances of the models, and the outputs indicate that the models can deliver a bus network which provides a higher level of accessibility under the alternative regulatory environment. Because it makes use of widely available input data, this developed methodology could be easily applied to any public transport network in Great Britain, and potentially also in other contexts around the world.

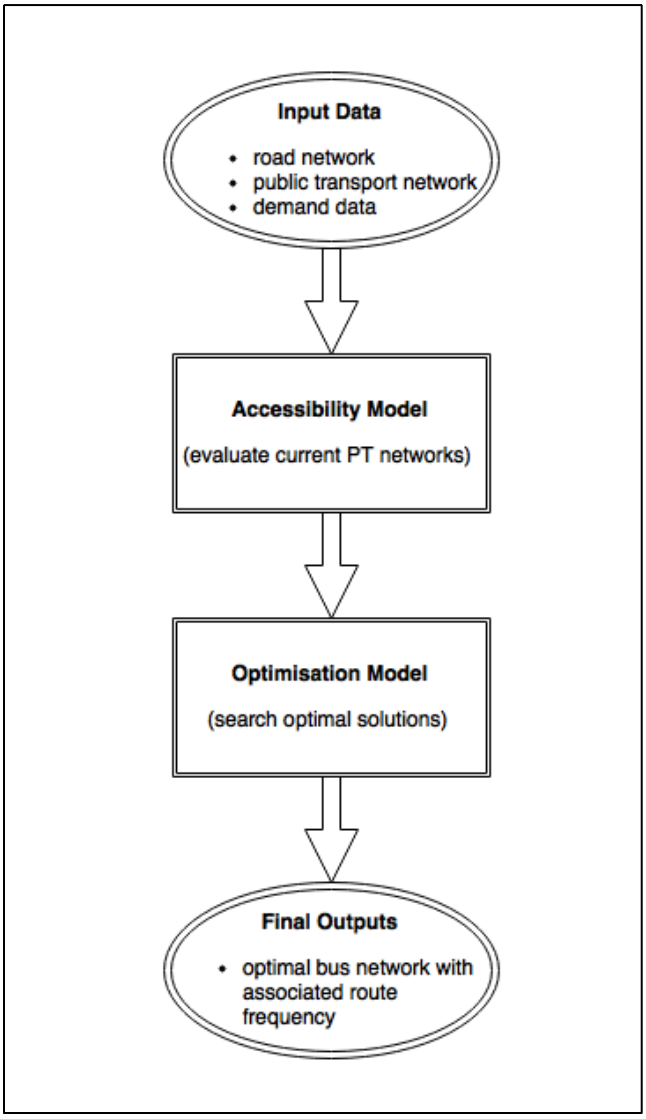

Figure 1-2 Methodology

1.5 Thesis Structure

Following the introduction contained in this chapter, the remainder of this thesis has been divided into 7 chapters. The contents of each chapter are summarised below to provide a brief introduction and guide through the dissertation.

Chapter 2: Background: Bus Deregulation

Chapter 2 is an introductory chapter which provides more detailed background information on the current contrasting regulatory systems adopted in London and rest of country. The performances of the two contrasting systems are traced and compared after the mid-1980s policy reforms, and some key policy developments (such as Bus Quality Partnerships and Quality Contracts) after the reforms are also discussed in this chapter.

Chapter 3: Review of Evaluation Measures for Bus Network Performance

Chapter 3 reviews the previous studies of accessibility models. A four-step process of designing accessibility models is displayed in this chapter together with a comparison of available accessibility measures. Each category of them is traced respectively, and their advantages and shortcomings are compared and discussed as well.

Chapter 4: Review of Optimisation Models for Public Transport Networks

Chapter 4 reviews published literature on optimising public transport networks, and focuses on three key components of formulating the optimisation model: objective function and constraints, demand and passenger behaviour modelling, and solution techniques. The shortcomings of these available optimisation models are summarized and discussed at the end of this chapter.

Chapter 5: Accessibility Model

Chapter 5 focuses on building an accessibility model to evaluate the performance of bus services by calculating gravity-based accessibility levels from population-weighted centroids of postcodes to key services (including education, health, city/town/district centres, employment centres, and open spaces). Detailed information on data preparation, methodology, and procedures of model building are represented in this chapter.

Chapter 6: Optimisation Model

Chapter 6 focuses on exploring improvement methods, including both route planning and frequency setting, for bus services based on the alternative regulated environment using an adapted tabu search algorithm. Details of data preparation, model formulation, and methodology can be found in this chapter.

Chapter 7: Case Study Application

In this chapter, a real-world city-scale bus network, the current Southampton bus network, is selected as a case study, and is implemented to the accessibility model, as well as the optimisation model. Output results are carefully represented and discussed in this chapter.

Chapter 8: Conclusions

Final chapter summarises and discusses the results obtained so far, highlights main achievements, and recommends some priorities for further research.

Chapter 2: Background: Bus Deregulation

2.1 Introduction

By the *Transport Act 1985,* bus markets in Great Britain outside London were deregulated. Operators could freely enter the market by previously registering their services. Privatisation and subsidy reduction occurred together with the deregulation (Preston and Mackie, 2003). Instead of deregulation, the London bus market retained its regulated system with competitive tendering gradually introduced from 1985 to 1994 (Hibbs and Higginson, 2013). Therefore, there are two totally different planning and operating systems available in current bus networks in Great Britain: the bus market in London retains its regulated system, while the rest of country has a deregulated system. The contrasting regulatory systems adopted in London and rest of country have given opportunities for researchers to compare and evaluate the performance of them. This introductory chapter therefore traces and compares the performance of the two contrasting systems, and outlines some key policy developments after the mid-1980s policy reforms.

The remainder of this chapter therefore is divided into four sections. International context of regulatory reforms is displayed in section 2.2, including the deregulation (‘*competition on the road*’), the competitive tendering (‘*competition off the roa*d’) and the hybrid option. In section 2.3, the performances of both London and areas outside London bus markets between 1981/82 and 2014/15 are compared with respect to supply, demand, subsidy, operating costs, and fares. Some potential solutions to overcome disadvantages of deregulation, including Bus Quality Partnerships (BQPs) (both voluntary and statutory) and Quality Contracts, are discussed in section 2.4. The final section summarises the whole chapter.

2.2 International Context of Regulatory reforms

Since the 1980s, regulatory reforms in public transport sector subsequently spread in many countries of the world. This has led to the emergence of two alternative market structures, which can broadly be classified as ‘*competition on the road*’ and ‘*competition off the roa*d’. The ‘*competition on the road*’ gives operators the freedoms to design services as they like, while the ‘*competition off the road*’ usually specifies very tightly the services to be provided. Detailed information on the regulatory reforms and corresponding global examples have been summarized and compared in research by Cox et al. (1997), Cox (2004) and Van De Velde (1999 and 2015). In this section, three main categories of the regulatory reforms will be described below in turn: the deregulation (‘*competition on the road*’), the competitive tendering (‘*competition off the roa*d’) and the hybrid option.

2.2.1 The Deregulation Option

The deregulation in public transport markets is defined as the process of enhancing freedoms for the operators in terms of the determination of their service characteristics and production process (Van De Velde, 1999 and 2015). The process of deregulation usually includes the process of liberalisation and privatisation. Liberalisation is defined as the process of allowing other operators than the incumbent to access the market, while the privatisation is the process of transferring the ownership of a company or agency from a public sector (such as national or a local government) to a private sector (Van De Velde, 1999 and 2015).

The most well-known example of the deregulation is the current local bus markets in Great Britain outside London (Van De Velde, 2015). Bus services in Great Britain outside London were deregulated in October 1986, with the previous system of road service licensing (which imposed quantity control on bus service supply) replaced with a system where operators merely had to register their plans to operate a route 42 days (subsequently increased to 56 days) before operations commenced (Preston and Mackie, 2003). This permitted full inter-operator ‘on the road’ competition for passengers, which led to major changes in service patterns and frequencies in many areas. While deregulation helped increase local bus supply, drove some reductions in average operating costs, and cut subsidies, it also tended to lead to increased fares and inadequate regulation for poor quality operators to become established in some areas of the country (Hibbs and Higginson, 2013; Preston and Almutairi, 2013). Consequently, although the competitive market produced by the deregulation was assumed to be more customer-attractive, it continues to lose customers after the deregulation in reality. According to the data from *Bus Statistics* (Department for Transport, 2016b), the bus market outside London in total lost 35% of journeys during the past three decades after the deregulation in 1986. Other examples of the deregulation include the deregulation of the long distance coach market in Great Britain in 1980, and local bus markets in New Zealand in 1989 (Van De Velde, 2015).

2.2.2 The Competitive Tendering Option

Under the competitive tendering option, local authorities retain full control over policy, routes, schedules, fares, vehicles and service standards, while operators provide the services by competing in formal tendering procedure for public transport contracts (Cox et al., 1997; Cox, 2004). Some contracts specified very tightly the services to be provided (by route-level contracts), restricting the possibility for operators to efficiency improvements and innovation in service production, while others gave operators more freedom in service design (by sub-area contracts) (Van De Velde, 2015).

Examples of route-level contracts that define very precisely the services to be provided are the bus contracts tendered in London, Copenhagen, more generally in Denmark and Sweden, and a few cases in Germany (Cox et al., 1997; Cox, 2004; Van De Velde, 2015), and the typical London and Copenhagen case studies were discussed below.

In contrast with the deregulated networks in the rest of Great Britain, the London bus market retained its regulated system with competitive tendering gradually introduced from 1985 to 1994 (Preston and Mackie, 2003; Kennedy, 1995). As a result, current London's bus network is unique in the mainland United Kingdom in that it is operated under a fully regulated environment. London Bus Services Limited (London Buses) is part of Transport for London (TfL), and manages bus services in London. It plans routes, specifies service levels and ensures services quality. It is also responsible for bus stations, bus stops and other support services. The bus services are operated by privately owned operating companies, which work under quality incentive contracts to London Buses by tendering process (Transport for London, 2008). Compared with the shrinking bus markets in areas outside London, the demand in London bus market kept increasing during the past three decades. According to the data from *Bus Statistics* (Department for Transport, 2016b), the number of passenger journeys has doubled during 1985/86 and 2015/16.

The competitive tendering of Copenhagen bus market (involving approximately 1200 buses, with annual ridership of approximately 260 million) started in 1989. The law originally prohibited the government-owned operating agencies from participating in tendering, as lawmakers were concerned that the local authority could not objectively administer a process in which it was also a bidder. Later, once the government-owned operating agencies were sold to private companies, the prohibition was lifted. The whole tendering process was completed in 1995 (Cox et al., 1997; Cox, 2004). The competitive tendering not only helped to cut down the operating cost (declines in operating costs occurred mostly during the period of tendering, with 24% operating cost savings per vehicle-kilometre), but also reversed the falling ridership trend in Copenhagen bus market (patronage has risen 9% during the period of tendering) (Cox et al., 1997; Cox, 2004).

The alternative sub-area tendering contracts are organised at the level of small networks (sub-areas) instead of at the route level, and thus could give operators more freedom to re-design the services in their area of operation (Van De Velde, 2015). Corresponding examples are available in the Netherlands, France, and Australia (such as Adelaide, Melbourne and Perth) (Radbone, 1997; Wallis and Bray, 2001), and the typical Adelaide case study were discussed at this section.

Bus services in Adelaide, South Australia, were regulated and operated by the Government until 1995. Since then all the bus services (approximately 760 buses and 49.6 million passengers per year) have been competitively tendered (by two stages of tendering) and now operate by private operators (Radbone, 1997; Wallis and Bray, 2001):

- Stage1 tendering (1995-1997): services were contracted out primarily on an area basis, with ten areas and four route contracts. Half of the bus services were tendered out in this tendering stage, while the remaining services were provided by the Government through negotiated contracts.
- Stage2 tendering (1999-2000): all the services were tendered out, including re-tendering of those previously tendered in stage1.

The Adelaide experience provides clear evidence of the effectiveness of competitive tendering in reducing the operating costs and public subsidies (Bray and Wallis, 2008). According to the data from *Urban Public Transport: Updated Trends* (Department of Infrastructure and Regional Development [AU], 2014), the tendering has helped to save around 30% of the operating costs in Adelaide. Although the competitive tendering helped to stop the long-term declining trend (declining by 2.5% per annum before 1995) in bus patronage in Adelaide, it has not attracted more customers as predicted (the number of bus patronage remained approximately constant at 50 million during 1995 and 2014) (Department of Infrastructure and Regional Development [AU], 2014).

2.2.3 Hybrid Options

Some real-world examples do not always exactly fit in the classification options presented above, and two British examples were given at this section to illustrate this point. The first hybrid case study is the 'social' bus services in Great Britain outside London, usually additional evening and Sunday services together with services to rural areas or very low population density areas, which are not provided on a commercial basis by market initiative (Van De Velde, 1999). These 'social' bus services are complements to the current commercial bus networks generated based on the deregulation environment in Great Britain outside London, and could help to deliver an integrated bus network with more equal network distribution. The second hybrid option is to introduce a share of free-market (deregulation) in regimes based on monopoly regulation (Van De Velde, 2015). This hybrid option gives freedoms of network design to operators, but these freedoms are limited by the minimum standards defined by local authorities (Van De Velde, 1999). The best example of this hybrid option is the deregulation process of the British Rail (Van De Velde, 1999 and 2015).

2.3 Changes in Bus Markets after Deregulation

According to the classification of the regulatory reforms presented above, there are two totally different planning and operating systems available in current bus networks in Great Britain: the bus market in London retains its regulated system, while in the rest of country this has been replaced with a deregulated system. The contrasting regulatory systems adopted in London and rest of country have given opportunities for researchers to compare and evaluate the performance of them. This section therefore traces and compares the performances of the two contrasting systems.

Based on the research by Preston and Almutairi (2013) and the data from the DFT's *Bus Statistics* (Department for Transport, 2016b), five measures were chosen to trace the performance of the bus market in Great Britain between 1981/82 and 2014/15, including local bus supply (measured by vehicle kilometres), local bus demand (measured by passenger journeys), subsidy trends, operating costs (measured by pence per vehicle kilometre) and fares trends (measured by receipts per passenger). Due to the difference between London and the areas outside London, performances of both bus markets are traced and compared respectively.

2.3.1 Local Bus Supply

The index used to quantify the local bus supply in Great Britain is vehicle-kilometres. Although vehicle-kilometres vary both spatially and temporally, the whole bus market of Great Britain supplied more services during the past thirty years, with a total of 25% increase between 1981 and 2014/15. According to Figure 2-1, there is a large increase in the supply of bus market in Great Britain outside London in 1986. The large increase in 1986 is due to the deregulation, while the London market did not see a similar increase (Preston and Mackie, 2003). After that, the service supply in Great Britain outside London continued to increase in the 1990s, followed by a slow declining trend since 2000 although there is a slight increase between 2005/06 and 2008/09 (due to the introduction of concessionary fare scheme since 2006). While the supply of bus market in London has a stable increasing trend for the two decades from 1981, and has remained approximately constant at 500 million per vehicle-kilometres from 2004/05.

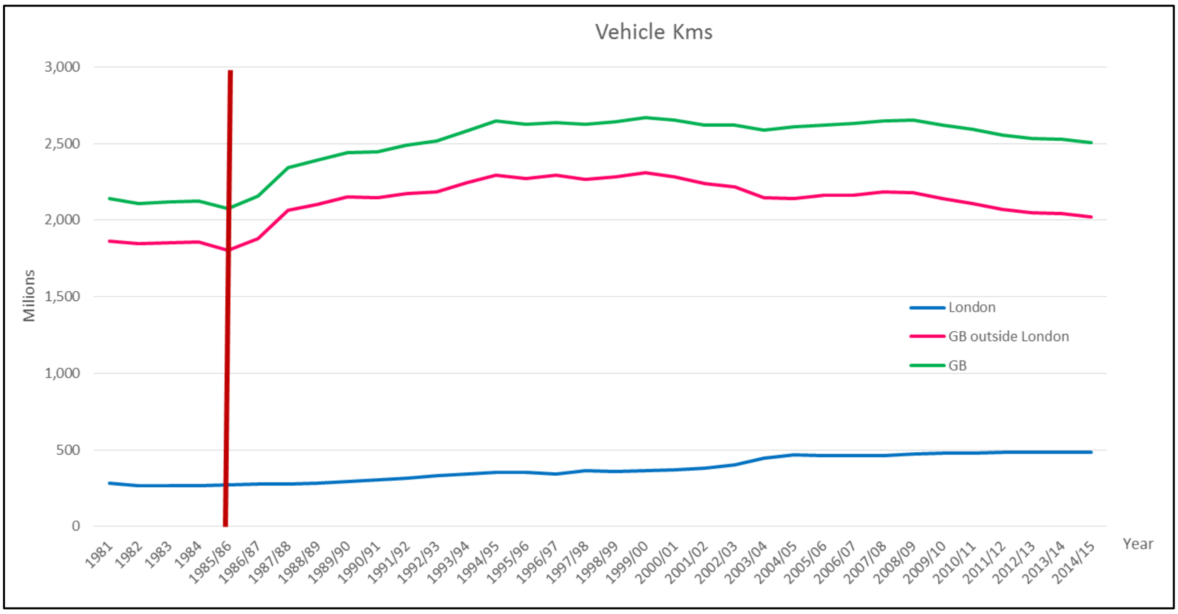

Figure 2-1 Local Bus Supply (London v.s. GB outside London)

Data Source: *Bus Statistics* (Department for Transport, 2016b), table BUS 0203[1].

The deregulation has contributed to a moderate increase in service supply, but it also resulted in a large degree of concentration in service supply. Although there are more than 1000 local operators in Great Britain outside London, the 'big five' bus groups (i.e. Arriva, FirstGroup, Go-Ahead, National Express and Stagecoach) accounted for 69% of all provided local bus services and 71% of total operating revenue in 2011 (British Competition Commission, 2011). At local level, most areas have only one or two operators with a significant share or supply: the average service proportion provided by two largest local operators is around 86% (British Competition Commission, 2011).

Figure 2-2 illustrates the geographic distribution of the 'big five' operators, middle-sized non-municipal operators[2], middle-sized municipal operators [3]and small operators across local authorities in Great Britain. Block colors illustrate areas where the indicated operator is the principal supplier of local bus services in that area (making up 61% of all local authorities). The principal supplier is defined as the largest local operator has a share of supply which is at least 35%

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[1] Table BUS 0203: vehicle distance travelled (miles and kilometres) on local bus services by metropolitan area status and country: Great Britain, annual from 1970. Available at: https://www.gov.uk/government/statistical-data-sets/bus02-vehicle-distance-travelled.

[2] Middle-sized non-municipal operators: largest independent operators, i.e. EYMS, Wellglade, Rotala, Transdev and Veolia Transport UK Ltd (Veolia).

[3] Middle-sized municipal operators: Operators which are wholly or majority owned by local authorities are classified as municipal operators, such as Lothian Buses, Nottingham City Transport, Cardiff Bus, Reading Transport, Blackpool Transport, etc.

higher than the share of supply of the next largest operator in that authority. If the largest operator could not hold this condition, and the second largest operator in a local authority has a supply share of at least 20%, the identity of the second operator is shown with hatched shading (accounting for 28% of all local authorities). Black shading indicates areas where three operators operate 20% or more of local bus services in an area (accounting for 2% of all local authorities). Other areas, where no operator has a share of supply that is 35% more than another operator, and no two or three operators have a share of supply of 20% or more, are shaded grey.

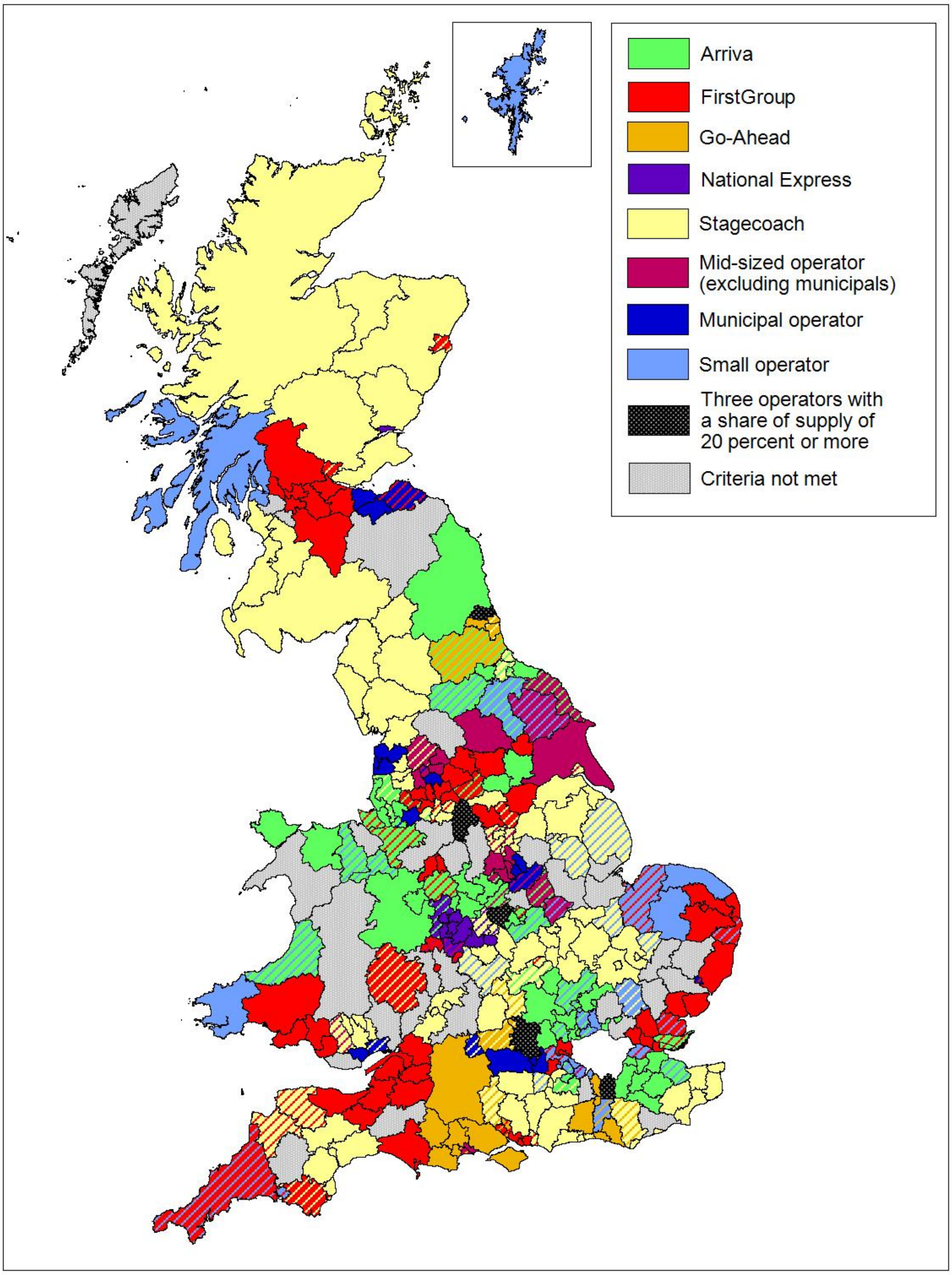

Figure 2-2 Geographic Distribution of Operators

Source: *Local Bus Services Market Investigation* (British Competition Commission, 2011), Figure 2.9.

2.3.2 Local Bus Demand

In this section, the passenger journeys are used to represent the trends of local bus demand.

Figure 2-3 suggests that London has outperformed the rest of Great Britain in terms of passenger journeys. The demand in the London bus market kept increasing during the past three decades: in the 1980s, the demand kept stable; it started to increase from the early 1990s, followed by a sharper growth in the 2000s. As a result, the size of the London bus market has doubled during the past thirty years. However, the market outside London has not performed as well: there was a moderate decline in 1980s and 1990s, then the demand kept stable at around 3 billion passenger journeys since the year 2000. As a result, the bus market outside London in total lost 35% of passenger journeys between 1981 and 2014/15. An acceleration of decline can be found in the trend line around 1986 when deregulation was introduced. The idea behind the deregulation process was that competition, or the threat of competition, could provide a more efficient service, thus could attract more passengers (Davison and Knowles, 2006). In terms of the loss of the passenger journeys, the deregulation process did not deliver its predicted benefit. Although the introduction of free concessionary travel scheme since 2006 contributed to a slight increase in demand between 2005/06 and 2007/08, it did not have a long-term impact on saving the shrinking bus market outside London.

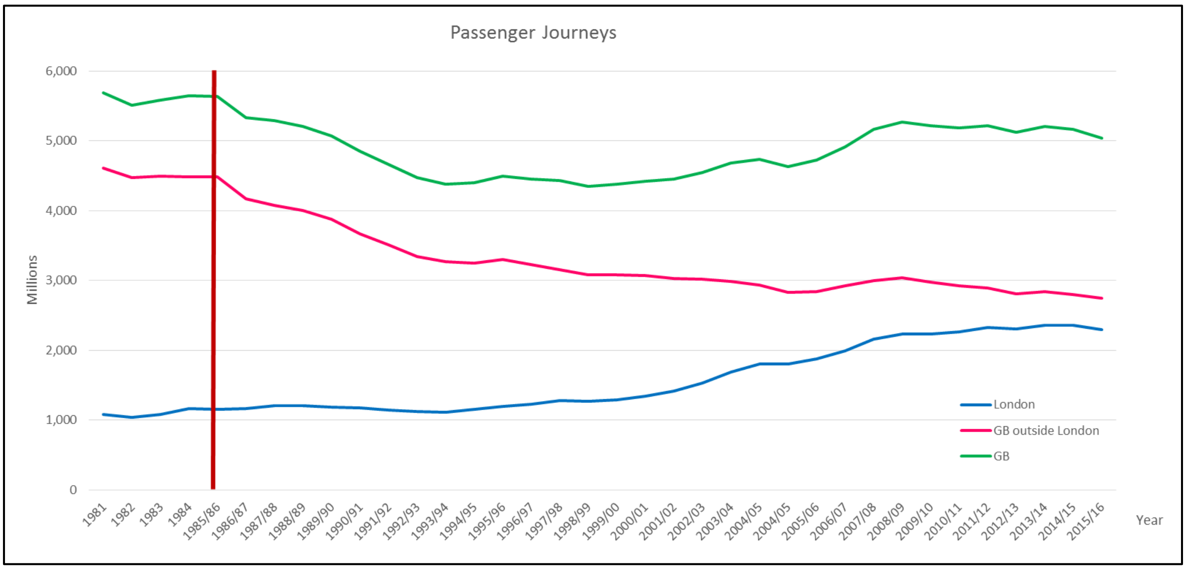

Figure 2-3 Local Bus Demand (London v.s. GB outside London)

Data Source: *Bus Statistics* (Department for Transport, 2016b), table BUS 0103[4].

[4] Table BUS 0103: passenger journeys on local bus services by metropolitan area status and country: Great Britain, annual from 1970. Available at: https://www.gov.uk/government/statistical-data-sets/bus01-local-bus-passenger-journeys.

2.3.3 Trends in Subsidy

In this section, the subsidy is defined as Concessionary Fare Rebates (CFR)[5]and Public Transport Support (PTS)[6], excluding Bus Service Operators Grant (BSOG)[7](previously Fuel Duty Rebate) (Preston and Almutairi, 2013). According to Figure 2-4, the total trends of subsidy in Great Britain outside London can be divided into three stages: In the early 1980s, the total subsidy of bus services exceeded £1.25 billion; during the late 1980s and 1990s, the bus subsidy subsequently came down very sharply, especially when deregulation was introduced in 1986; from the 2000s, there is an upturn. In London, the subsidy declined with some fluctuation during the 1980s and the 1990s, followed by a sharp increase in the 2000s. The subsidy upturns in the 2000s are followed by the introduction of free bus travel in England for over 60s and eligible disabled people between 09:30 am and 11:00 pm Monday to Friday and all day on Saturdays and Sundays since 2006, followed by a national scheme which extended free travel for concessionaires to any journey on a local bus in England since April 2008 (Baker and White, 2010). Furthermore, the service expansion in the London market due to the introduction of the congestion charge scheme in 2003 (according to the data from TfL, 300 more buses (accounting for 4% of the total fleet size) were added into the network on the launch date of the London congestion zone) also contributes to the subsidy upturns in London in the 2000s.

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[5] Concessionary Fare Rebate: a total of all local authorities' net costs of statutory or discretionary concessionary bus travel (including related administration costs).
[6] Public Transport Support: a total of all local authorities' gross costs incurred in support of bus services, either directly or by subsidies to operators or individuals.
[7] Bus Service Operators Grant (previously Fuel Duty Rebate): a subsidy provided by Central Government to operators of local bus services.

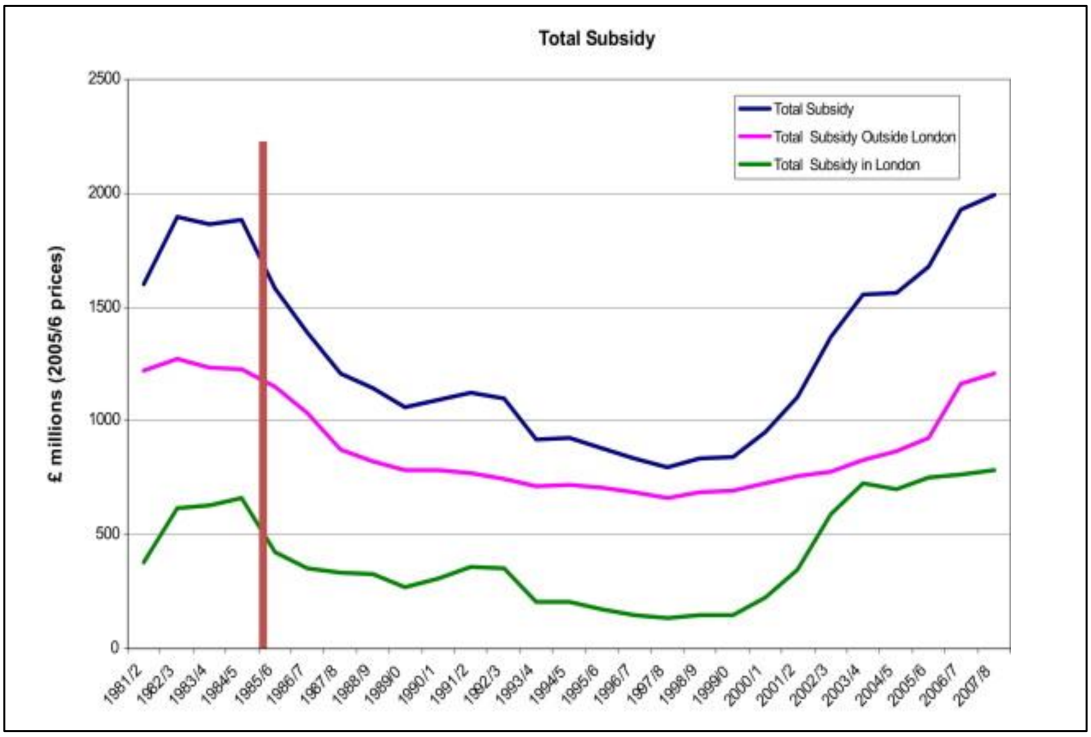

Figure 2-4 Trends in Subsidy (London v.s. GB outside London)

Source: Evaluating the long term impacts of transport policy: an initial assessment of bus deregulation (Preston and Almutairi, 2013), p.211. Fig.5.

2.3.4 Operating Costs

In this section, pence per vehicle kilometre is chosen as an index to represent the trends of operating cost. According to Figure 2-5, the operating costs per vehicle kilometre are substantially higher in London than the rest of country. Due to their different operation environments, the comparisons on operating costs between London and the rest of the country have little meaning (Department for Transport, 2016b). Furthermore, the results might differ if choosing other measurement indices, such as operating costs per passenger kilometres.

Illustrated by Figure 2-5, the operating cost trends of the bus market in both London and the rest of Great Britain outside London are similar: declining in the 1980s and the 1990s, and increasing in the 2000s. Declines in operating costs in London occurred mostly during the period of competitive tendering (from 1985 to 1994), with two dips: one in 1985/6 (when tendering was first introduced), and another one in the early 1990s (due to the privatisation of London Buses Limited). The savings on operating costs in Great Britain outside London in 1980s and 1990s mainly come from savings on fuel and labour (White, 1995). The Fuel Duty Rebate (lately the Bus Service Operators Grant) help to save more than half of the fuel costs for local bus companies, although this is not directly linked to deregulation. The savings on labour came from increasing labour productivity and lower wage levels. Although there are some upturns in the 2000s, the operating costs are still below the level they were at before deregulation in both areas: 40% decline in London and 20% less in other areas. In terms of cutting operating costs, the tendering process adopted in London market therefore is more effective than the deregulation in the rest of country.

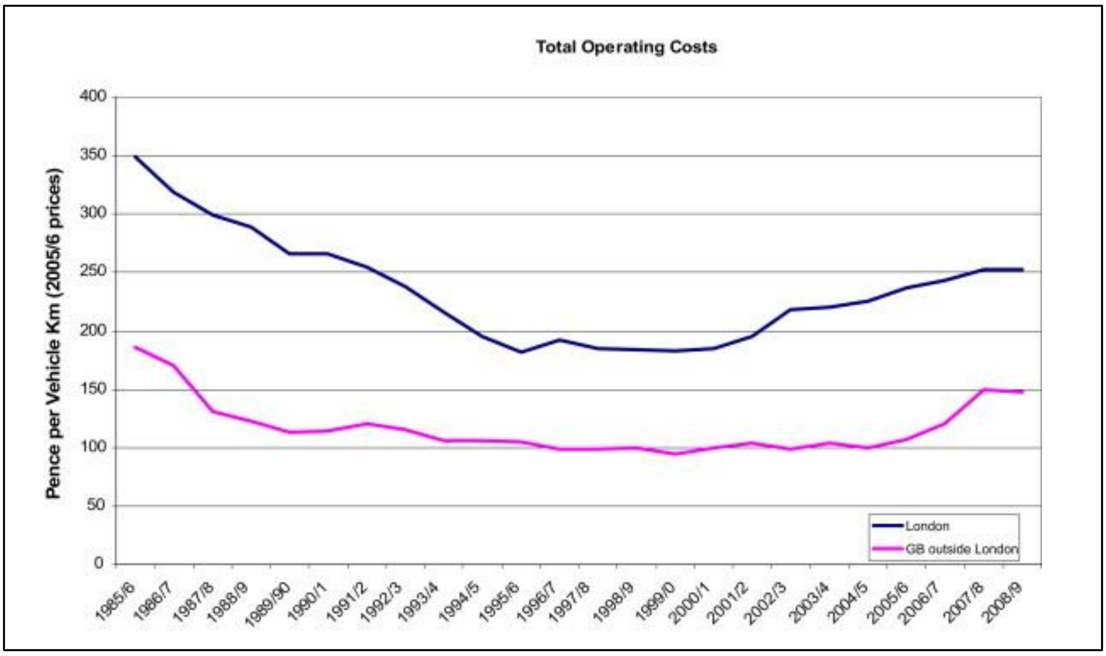

Figure 2-5 Trends in Operating Costs (London v.s. GB outside London)

Source: Evaluating the long term impacts of transport policy: an initial assessment of bus deregulation (Preston and Almutairi, 2013), p.211. Fig.4.

2.3.5 Trends in Fares

In this section, receipts per passenger is chosen as an index to trace fare trends in Great Britain, although it will be distorted by changes in trip length, fare structure (travel cards or multi-journey tickets), and concessionary travel arrangements for the elderly and children (who account for a large proportion of bus travellers). The bus market of Great Britain outside London witnessed an increasing fare trend, with a total of 60% increase during the past three decades (see Figure 2-6). With some fluctuation, the fares in London increased at a slower rate than the rest of areas in Great Britain, with a total increase of 20%. Furthermore, there are two valleys in the trend line of London: one in 1983/4 (because of the introduction of the travel card), and another one in 2003/4 (Preston and Mackie, 2003). The real reason for the increasing fare trends is that subsidy withdrawal and vehicle-kilometres increase offset the saved part of operating cost (White 1995, Mackie et al., 1995).

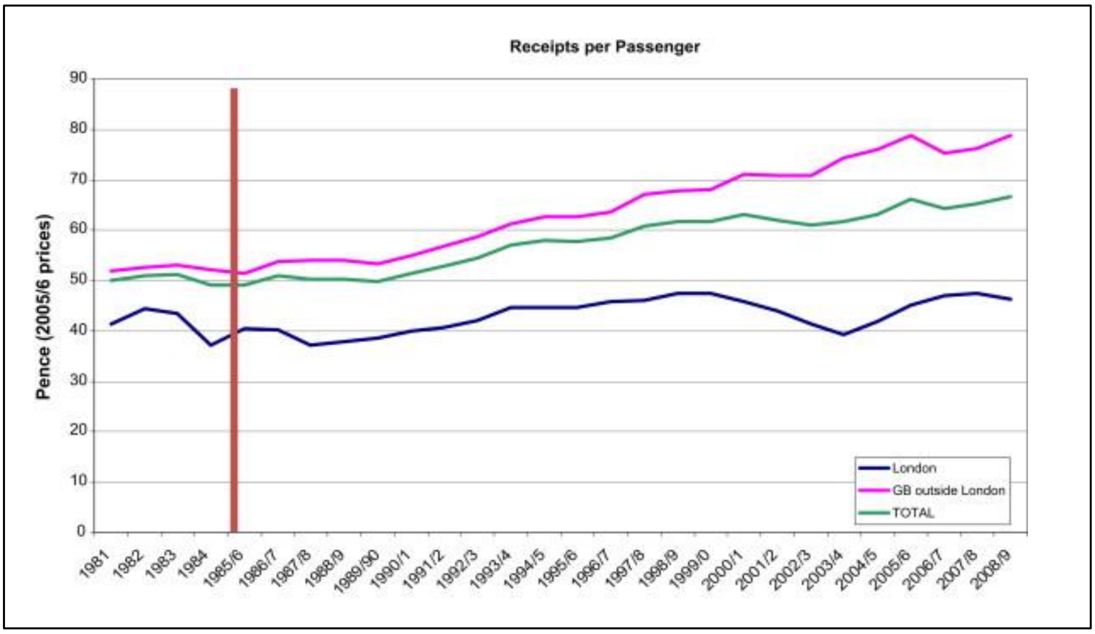

Figure 2-6 Trends in Fares (London v.s. GB outside London)

Source: Evaluating the long term impacts of transport policy: an initial assessment of bus deregulation (Preston and Almutairi, 2013), p.210. Fig.3.

2.3.6 Summary

The comparisons displayed above have demonstrated that although deregulation helped increase local bus supply, drive some reductions in operating costs, and cut subsidies, it has not delivered all the predicted benefits. For example, the performance of the London bus market is much better than other areas in Great Britain in terms of passenger numbers: the bus market outside London in total lost 35% journeys during the past three decades, while the usage of the London bus market has doubled. Deregulation also made it very difficult for transport planners to maintain coherent and integrated public transport systems within particular areas, with for example competition legislation limiting the potential for network-wide ticketing structures. The results of welfare analysis by Preston and Almutairi (2013) also provide some relatively strong evidence that deregulation led to a reduction in overall welfare compared to the system of regulation in London (in other words, competition for the market is preferable to competition in the market).

2.4 Potential Solutions

In order to reverse the current shrinking bus markets in areas outside London, the *Transport Act 2000* and *Local Transport Act 2008* have provided some potential solutions, such as Bus Quality Partnerships (BQPs) (both voluntary and statutory) and Quality Contracts. The definitions and characteristics of BQPs and Quality Contracts are available in the remaining of this section, and Table 2-1 summarises and compares them at the end of this section.

Proposed by the Chartered Institute of Transport in their report *Bus Route to Success* (1993), Bus Quality Partnerships (BQPs) deliver a solution by reversing the current shrinking bus markets in areas outside London under the deregulation environment. Within the BQPs, bus operators concentrate on providing an improved bus service such as high-quality vehicles (new, low-floor, and environmentally-friendly) and an enhanced service (increased frequency and so on). Local authorities invest in traffic management schemes, which give buses priority (lanes and at signals), passenger information, and passenger infrastructure (better bus stops, stations, shelters) (Davison and Knowles, 2006; Wall and McDonald, 2007; Nelson 2013).

In Britain, BQPs have been developing widely across England, Scotland and Wales, on a voluntary basis. In total, DfT awarded funding to 96 BQPs from 77 local authorities between 2011 and 2015 (Ricci et al., 2016). They arise from the fact that, as a result of deregulation in 1986, no single organisation has control over all of the factors that govern the quality of supply of bus services in Britain, outside London. Although BQPs were initiated to overcome this, there was a potential problem that operators who do not agree to raise their standards could not be excluded from using the new facilities. This problem, however, has been addressed by the *Transport Act 2000*, which made provision for these BQPs to become statutory. Within the statutory BQPs, local authorities must provide the specified bus infrastructures while bus operators must run a service up to the specified standard, otherwise financial penalties may be imposed by the traffic commissioner. In addition, only bus operators within the partnership can operate on that route. According to Van de Velde and Wallis (2013) and Rye and Wretstrand (2014), there are only 7 statutory BQPs are available so far, they are Sheffield (2006), Barnsley (2010), Nottingham (2010), Bristol (2011), Merseyside (2011), Birmingham (2012) and Greater Manchester (2012). BQPs show no direct benefit to the local authorities, which see their investments in infrastructure captured as profits for the operators. This might be one of the main reasons that statutory BQPs are only being adopted slowly (Preston et al., 2005).

The limited success of BQPs together with a desire to increase bus usage levels as a means of dealing with congestion and pollution has in recent years led several British local authorities to consider a system of Quality Contracts for bus services (as permitted by the *Transport Act 2000 and Local Transport Act 2008*). This would involve the introduction of centralised planning for bus services, effectively reproducing the structure that exists in London across the rest of the country. With this system the local authority would specify the services to be provided with the private bus companies then competing for the contracts to provide them. Such Quality Contracts could attract positive bids which would permit the local authority to be recompensed for its quality investments, and would also allow for simple integrated ticketing across the bus network, fares capping and enforceable standards for performance and quality (pteg, 2014). So far only one authority, the North East Combined Authority, has submitted their proposal for a Quality Contract Scheme (QCS) for Tyne and Wear to a Quality Contract Scheme Board on October 21st 2014 (Nexus, 2014), which was subsequently rejected by the Board on 3rd November 2015. However, on 3rd November 2014, the Greater Manchester Combined Authority signed a deal with the government which stated that Transport for Greater Manchester (TfGM) would be able to bring forward a Quality Contract scheme following a consultation. Other UK Local Transport Authorities which are currently actively pursuing the Quality Contract option (but have not triggered the formal legislative process) include West Yorkshire and Merseyside (pteg, 2014).

Compared with BQPs, QCS enable local authorities to determine what services need to be provided in their area and to what standard. Thus, there are mainly three approaches when implementing QCS in practice:

1) The current network pattern is retained by the local authorities, with some adjustments in related service levels.
2) In spite of current bus network, local authorities start from scratch and try to design an optimal network based on passenger demand.
3) Local authorities consider both the performance of the current bus network and passenger demand when they design new bus network and decide related service levels (something in between the above two approaches).

In terms of demand satisfaction, the approach of designing an alternative optimal network (approach 2) is the best choice. When adding constraints which reflect system performance and/or resource limitations, this approach should output more well-integrated and customer-friendly services compared with other two approaches, and obviously demands more complicated methodology and much longer computation time.

Table 2-1 Comparison of three categories of quality partnership

Term	**Characteristics**
Voluntary Quality Bus Partnership	• Local authority: provide better infrastructure to enhance the attractiveness of the bus products, but cannot impose service/ frequency requirements on the bus operating companies. • Bus operating companies: provide an improved service with a high standard of vehicles, customer services and frequencies.
Statutory Quality Partnership Scheme	• Local authority: provide and maintain facilities to enhance the attractiveness of the bus product, but cannot impose service/ frequency requirements on the bus operating companies. • Bus operating companies: use the facilities are legally responsible for providing services up to the standard specified by the local authority.
Quality Contract Scheme	• Local authority: determine what bus services should be provided in their area and to what standard, and provide the facilities to enhance the attractiveness of the bus product. • Bus operating companies: provide bus services under quality incentive contracts to local authority. • Contracts length: maximum of 5 years.

2.5 Conclusion

This chapter traced and compared the performances of two contrasting regulatory systems adopted in London and rest of country between 1981/82 and 2014/15 with respect to supply, demand, subsidy, operating costs, and fares. Some key policy developments after the mid-1980 reforms, such as Bus Quality Partnerships (BQPs) and Quality Contracts, were also discussed in this chapter. Although the BQPs and Quality Contracts are introduced to reverse the current shrinking bus markets in areas outside London, there are no tools readily available to ensure this centralised service planning will reproduce the success of the London model across the rest of the country. This thesis therefore describes the development of a methodology to fill this gap, and more details could be found in following chapters.

Chapter 3: Review of Evaluation Measures for Bus Network Performance

3.1 Introduction

In order to achieve the research aim, an evaluation model needs to be firstly developed to measure the performance of the current bus networks, followed by an optimisation model to re-planning the local bus networks based on the alternative regulatory environment. Hence, it is necessary to review the related literatures in both evaluation models and optimisation models. This chapter is going to discuss the published research for the evaluation models, followed by Chapter 4 for the optimisation models.

In this research, the accessibility levels were chosen as a major indicator to measure the performance of current bus networks. Therefore, the main objective of this chapter is to compare and discuss accessibility models in current published literature. The remainder of this chapter is divided into five sections. Section 3.2 explains why the accessibility levels were chosen as the indicator to evaluate the performance of public transport networks. The definition of 'accessibility' is represented in section 3.3. Section 3.4 displays a 4-step process of accessibility analysis used by the majority of the published models, they are concept formulation, measure selection and specification, accessibility measurement, and interpretation and evaluation. Section 3.5 lists available accessibility measures used in the published literature, and their advantages and shortcomings were compared and discussed as well. The final section summarises and discusses the whole chapter.

3.2 Performance Measures for Public Transport Networks

3.2.1 Concepts of Effectiveness and Efficiency

The performance measures for public transport networks quantify how well the existing network is used and whether the service is comfortable and reliable for the passengers, thus relying on conceptions of both effectiveness and efficiency (Karlaftis and Tsamboulas, 2012; Van De Velde, 2015). Effectiveness measures the consumption and satisfaction of services to evaluate the social impact of the services. Efficiency is defined as the relationship between the inputs (such as capital, labour, fuel, etc.) and outputs (such as vehicle-kilometres, vehicle-hour, etc.), and can be further divided into two categories: technical and allocative efficiency (Karlaftis and Tsamboulas, 2012;

Van De Velde, 2015). The technical efficiency captures the degree to which bus operators attain maximum outputs (vehicle-kilometres or vehicle-hour) with given inputs (labour, fuel, capital, etc.), or the minimum level of inputs that can be used to produce a given level of outputs. Allocative efficiency refers to which input mix is used to produce a given level of outputs at minimum possible cost.

In general, the efficiency and effectiveness are negatively corrected, and a balance should be pursued (Karlaftis and Tsamboulas, 2012). For example, if a bus operator replaces the current vehicles with smaller size ones, this will result in an increase in network efficiency by reducing its inputs in fuels and retaining the outputs (vehicle-kilometres or vehicle-hour) at the current level. However, smaller size vehicles could cause queuing and overcrowding problems, thus reducing the network effectiveness in providing satisfactory services for passengers.

3.2.2 Categories of Performance Measures

3.2.2.1 Performance Indicators

In practice, the most commonly used performance measures are performance indicators, which are defined as the ratios of the outputs of bus services to the input. According to Ceder (2007) and Nelson & Merkert (2013), the performance indicators can be divided into two categories: measures of system performance and measures of connectivity performance. Table 3-1 lists some commonly used measures for each category, as well as their interpretations. As its name implies, the measures of system performance are indicators of evaluating the system performance of independent public transport systems, such as vehicle-kilometres of travel, vehicle-hour of travel, passengers per vehicle-kilometre/ vehicle-hour, missed trips, reliability and so on. The measures of connectivity performance focus on assessing the connectivity performance of the public transport networks by using indicators, such as waiting time or number of transfers alongside passenger journeys. The most widely used index of the measures of connectivity performance is connectivity-production costs (travel costs), which is a combination of waiting time, transfer time, and on-board travel time, and could be used to calculate the accessibility levels for passengers to access their destinations. Thus, the indicator of connectivity-production costs integrates the evaluation of transport systems with land use patterns.

Integration of land use planning and transport planning is a widely stated aim of public policy in the UK. The Department of Environment and the Department of Transport jointly published *Planning Policy Guidance Note 13 – Transport (PPG13)* in 1994, followed by *PPG13: A Guide to Better Practice– Reducing the Need to Travel through Land Use and Transport Planning* in 1995. Both documents encouraged more integrated land-use planning and transport planning at both policy and practical level. PPG13 was revised in 2001 and emphasised the role of improving accessibility by public transport in reducing dependence upon car-use, and enabling people to make more sustainable transport choices. In 2012, the Department for Communities and Local Government (DCLG) published *National Planning Policy Framework (NPPF),* which replaced the former PPG13. The new-published NPPF promotes the notion of 'sustainable transport', and emphasises the balance between land-use planning and transport planning.

Table 3-1 Performance Indicators of Public Transport Networks

Type of measures	**Measures**	**Definition**
Measures of System Performance	Vehicle trips	Number of vehicle trips by specific route and specific time-of-day
	Vehicle-kilometres of travel (VKM)	Vehicle-kilometres of travel by specific route and specific time-of-day
	Vehicle-hours of travel (VH)	Vehicle-hours of travel by specific route and specific time-of-day
	Number of passengers	Number of passengers by specific route and specific time-of-day
	Passengers per vehicle-kilometres	Number of passengers per vehicle-kilometre by specific route and specific time-of-day
	Passengers per vehicle-hour	Number of passengers per vehicle-hour by specific route and specific time-of-day
	Reliability	Differences between actual journey time (include waiting time, transfer time, and on-board time) and expected journey time based on the timetable
	Missed trips	Number of missed scheduled trips by specific route and specific time-of-day
Measure of Connectivity Performance	Passenger waiting time	Passenger waiting time based on number of passengers and service frequency by specific route and specific time-of-day
	Passenger transfers	Number of passenger transfers per passenger journey
	Connectivity-production cost	Costs of passenger waiting time, transfer penalty and on-board travel time per passenger journey

Source: *Public transit planning and operation—theory, modelling and practice* (Ceder, 2007), p 373, Table 13.2.

Although the performance indicators in Table 3-1 are very simple to understand and to calculate, they cannot evaluate each dimension of the network performance, and might in some circumstances provide very puzzling results and lead to arbitrary decisions. For example, bus network A operates 500 vehicle trips per hour, but the average number of missed scheduled trips per hour is 3; while bus network B operates 300 vehicle trips per hour, but the number of missed scheduled trips per hour is 1. Based on the measure of vehicle trips, the performance of bus network A is better than network B. however, the result will be opposite when choosing the missed trips as the performance measure.

An alternative approach, called total factor productivity (TFP), therefore is developed (Kim, 1985). The TFP is defined as the ratio between the sum of the change in all (weighted) outputs and the sum of the change of all (weighted) input, thus could describe the overall levels of performance of public transport networks. Detailed guidelines for measurement and implementation of TFP have been reviewed by Talvitie & Obeng (1991) and Obeng et al. (1992). The major advantage of TFP is that it derived from the economic theory of cost and production functions instead of being just an arbitrary measure. Furthermore, it is theoretically justified and, consequently, superior to the other performance indicators in Table 3-1 (Obeng et al., 1992).

3.2.2.2 Approaches Based on Production Possibility Frontier

As an alternative to performance indicators, the performance of public transport networks can be estimated by production possibility frontier, which computes a frontier delineating the maximum achievable level of output (production) for various levels of input (Karlaftis and Tsamboulas, 2012; Zhu et al., 2016). Two main approaches exist to compute the frontiers: parametric and non-parametric (Van De Velde, 2015). The parametric methods assume a functional relation for the frontier (for example, stochastic frontier production function is the most widely used parametric approach, developed by Aigner et al. (1977) and Meeusen and Van Den Broeck (1977)), whereas the non-parametric methods construct a piecewise linear frontier enveloping the data obtained from observations (for example, data envelopment analysis approach, firstly proposed by Charnes et al. (1978)). A further comparison and implementation of the approaches based on production possibility frontier can be found in Kerstens (1996), Graham (2008), Karlaftis & Tsamboulas (2012) and Zhu et al. (2016).

3.2.2.3 Summary

Although various performance measures are available in published research, the crucial question is how to selecting the ‘best’ or most suitable approach based on different situations and research objectives. The traditional performance indicators, especially the measures of system performance, are attractive because of undemanding input data and simplicity of the calculations, but their chief limitation is that they might output arbitrary results. Based on the economic theory of cost and production functions, approaches such as total factor productivity and production possibility frontier describe the overall levels of performance of public transport networks, and thus could provide more accurate results. However, they are more input data demanding and are sensitive to the selection of input and output variables (Karlaftis and Tsamboulas, 2012).

Based on the research aim and available input data, accessibility levels (based on the connectivity-production cost) were chosen and calculated as a major indicator to measure the performance of current bus networks in this thesis. The accessibility levels are derived from the indicator of connectivity production cost, thus can be categorized as one of the traditional performance indicators. Compared with other indicators in the category, the accessibility levels quantify the performance of public transport network by integrating it with land use patterns, thus could provide more accurate results in evaluating how efficient the network is and could display the detailed information on equity and distribution of the network performance.

3.3 Definition of Accessibility

Accessibility is a concept that is not entirely easy to define and measure. Accessibility can be broadly defined as the ease with which activities at one place may be reached from another via a particular travel mode or any available modes (such as walk, bus, rail, bike, car, etc.) (Hillman and Pool, 1997; Murray et al., 1998; Lei and Church, 2010). It is dependent on the spatial distribution of origins and destinations, the performance of the transport system, the characteristics of the individual, the attractiveness of the destinations, and the time at which the individual is able to participate in the activity and whether the activity is available (Liu and Zhu, 2004a; Thill and Kim, 2005). Accessibility analysis therefore encompasses spatial and socioeconomic aspects.

In the context of public transport accessibility, Murray et al. (1998) distinguishes between the terms ‘access’ and ‘accessibility’. Access is the opportunity for passengers based on proximity to board the services. Accessibility is the ability of the network to get individuals from their system entry point to their system exit location in a reasonable amount of time. Hillman and Pool (1997) make a distinction between ‘local’ and ‘network’ public transport accessibility. Local accessibility is seen as the accessibility of a particular residential or other location to public transport. Network accessibility is used to describe the accessibility of origin locations to access specific destinations by using public transport. When considering public transport accessibility, the term ‘network accessibility’, as used by Hillman and Pool (1997), is akin to the term ‘accessibility’ described by Murray et al. (1998); while the term ‘local accessibility’ can be considered similar to the ‘access’ element. As a result, the definition of the public transport accessibility includes the accessibility to the public transport (or ‘access’ or ‘local’ accessibility), as well as accessibility by the public transport (or ‘accessibility’ or ‘network accessibility’).

3.4 The Process of Accessibility Analysis

Liu and Zhu (2004a, 2004b) reviewed current research on accessibility analysis, and summarised a four-step process for solving the accessibility measurement problems (see Figure 3-1):

1) Step 1: Concept Formulation

   This first step defines the purpose of analysis, understands the planning context, and formulates the concept of accessibility.

2) Step 2: Measure Selection and Specification

   According to corresponding research objectives, accessibility measures are selected or developed in this step. An accessibility measurement can be specified in terms of the spatial unit for analysis, the socioeconomic groups whose accessibility is to be assessed, the type of opportunities, the mode of travel, the origins and destinations, the attractiveness of the destinations, and travel impedance. Each of them is defined as follows:

   - One spatial unit can be a zone (such as census tracts), a building block, a household, or an individual.
   - The socioeconomic groups refer to population groups defined according to their socioeconomic characteristics, such as household income, employment status, occupation and gender.
   - The factors considered in 'types of opportunities' vary among different research projects. They can be, for example, retail outlets, job opportunities, schools, child-care centres, etc.
   - The options of travel mode are walking, private car, bus, train, tram and so on.
   - The definition of origin and destinations specifies from where and to where accessibility will be measured.
   - The definition of the factor 'attractiveness of the destinations' is based on those characteristics of a potential destination that are important to destination choice, such as the number of establishments (e.g. the number of retail shops), the physical size (e.g. the gross floor space and parking area of shopping centres), or the economic size (e.g. the number of jobs).
   - The travel impedance represents travel distance, time or cost between origins and destinations.

3) Step 3: Accessibility Measurement

This step applies the available methodologies (selected or developed in the above step) to case studies, including the following three steps: calculating travel impedance, measuring accessibility, and calibrating the accessibility measures.

4) Step 4: Interpretation and Evaluation

The final step focuses on presentation, interpretation and evaluation of the results of accessibility measurement. It aims to interpret the results and translate them into useful information for policy making.

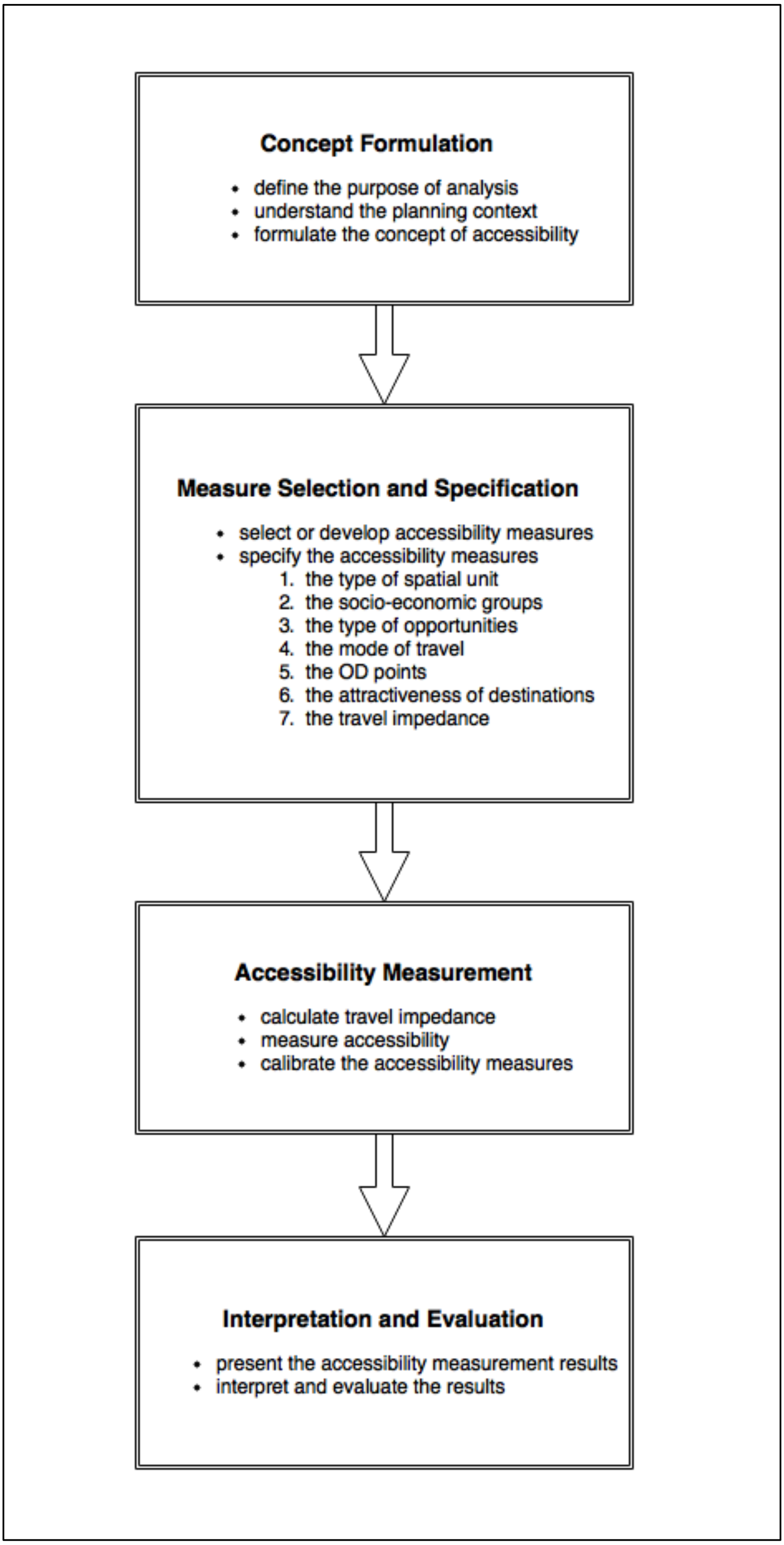

Figure 3-1 The Process of Accessibility Analysis

3.5 Measures of Accessibility

Because the definition of the public transport accessibility includes both local and network accessibility, the measurement methods were grouped into two categories: measures of local accessibility and measures of network accessibility. In this section, available measures belonging to both categories were traced respectively, and their advantages and shortcomings were compared and discussed as well.

3.5.1 Measures of Local Accessibility

The local accessibility problem emphasises physical access to the transit system itself, based on the distance, time or effort required to reach it. In the specific context of local accessibility to public transport, the majority of studies to date focus exclusively on distance-based measures and the concept of 'transit coverage' based on a quantification of the percentage of population deemed to be served within a reasonable walking distance of the transit facilities (O'Neill et al., 1992; Peng and Dueker, 1995; Hsiao et al., 1997; O'Sullivan et al., 2000; Ayvalik and Khisty, 2002; Foda and Osman, 2010; Biba et al., 2010; Langford et al., 2011). A figure of 400 metres is widely used in the published literature as a walk-able catchment for bus stops (O'Neill et al., 1992; Hsiao et al., 1997; Phillips and Edwards, 2002; Foda and Osman, 2010; Biba et al., 2010; Langford et al., 2011). Undoubtedly, this distance varies somewhat depending on the characteristics of passengers (such as age, gender, health condition, etc.), the purposes of trips, safety concerns, and topography of research areas.

Based on the various definitions of walking distance (straight-line distance versus network distance) and different methods in distributing demographic characteristics (uniformly distributed within research areas or on every street, or aggregate into population centroids), methods of local accessibility measurement are grouped into three categories in this section: area-ratio method, network-ratio method, and parcel-network method. Each category will be described below in turn, followed by a more advanced method, called Public Transport Accessibility Levels (PTALs), which has been adopted by Transport for London as the standard method for calculation of public transport accessibility levels in London.

3.5.1.1 Area-Ratio Method

Based on an assumption of uniform distribution of population within the research area (which may not be true in reality), the area-ratio method (also called Euclidean buffer method) calculates the local accessibility levels by creating a distance buffer using a threshold distance parameter (for example, 400 metres) around the transit route or stops along the route, and by evaluating the proportion of population that lies within this tolerable walking buffer (O'Neill et al., 1992; Hsiao et al., 1997; Peng and Dueker, 1995; Peng, 1997; Ayvalik and Khisty, 2002).

Although the methodology of area-ratio method is quiet simple, its disadvantages are obvious as well. Firstly, the Euclidean distance defined by spatial buffers is always shorter than true walking distance along a street network, which leads to a tendency to overestimate transit coverage of public transport services. Secondly, based on the hypothesis of a uniform distribution of population within the research areas, calculation errors are inevitable (Joyce and Dunn, 2009; Biba et al., 2010; Langford et al., 2012).

3.5.1.2 Network-Ratio Method

Developed by O'Neill et al. (1992), the network-ratio method evaluates the local accessibility levels by two variables: the total length of the streets within the analysis zone and the length of the streets within the maximum walking buffer of the transit facilities. Hence, the local accessibility levels of zone i (A_i) could be defined as follows:

$$A_i = \frac{W_i}{M_i} \times P_i \tag{3.1}$$

Where

M_i = total length of street network in the analysis zone i;

W_i = length of the street network within maximum walking buffer of the transit facilities in the zone i;

P_i = total population of the zone i.

Compared with the area-ratio method, the network-ratio method eliminates the calculation errors caused by the assumption of uniform distribution of population within the research areas. However, it assumes that there is a uniform distribution of population on every street that is (maybe) still far away from the population distribution in reality and will cause some inevitable errors. Furthermore, the method involves all roads within the research area in the calculation process, thus will lead to some substantial errors when motorways and their associated frontage roads and off-ramps are all included (Biba et al., 2010).

3.5.1.3 Parcel-Network Method

The parcel-network method has been widely used in land use planning and geographical studies, such as Xie (2006), Furth et al. (2007), Walker et al. (2007), Strager and Rosenberger (2007), Chapin et al. (2008), Wallace (2008), Biba et al. (2010), and Foda and Osman (2010). The calculation process of parcel-network method was summarized by Biba et al. (2010), including following three steps:

1) Aggregate the demographic characteristics to parcel centroids, which defined as population centroids of postcodes/census zones/or any self-defined zones. The smaller population zones are defined, the more detailed population distribution will be modelled.
2) Calculate walking distances from each parcel centroid to its nearest bus stop based on pedestrian road network.
3) Assess the population that can access the transit facility across the walking network based on the pre-set maximum walking distance.

The population data is distributed into parcel centroids by the parcel-network method, instead of being uniformly distributed within research areas (assumed by area-ratio method) or on every street (assumed by network-ratio method). Compared with the area-ratio and network-ratio method, this assumption is closer to the population distribution in reality when the parcel centroids are carefully defined. Furthermore, the walking distances are evaluated based on actual pedestrian road network, instead of straight lines linking parcel centroids and transit facilities. Thus, the method considers natural or man-made barriers (such as roads with limited access, canals or fences) in the calculation process, and will output more accurate walking distance for accessibility measurement compared with the area-ratio and network-ratio method (Biba et al., 2010; Foda and Osman, 2010).

3.5.1.4 Public Transport Accessibility Levels

All the above three methods only concern the accessibility levels to access the public transport facilities, and do not consider the quantity of services provided by the public transport network, and this omission may lead to some errors. For example, bus stop A is located 300 metres away from one resident point, but there is only one bus route serving this stop; while stop B is located 500 metres away from the same resident point, but there are more than 10 bus routes serving it. Based on the above three methods, the accessibility level provided by stop A is higher than stop B. In practice, the accuracy of this result is doubtful. Some improved methods have appeared to solve this problem, such as Public Transport Accessibility Levels (PTALs), which has been adopted by Transport for London as the standard method for calculation of public transport accessibility in London (Transport for London, 2010) and has been used in accessibility studies by Wu and Hine (2003) and Gent and Symmonds (2005).

The PTALs method is a measure of local accessibility, taking into account both walk access time and service availability. According to *Measuring Public Transport Accessibility Levels: PTALs* by Transport for London (2010), the process of calculating PTAL values can be broken down into following stages:

1) Define the points of interest (POI): the point for which the PTALs is being calculated, such as population centroids of postcodes or census zones.
2) Calculate walking time (WKT) from the POI to the service access points (SAPs) (such as bus stops, railway stations, etc.) located within the maximum walking buffer. Distances between the POI and the SAPs are converted to a measure of time using an assumed average walk speed of 4.8 kilometre/hour. For buses the maximum walk time is defined as 8 minutes or a distance of 640 metres.
3) Calculate average waiting time (AWT) for each SAP by following formula:

$$AWT = k + SWT \tag{3.2}$$

Where
SWT = scheduled waiting time, equals to half of headway;
k = a reliability factor relating to the reliability of the service, and k = 2 minutes for bus services.

4) Calculate total access time (TAT) for each SAP by combining the WKT and AWT:

$$TAT = WKT + AWT \tag{3.3}$$

5) Calculate Equivalent Doorstep Frequency (EDF) for each SAP: by converting the TAT to a notional average waiting time as though the route were available on the POI's 'doorstep'.

$$EDF = \frac{30}{TAT} \tag{3.4}$$

6) Calculate PTAL for each POI: to account for routes travelling in parallel for some distance, and passengers having to change routes causing large delays, the EDF is halved for all but the most accessible or dominant SAP. The value of PTAL for each POI therefore is a summation of all EDF values by following function:

$$PTAL = EDF_{max} + 0.5 \times \sum EDF_{other} \tag{3.5}$$

7) PTALs are then grouped using following six-banded levels (shown in Table 3-2).

Table 3-2 Public Transport Accessibility Levels

Range of PTAL Values	Map of Colour	Description
0.01-2.50		Very poor
2.51-5.00		Very poor
5.01-10.00		Poor
10.01-15.00		Moderate
15.01-20.00		Good
20.01-25.00		Very good
25.01-40.00		Excellent
40.01+		Excellent

The main strength of the PTALs method is that it is easy to understand and calculate, as well as could output realistic results. Compared with the three traditional methods listed in the previous sections, the PTALs method considers the level of services at access points (using frequency information to calculate average waiting time) as well as walking access time in the process of calculation. In addition, it also provides a direct visualization of output results using the coloured contour map in which patterns of provisions are clearly shown (Wu and Hine, 2003; Transport for London, 2010).

3.5.1.5 Summary

Table 3-3 lists and compares these available measures for local accessibility. The three traditional methods, including area-ratio, network-ratio, and parcel-network method, evaluate the local accessibility levels by quantifying the number of population to be serviced within a maximum acceptable walking distance of the transit facilities. The accuracy of final results therefore is determined by the definitions of walking distance (straight-line distance versus network distance based on pedestrian network) and methods chosen to locate the population data (uniformly distributed within research areas or on every street, or aggregate into population centroids). The more accurate the walking distance is measured and more detailed the demographic characteristics are distributed, the more realistic the results. According to this, the parcel-network method wins against the other two when the population centroids are carefully defined. However, all three traditional methods only concern the accessibility levels to access the nearest public transport facilities and ignore the quantity of services provided by the public transport network, and this omission is avoided by the PTALs. Considering the service availability as well as the accessibility to public transport network, the PTALs method provides a practical methodology to output more realistic results in measuring local accessibility.

Table 3-3 Measures of Local Accessibility

Methods		Characteristics
Traditional methods	Area-ratio method	• Straight-line buffering distance; • Uniform distribution of population within the research area.
	Network-ratio method	• Straight-line buffering distance; • Uniform distribution of population on every street.
	Parcel-network method	• walking distance based on actual pedestrian road network; • Population centroids; • The most accurate method among these three traditional methods.
Public Transport Accessibility Levels (PTALs)		• Considers both walk access time and service availability; • Easy to understand and calculate; • Provide a direct visualization of data using the coloured contour map.

3.5.2 Measures of Network Accessibility

According to the literature reviews by Handy and Niemeier (1997), Geurs and van Wee (2004), Curl et al. (2011 and 2015), measures of network accessibility available in the published research are grouped into four categories. In this section, they are distance, contour, gravity-based, and utility-based measures. Each category of measures will be described below in turn, and Table 3-4 will compare their advantages and shortcomings at the end of this section.

3.5.2.1 Distance Measures

Developed by Ingram (1971), the distance measures (also called connectivity measures) demonstrate the network accessibility levels by calculating the travel distance, time or cost between origins and destinations. Compared with other measures of network accessibility, the distance measures are undemanding of data and have a relatively simple calculation process; therefore they are widely used in practice, such as *Accessibility Statistics* (Department for Transport, 2012) and *Access To Opportunities and Services (ATOS)* (Transport for London, 2009). Both methods measure network accessibility by average shortest travel time from population centroids to key services (such as employment centre, educational establishments, health services, food stores, town centres, and open spaces) by multiple transport modes (such as walking, bus, rail, cycle, and car). Compared with the closest destination chosen in the process of Accessibility Statistics calculation, ATOS looks at access to the 10 nearest destinations based on walking network distance, thereby reflecting a degree of ‘user choice’ in the methodology.

3.5.2.2 Contour Measures

Contour measures (also known as isochronic measures, or cumulative opportunities measures) are popular in urban planning and geographical studies (Wickstorm, 1971; Wachs and Kumagai, 1973; Gutierrez and Urbano, 1996; Bruinsma and Rietveld, 1998; O'Sullivan, 2000). The contour measures evaluate the network accessibility levels by counting the number of opportunities which can be reached within a given travel distance, time or cost. Hence, the accessibility of zone i (A_i) could be measured by:

$$A_i = \begin{cases} \sum_j B_j, & if\ d_{ij} \leq L \\ 0, & if\ d_{ij} > L \end{cases} \tag{3.6}$$

Where:

B_j = the opportunities at zone j for a given purpose;

d_{ij} = distance from zone i to zone j;

L = a given travel distance, time or cost limit.

The contour measures are relatively undemanding of data and are easy to be calculated and interpreted. However, the final results are highly sensitive to the choice of the cut-off travel distance, time or cost. The literature does not provide a clear rule on how to make this choice, and the value of the cut-offs varies by different research objectives and travel modes (Handy and Niemeier, 1997; Geurs and Wee, 2004).

3.5.2.3 Gravity-based Measures

Gravity-based measures (also called potential measures), derived from the gravity model of spatial interaction, are widely applied in solving integrated accessibility problems; well-known studies are from Hansen (1959), Ingram (1971), Wilson (1971) and Vickerman (1974). They suggest that the potential of opportunity between two places is positively related to the level of attractiveness of the destination and negatively related to the travel impedance between them. Hence, the accessibility of zone i (A_i) could be measured by:

$$A_i = \sum_j (B_j / d_{ij}^a) \tag{3.7}$$

Where:

B_j = the opportunities at zone j for a given purpose;

d_{ij} = distance from zone i to zone j;

α = some constant.

This original model, formulated by Hansen (1959), measures the deterrence to travel by a negative power function of distance ($1/d_{ij}^{a}$). However, distance is not the best measure of travel difficulty (because passengers usually choose the quickest route or cheapest route, not the shortest route), and the deterrent effect of this difficulty could be measured by functions other than the negative power function. Therefore, the idea has been extended by Ingram (1971) to the generalised gravity-based measure:

$$A_i = \sum_j B_j f(c_{ij}) \qquad (3.8)$$

Where:

B_j = the opportunities at zone j for a given purpose;

c_{ij} = travel cost from zone i to zone j;

$f(c_{ij})$ = function to represent the deterrent effect of the travel cost. Different functions adopted by different researchers to represent the deterrent effect of the travel cost, such as Gaussian functions (e.g. Ingram, 1971), logistic functions (e.g. Hilbers and Verroen, 1993), and negative exponential functions (e.g. Dalvi and Martin, 1976; Handy 1994). According to Handy and Niemeier (1997), the most widely used function is the negative exponential function:

$$f\left(c_{ij}\right) = e^{-\beta \times c_{ij}} \qquad (3.9)$$

Where:

β = some constant.

There are two fairly common variations of the generalised gravity-based measure: the normalised and the population weighted measures. Introduced by Dalvi and Martin (1976), the normalised measure is:

$$A_i = \frac{\sum_j B_j f(c_{ij})}{\sum_j B_j} \qquad (3.10)$$

Instead of using the absolute number of opportunities (B_j) in zone j, the normalised measure uses the proportion of the opportunities in the entire study area which zone j possesses, namely $\frac{B_j}{\sum_j B_j}$.

The other is the population-weighted measure, firstly developed by Scheider and Beck (1974):

$$A_i = P_i \sum_j B_j f(c_{ij}) \qquad (3.11)$$

Where:

P_i = the population number at zone i.

The population-weighted measure combines the accessibility of an area with the number of residents (P_i) who have the opportunity to take part in a particular activity or set of activities that are available at the set of destinations.

The gravity-based measures overcome some of the shortcomings of the distance and contour measures. They add the attractiveness of destinations into the network accessibility calculation, and incorporate assumptions about a person's perceptions of transport by using a distance decay function. Furthermore, the gravity-based measures have the practical advantage that they can be easily computed using existing land-use and transport data. However, compared with distance and contour measures, the gravity-based measure has relatively more complex calculation process and is not easily interpreted and communicated (Handy and Niemeier, 1997; Geurs and Wee, 2004; Ford et al., 2015).

3.5.2.4 Utility-based Measures

Utility-based measures have their origin in economic studies, and specifically in random utility theory. The utility theory is based on the assumption that individuals aim to maximise their utility. This means that the individual gives each destination a utility value, and that likelihood of an individual choosing a particular destination depends on the utility of that choice compared to the utility of all choices. The utility values of the destinations are decided by the attractiveness of the destination, the travel impedance, the socio-economic characteristics of the individual and so on. Therefore, accessibility is defined as the denominator of the multinomial logit model, also known as the logsum (Ben-Akiva and Lerman, 1985; Mcfadden, 1981). Then accessibility A_n for individual n can be measured as:

$$A_n = \ln(\textstyle\sum_{\forall \in C_n} \exp(V_{n(c)})) \tag{3.12}$$

Where:

C_n = the choice set for individual n;

$V_{n(c)}$ = the utility value of choice c for the individual n, decided by the attractiveness of the destination, the travel impedance, the socio-economic characteristics of the individual and so on.

By adopting individuals' perceptions and preferences into account, the utility-based measures best match actual travel behaviour, and could output more realistic results than other measures. Although the utility-based measures have advantages in theory, their shortcomings in practice could not be ignored, such as requirements for highly detailed input data and complicated calculation process (Handy and Niemeier, 1997; Geurs and Wee, 2004).

3.5.2.5 Summary

Table 3-4 lists and compares these available network accessibility measures by their methodology, advantages, and shortcomings. In terms of the accuracy of the final results, the utility-based measures are the best choices. However, its application in accessibility studies is relatively rare compared with other three categories of measures. Lack of input data and complicated calculation process are the two main application difficulties. Besides the utility-based measures, the remaining three categories of measures (distance, contour, and gravity-based measures) have the practical advantage that they can be easily computed using existing land-use and transport data. Compared with the gravity-based measures, the distance and contour measures have relatively simple calculation processes and are easy to interpret for researchers and policy makers, thus are widely used in published studies. However, both distance and contour measures have obvious limitations. The chief limitation of the distance measures is that they always assume passengers will choose the nearest destinations, without considering the attractiveness of destinations in the calculation process. For the contour measures, the final results are highly sensitive to the choice of the cut-off travel distance, time or cost. Therefore, the gravity-based measures were designed to overcome these chief limitations: they add the attractiveness of destinations into accessibility calculation, and incorporate assumptions about a person's perceptions of transport by using a distance decay function. In summary, there is no single 'best' approach to measuring the network accessibility, and different situations and research objectives demand different approaches.

Table 3-4 Measures of Network Accessibility

Category	Methodology	Advantages	Shortcomings
Distance measures	Calculate travel time, distance, or cost between origins and destinations.	• Undemanding of data; • Easy to understand and calculation.	• Do not consider the attractiveness of the destination; • Do not take individuals' perceptions and preferences into account.
Contour measures	Count the number of opportunities which can be reached within a given travel distance, time or cost.	• Undemanding of data; • Easy to understand and calculation.	• Highly sensitive to the choice of cut-offs; • Do not take individuals' perceptions and preferences into account.
Gravity-based measures	Positively related to the level of attractiveness of the destination; negatively related to the travel impedance between origin and destination.	• Undemanding of data; • Add the attractiveness of the destination into accessibility calculation; • Using a distance decay function to overcome the distance cut off limits caused by contour measures.	• Not easily interpreted and communicated, compared with distance and contour measures; • Do not take individuals' perceptions and preferences into account.
Utility-based measures	One individual gives each destination a utility value, and chose the particular destination with the maximum utility value.	• Take individuals' perceptions and preferences into account; • Best match actual travel behaviour.	• Complicated calculation process; • Not easily interpreted and communicated.

3.6 Conclusion

This chapter reviewed available accessibility models designed by current studies. Based on the research aim and available input data, gravity-based measures were considered to be an effective method of demonstrating the levels of accessibility in this thesis. An accessibility model was therefore developed based on the processes of accessibility analysis described in section 3.4. Detailed information on this development, including data preparation, methodology, and model building using ArcGIS, are provided in Chapter 5.

Chapter 4: Review of Optimisation Models for Public Transport Networks

4.1 Introduction

This chapter focuses on discussing available methods of optimising public transport networks described in the literature. Improvement methods, including both route planning and frequency setting, also known as methods for solving the Transit Network Design Problem (TNDP), are considered in this thesis. According to global reviews carried out by Desaulniers and Hickman (2007), Guihaire and Hao (2008), Kepaptsoglou and Karlaftis (2009), and Ibarra-Rojas et al. (2015), three components need to be considered in the process of solving the TNDP, which can be summarised as follows:

- Objective function and constraints: TNDP is usually formulated as a non-linear optimisation problem by minimising (or maximising) intended objectives subject to a variety of constraints which reflect system performance and/or resource limitations.
- Demand and passenger behaviour modelling (assignment sub-model): demand data is an essential input for solving TNDP, and the usual way of representing this public demand is an origin-destination (OD) matrix. Based on the given OD matrix demand data, the passenger assignment problem, which decides which route through the transit network passengers will take, also needs to be modelled.
- Solution techniques: analytical methods, developed by Mohring (1972) and Jansson (1984), provide solutions to TNDP for a stand-alone corridor. For public transport networks, there are mainly three categories of solution techniques applied in published studies, they are mathematical, heuristic, and meta-heuristic approach. Compared with the other two solution techniques, meta-heuristic approaches have proved to be practical methods to solve realistic and large-sized problem instances, as well as guarantee to output global optimal solution. Recently published research therefore heavily relies on the meta-heuristic techniques, and widely used examples covered in the literature are genetic algorithm (GA), Neighbourhood Search (NS), Simulated Annealing (SA), and Tabu Search (TS).

The remainder of this chapter will provide more detailed discussion of each of these components, and is divided into the following seven sections. All the possible decision variables of the optimisation models for public transport networks are represented in section 4.2. The following three sections, 4.3, 4.4, and 4.5, discuss the three key components of formulating the TNDP respectively. Section 4.3 lists widely used objective functions and constraints covered in the literature. The input demand data and related assignment methods are discussed in section 4.4. Section 4.5 summarises and compares the solution techniques applied in the literature, focusing on meta-heuristic techniques. Four categories of most-widely used algorithms, GA, NS, SA, and TS, are detailed discussed and compared in this section. Section 4.6 summarises the methodology of solving TNDP by applying meta-heuristics. The shortcomings of current published studies for solving TNDP are summarized and discussed in section 4.7. The final section makes a conclusion of the whole chapter.

4.2 Decision Variables

In general, the characteristics of a bus network are decided by three attributes: quantity (service levels), fare, and service quality. According to Ceder (2007), the process of determining optimal service levels, known as the Transit Network Planning (TNP) problem, can be decomposed into four stages: network route design, network scheduling (includes frequency setting and timetable development), vehicle scheduling and crew scheduling, which are sometimes alternatively termed strategic (step 1), tactical (step 2) and operational (step 3 and 4) planning, respectively (Desaulniers and Hickman, 2007). Besides the service levels, the fares charged and the ticketing system are also an essential attribute to estimate the performance of bus networks. If a well-integrated bus network is combined with the introduction of lower fare prices, a discounted fare system by travel cards, and a simple ticketing system among multiple operators, it would contribute to the provision of better bus services to passengers. According to *WebTAG Public Transport Assignment* (Department for Transport, 2014a), the service quality is defined as providing comfortable, secure and convenient services to passengers, such as investment in new buses with low floor, station and bus stop quality improvements (such as new bus shelters, CCTV at bus stops), live information provision (by audio announcement and on-screen displays), ease of interchange, etc. Furthermore, bus priority system is an efficient support for bus system operations, especially for large and multiple-modal transport networks (London, for example), and the corresponding modelling process and discussions have been undertaken in previous research, such as McLeod (1998), Liu et al. (1999), Shrestha (2003) and Hounsell et al. (2007).

Although fares, service quality and bus priority are key attributes of bus networks, they were excluded from this research. This is because the bus network improvement methods considered in this research only include the service level improvements, while the fare system, service quality and bus priority system remain at current levels. Among Ceder's (2007) four-step network planning process, the network route design (or strategic planning) is the single most important planning step, because it will invariably affect frequency setting, bus and crew scheduling (Ceder and Wilson, 1986; Pattnaik et al., 1998). The research described in this thesis therefore focuses on the problem of designing a system of bus routes and their corresponding frequencies, which is also known as the Transit Network Design Problem (TNDP).

4.3 Objective Functions and Constraints

TNDP is usually formulated as a non-linear optimisation problem by minimising (or maximising) intended objectives subject to a variety of constraints which reflect system performance and/or resource limitations (Desaulniers and Hickman, 2007; Guihaire and Hao, 2008; Kepaptsoglou and Karlaftis, 2009; Ibarra-Rojas et al., 2015). This section therefore reviews some of the most widely used objective functions and constraints in previous research.

4.3.1 Objective Functions

The choice of planning objective will differ when varying the priority given to the conflicting interests of passengers and operators. Passengers expect the bus network to be fully compatible with their demand, with features such as highly accessible stops, short travel times, and cheap and direct services (Ibarra-Rojas et al., 2015). Therefore, the objective of bus service planning, from the passengers' perspective, is to minimise transfer time or waiting time (Chakroborty, 2003) or to minimise travel time or travel cost (Chakroborty and Dwivedi, 2002; Zhao, 2006; Szeto and Wu, 2012). However, from the operators' perspective, the number of routes and the level of services should be determined by the relationship between the operating costs and the revenue generated. (profit maximisation). Operator cost minimisation (Yan et al., 2013) will therefore be chosen as the objective function when the revenue remains fixed (i.e. under a quality contract system where revenue risk is taken by the government body which awards the contracts). Cost functions have been built up by a number of previous studies to meet these various planning objectives, and are grouped and displayed in the remainder of this section.

4.3.1.1 User Cost

Based on the research by Jansson (1984), the total (non-monetary) user cost of travelling by the public transport services is a function of transport volume (Q) and average user cost per journey (AC_{user}), and the corresponding equation is:

$$total\ user\ cost = Q \times AC_{user} \tag{4.1}$$

Where AC_{user} is defined as a function as occupancy rate (φ), average speed of vehicles (V) and service frequency (F), and can be expressed as follows:

$$AC_{user} = w(F) + q(\varphi, F) + t(\varphi, V) \tag{4.2}$$

Where

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

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

$t(\varphi, V)$ = travel time cost as a function of φ and V.

Thus, the user cost calculation by Jansson (1984) considers waiting time, in-vehicle time and transferring time of the passenger in the journey. However, other essential attributes were excluded, such as walking time and the charges on the passenger (ticket price).

A more detailed and comprehensive user cost function is displayed in *WebTAG Public Transport Assignment* (Department for Transport, 2014a). According to it, user cost is a combination of a number of attributes, with each attribute being given a weight. These attributes are listed as follows:

- Walking time (WKT): includes access time (from trip origin to PT stop), egress time (from PT stop to trip destination) and transfer walking time between PT stops (walking time from one PT stop to another to change PT services);
- Waiting time (WTT): include both origin wait time (time spent waiting for first PT service) and transfer wait time (time spent waiting for subsequent services);
- In-vehicle time (IVT);
- Transfer penalty ($T_{penalty}$): a fixed penalty based on the number of transfers;
- Fare.

Accordingly, the passengers' travel cost can be expressed as follows:

$$user\ cost = C_{ivt}\left(IVT + W_{wkt}WKT + W_{wtt}WTT + T_{penalty}T_n\right) + fare \tag{4.3}$$

Where

C_{ivt} = value of in-vehicle time;

W_{wkt} = weighting factor to account for perception of WKT compared to IVT;

W_{wtt} = weighting factor to account for perception of WTT compared to IVT;

T_n = number of transfers within the journey.

4.3.1.2 Operator Cost

According to the review by Small (1992), there are three main approaches to operator cost calculation: accounting approach, engineering approach and productivity approach.

4.3.1.2.1 Accounting Approach

According to Small (1992), the accounting approach assumes that a linear operator cost function of several variables of the public transport operation outputs, such as route miles (RM), peak vehicles in service (PV), vehicle hours (VH), and vehicle miles (VM), and the corresponding mathematical equation is:

$$operator\ cost = c_1 RM + \ c_2 PV + \ c_3 VH + c_4 VM \tag{4.4}$$

Where

C_1 = unit operation cost, route length related ($ per route mile);

C_2 = unit operation cost, vehicle related ($ per vehicle per year);

C_3 = unit operation cost, time related ($ per vehicle hour);

C_4 = unit operation cost, distance related ($ per vehicle mile).

White (2009) summarised a typical cost structure for the operator cost of bus industry (see Table 4-1), thus provided practical guidelines for operator cost calculation in engineering approach. Based on it, 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 in his bus cost allocation example.

Table 4-1 Bus Operator Cost Structure

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

Source: *Public Transport: Its Planning, Management, And Operation* (While, 2009), Table 6.1

4.3.1.2.2 Engineering Approach

The engineering approach is to evaluate the total cost of the project or the services over a specific time period, such as one year over the entire lifetime of the project (Small, 1992). Meyer et al. (1965) undertook a pioneering study on developing an operator cost function in an engineering approach. They identified the operator cost is a function of the number of vehicle, the total travel distance, the costs of the structure and the maintenance costs, thus expressed as follows:

$$operator\ cost = \alpha U + \beta M + \gamma L + S \tag{4.5}$$

Where

U = number of needed vehicles;

M = length of travel distance (miles);

L = lane or track length of needed roadway or roadbed (miles);

S = structure and related costs (e.g. highways, roadbed, right-of-way);

α = unit operation cost, vehicle related ($ per vehicle);

β = unit operation cost, travel distance related ($ per mile);

γ = unit operation cost, roadway or roadbed related ($ per mile).

A more comprehensive operator cost function 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 calculated the operator costs of public transport technologies operating on a stand-alone corridor without network. The operator cost in the TEST project includes the costs that arose during the operating stage (be divided into time-related, distance-related, vehicle-related and route maintenance related cost) and the capital investments of the public transport technology, and was calculated using the following function:

$$operator\ cost = \ OC^T + OC^D + OC^V + OC^R + CC \tag{4.6}$$

Where

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

OC^D = distance related operation cost arose during operation;

OC^V = vehicle related operation cost arose during operation;

OC^R = route maintenance related operation cost arose during operation;

CC = capital investment costs of vehicles and infrastructures.

4.3.1.2.3 Productivity Approach

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

$$Y = AL^{\alpha}E^{\beta}T^{\gamma} \tag{4.7}$$

Where

Y= total output production (measured by vehicle miles in Viton (1980));

A = total factor productivity;

L = man-hours of labour;

E = kilowatt-hours of electricity;

T= miles of track;

α, β, γ = output elasticities.

As cost is a function of output, the operator cost function therefore could be defined as follows:

$$operator\ cost = c\ (Y, P_L, P_E, P_T) \tag{4.8}$$

Where P_L, P_E, P_T are factor prices of the input requirements, i.e. L, E and T.

Other studies that adopted the productivity approach include Kim (1985), Talvitie and Obeng (1991), Obeng et al. (1992), Cantos et al. (1999), Oum et al. (1999), Cantos et al. (2002), De Borger et al. (2002), De Borger et al. (2008), and Batarce and Galilea (2013).

4.3.1.3 Social Cost

Most commonly, the objective function is minimising social cost, including both the generalised cost of travel (user cost) and operating cost, meaning that the bus network improvement problem is specified as a multi-objective programming problem (Mohring, 1972; Jansson, 1984; Ceder and Wilson, 1986; Pattnaik et al., 1998; Ngamchai et al., 2003; Tom and Mohan, 2003; Argwal and Mathew, 2004; Ceder, 2007; Fan and Machemehl, 2004, 2006a, 2006b, 2008a, 2008b, 2011; Zhao and Zeng, 2006, 2007; Cipriani et al., 2012; Roca-Riu et al., 2012; Chew et al., 2013; Jansson, et al., 2015; Camporeale et al., 2016). The corresponding equation is:

$$social\ cost = \gamma_1 user\ cost + \gamma_2\ operator\ cost \qquad (4.9)$$

Where γ_1, γ_2 are weights of user cost and operator cost, and the sum of them equals to 1.

In order to evaluate all costs generated in the process of public transport service production, more factors should be considered in the total social cost function, such as external environment cost (examples can be found in the TEST project by Brand and Preston (2001, 2002a, 2002b, 2003a, 2003b, 2006), and in research by Jakob et al. (2006) and Hodgson (2011)) and wider economic impacts (such as Eddington (2006)).

The external environment cost includes accident costs for potential traffic accidents and environmental externalities like air pollution costs, noise pollution costs and climate change effects (Small, 1992; Litman, 2002). As both the accident costs and environmental costs are associated with the level of traffic volume (such as VKM), the total external cost therefore can be calculated by using the sum of unit cost of each external (Brand and Preston, 2001, 2002a, 2002b, 2003a, 2003b, 2006; Jakob et al., 2006; Hodgson, 2011).

According to *WebTAG Unit A2-1* (Department for Transport, 2014c), four categories of wider economic impacts should be considered in transport services production, including agglomeration impacts, output changes in imperfectly competitive markets, labour supply impacts, and move to more or less productive jobs. Steps in calculation process and required input data are summarised in DfT (2014c). However, the wider economic impacts were seldom considered in the published models, as large amount of economic data required to be collected and complicated application process.

4.3.2 Constraints

The choices of applied constraints vary by research objectives, and some of the widely-used ones are listed as follows:

- Demand satisfaction: setting minimum proportion of OD pairs that can be served by the public transit network (Chakroborty and Dwivedi, 2002; Ngamchai et al., 2003; Argwal and Mathew, 2004; Fan and Machemehl, 2004, 2006a, 2006b, 2008a, 2008b, 2011; Cipriani et al., 2012; Roca-Riu et al., 2012; Chew et al., 2013; Yan et al., 2013; Camporeale et al., 2016).
- Number of routes or total route length: setting upper threshold for number of routes or total route length in order to control the operating cost (Fan and Machemehl, 2004, 2006a, 2006b, 2008a, 2008b, 2011; Chew et al., 2013; Camporeale et al., 2016).
- Frequency feasibility: setting minimum and maximum frequency on each route (Pattnaik et al., 1998; Chakroborty, 2003; Tom and Mohan, 2003; Argwal and Mathew, 2004; Fan and Machemehl, 2004, 2006a, 2006b, 2008a, 2008b, 2011; Zhao, 2006; Zhao and Zeng, 2006, 2007; Cipriani et al., 2012; Szeto and Wu, 2012; Yan et al., 2013; Camporeale et al., 2016).
- Route length feasibility: setting minimum and maximum route length on each route (Chakroborty and Dwivedi, 2002; Fan and Machemehl, 2004, 2006a, 2006b, 2008a, 2008b, 2011; Zhao, 2006; Zhao and Zeng, 2006, 2007; Cipriani et al., 2012; Yan et al., 2013; Camporeale et al., 2016).
- The size of bus fleet: the maximum fleet size is set as one of the constraints in most studies, guaranteeing the optimal networks never use more vehicles than are available (Chakroborty, 2003; Fan and Machemehl, 2004, 2006a, 2006b, 2008a, 2008b, 2011; Zhao, 2006; Zhao and Zeng, 2006, 2007; Cipriani et al., 2012; Yan et al., 2013; Camporeale et al., 2016).
- Load factor: guarantees the maximum passenger flow cannot exceed the bus capacity on that route (Pattnaik et al., 1998; Chakroborty, 2003; Tom and Mohan, 2003; Argwal and Mathew, 2004; Fan and Machemehl, 2004, 2006a, 2006b, 2008a, 2008b, 2011; Zhao and Zeng, 2006, 2007; Cipriani et al., 2012; Yan et al., 2013).

4.4 Demand and Assignment sub-model

Demand data is an essential input for solving TNDP, and the usual way of representing this passenger demand is through an origin-destination (OD) matrix. An OD matrix has the set of points or zones as coordinates, with rows corresponding to the origins and columns to the destinations of the users. The OD matrix contains the number of passengers who wish to go from each origin to each destination in a given time period. In reality, the passenger demand will change based on the changes of the performance of the services, rather than being externally fixed. This is because passengers not only need to pay fares to use the transport services, but also need to pay their time. When passenger demand increases, the service frequency also increases, resulting in a reduce in average passenger waiting time cost. This 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 services, which has been discussed by Mohring (1972) and known as the Morhing effect. In terms of simplification, demand is assumed as fixed and independent of the service performance in the majority of published studies (Desaulniers and Hickman, 2007; Guihaire and Hao, 2008; Kepaptsoglou and Karlaftis, 2009; Ibarra-Rojas et al., 2015).

Based on the OD matrix demand data, the next problem is the passenger assignment problem: given an OD, which route through the transit network will be taken by passengers? *WebTAG Public Transport Assignment* (Department for Transport, 2014a) has listed various assignment methods, and provides detailed guidelines in choosing appropriate approaches with practical considerations. According to the *WebTAG* (Department for Transport, 2014a), each assignment method is characterized by two dimensions: frequency-based or schedule-based, and deterministic or stochastic assignment approach.

Schedule-based assignment method calculates explicit attributes that passengers consider at the time when they make a choice, while an average value is used as an alternative by the frequency-based method. For example, exact waiting time for each possible journey paths can be calculated based on the actual vehicle arrival/departure time by the schedule-based assignment method, while an average value (such as half the headway for services with headways up to 15 minutes, and after which the waiting time is capped at 7.5 minutes) is set by the frequency-based method.

Both deterministic and stochastic assignment methods are based on a basic assumption, that is all passengers choose the cheapest option to their destinations in terms of travel time (or travel cost). Based on that, the deterministic assignment method (also called all-or-nothing assignment approach) assumes that that all passengers share a perfect and equal perception of the travel time (or travel cost) to their destinations and that all choose the cheapest option in terms of travel time (or travel cost). While the stochastic assignment approach considers individual variations into the method. Passengers still choose the cheapest option, but they do not necessarily agree on what the cheapest option is (because different individuals have different utility functions). For instance, some passengers consider the cheapest option is the journey path with less transfers but a bit longer in-vehicle time, but others may prefer the option with shorter in-vehicle time but one or two more transfers as their cheapest choice.

Compared with the schedule-based and stochastic assignment method, the frequency-based and deterministic assignment method is simpler, requires less input data and less computational power. For simplicity, almost all published research choose a frequency-based and deterministic assignment method in solving the assignment problem.

4.5 Solution Techniques

In this section, solution techniques applied in the literature were grouped into two categories: solution techniques for single corridors (see section 4.5.1) and for complete networks (see section 4.5.2). In section 4.5.1, although analytical methodologies originated with Mohring (1972) and Jansson (1984) do provide a practical solution for corridor-based optimisation problems, they require continuous differentiable functions and will cause complicated calculation process for realistic and large-sized instances of TNDP. Practical methods to solve real-world TNDP therefore were summarised and discussed in detail in section 4.5.2, and were categorized as mathematical, heuristic, and meta-heuristic approach.

4.5.1 For a Stand-alone Corridor

Mohring (1972) developed a simple optimisation model to find the optimal frequency for a stand-alone corridor. The methodology is to minimise the total social cost (TSC) per peak hour of this stand-alone corridor, which is defined as a sum of total operator cost (TOC) and total user cost (TUC). Accordingly, the mathematical formulation of the model can be expressed as follows:

$$TOC = c_p N \tag{4.10}$$

$$TUC = qc_w W = {}^{qc_w}/_{2N} \tag{4.11}$$

$$TSC = c_p N + {}^{qc_w}/_{2N} \tag{4.12}$$

Subject to

$$q \leq NC \tag{4.13}$$

Where

N = number of vehicles per peak hour;

c_p = unit cost of vehicle per hour;

q = the number of passengers per peak hour on this route;

W = average passenger waiting time, and equals to half the headway ($^1/_N$);

c_w = unit cost of passenger waiting time;

C = the capacity of each bus.

Thus the optimal bus frequency N^* can be found by setting the derivative of TSC with respect to N equals to zero, and the corresponding equation is:

$$\frac{\partial\, TSC}{\partial N} = c_p - \frac{qc_w}{2N^2} = 0 \tag{4.14}$$

$$N^* = \sqrt{^{qc_w}/_{2c_p}} \tag{4.15}$$

Based on Mohring's (1972) original model, a more realistic model was developed by Jansson (1984). Just like Mohring's model, the objective function, total social cost (TSC) is defined as a combination of total operator cost (TOC) and total user cost (TUC). The TOC per hour is equal to the product of the number of vehicles per hour on this bus route (N) and the unit cost of vehicles per hour (c_p). The TUC is a sum of waiting time and riding time: the average waiting time per passenger is assumed to be half of the headway ($^1/_F$), and the total riding time per hour for passengers is equal to the product of unit cost of passenger riding time (c_r), the number of vehicles (N), and the mean occupancy per bus ($^Q/_F$). Accordingly, the mathematical formulation of the model can be expressed as follows:

$$TOC = c_p N \tag{4.16}$$

$$TUC = {^{qc_w}/_{2F}} + c_r N \frac{Q}{F} \tag{4.17}$$

$$TSC = c_p N + {^{qc_w}/_{2F}} + c_r N \frac{Q}{F} \tag{4.18}$$

Where

N = number of vehicles per hour;

c_p = unit cost of vehicle per hour;

q = the number of passengers per hour on this route;

c_w = unit cost of passenger waiting time;

F = frequency of services;

c_r = unit cost of passenger riding time;

Q = average passenger flow per hour.

The total round trip time (R) is the sum of running time per round trip (T) and the total time of boarding and alighting per round trip (q/F). The frequency of service (F) is equal to the product of the density of buses on the route (measured by number of buses per kilometre, N/D) and the overall speed (D/R), and can be expressed as follows:

$$F = \frac{N}{D} \times \frac{D}{R} = \frac{N}{T+t(q/F)} = \frac{N-tq}{T} \quad (4.19)$$

Where

D = round trip distance of the route;

R = total round trip time;

T = running time per round trip;

t = boarding and alighting time per passenger;

Thus, TSC can be written as a function of N:

$$TSC = c_p N + \frac{q c_w T}{2(N-tq)} + \frac{c_r NQT}{N-tq} \quad (4.20)$$

The optimal number of buses on the route N^*therefore can be found by setting the derivative of total social cost with respect to N equals to zero, and the corresponding equation is:

$$\frac{\partial TSC}{\partial N} = c_p - \frac{q c_w T}{2(N-tq)^2} - \frac{c_r tqQT}{(N-tq)^2} = 0 \quad (4.21)$$

$$N^* = \sqrt{\frac{qT({}^{c_w}/_2 + c_r tQ)}{c_p}} + tq \quad (4.22)$$

Accordingly, the optimal frequency of service F^*can be obtained by following equation:

$$F^* = \frac{N^*-tq}{T} = \sqrt{\frac{q({}^{c_w}/_2 + c_r tQ)}{T c_p}} \quad (4.23)$$

Although the analytical methods developed by Mohring (1972) and Jansson (1984) are corridor based and require continuous differentiable functions, they do provide a practical methodology to find the optimal frequency. Based on the cost functions displayed above, methodologies of finding optimal bus size and best pricing system were discussed in the research of Jansson (1984 and 2015) as well.

4.5.2 For Bus Networks

According to global reviews carried out by Desaulniers and Hickman (2007), Guihaire and Hao (2008), Kepaptsoglou and Karlaftis (2009), and Ibarra-Rojas et al. (2015), there are mainly three categories of solution techniques that are applied in published studies for public transport network optimisation, they are mathematical, heuristic, and meta-heuristic approach.

4.5.2.1 Mathematical Techniques

The TNDP is known to be NP-hard (non-deterministic polynomial-time hard), which means that it is impossible to find a definitive optimal solution within a realistic span of calculation time. Instead, some reasonably 'good' solutions can be obtained by algorithms in a reasonable length of calculation time, which should provide a significant improvement on an initial or random solution. Therefore, the NP-hard intractability is due to the need to search for optimal solutions from a large search space made up by all possible solutions (i.e. the set of theoretically possible transit routes), and it causes difficulties in developing efficient optimisation methods with traditional mathematical programming techniques (Zhao, 2006; Desaulniers and Hickman, 2007; Guihaire and Hao, 2008; Kepaptsoglou and Karlaftis, 2009; Ibarra-Rojas et al., 2015). Hence, the mathematical approaches are only capable of solving small-size instances with a simple or idealized network structure, and available models have been presented by Holroyd (1967), Hurdle (1973), Byrne (1975, 1976), Kocur and Hendrickson (1982), Tsao and Schonfeld (1984), Chang and Schonfeld (1991, 1993a, 1993b), Spacovic and Schonfeld (1994), Spacovic et al. (1994), Chien and Schonfeld (1997), Chien and Spacovic (2001), Wan and Lo (2003), and Guan et al. (2003).

4.5.2.2 Heuristic Techniques

In order to explore practical methods to solve realistic and large-sized instances of TNDP, heuristic techniques are then employed as an alternative to the mathematical approaches. Heuristics are approaches which designed for finding optimal solutions of a practical optimisation problem with limited computation capacity. Detailed information in methodology developing and model performances for real-world size instances are proposed by Lampkin and Saalmans (1967), Silman et al. (1974), Bel (1979), Dubois et al. (1979), Ceder and Wilson (1986), Van Nes et al. (1988), Carrese and Gori (2002), Ceder (2003) and Lee and Vuchic (2005). Although the heuristic approaches have been proved to have ability to find reasonably good solutions for realistic and large-sized problem instances, but do not guarantee to output global or even local optimal solutions. This limitation can be solved by meta-heuristics algorithms, which employ efficiently iterative mechanisms to explore a large solution space aiming to find the global optimal solution or at least a local one, thus are widely adopted in current literature.

4.5.2.3 Meta-heuristic Techniques

New approaches based on meta-heuristic techniques have been widely applied to solve the TNDP, and widely used examples covered in the literature are genetic algorithm (GA) (e.g. Pattnaik et al., 1998; Chakroborty and Dwivedi, 2002; Chakroborty, 2003; Ngamchai et al., 2003; Tom and Mohan, 2003; Argwal and Mathew, 2004; Fan and Machemehl, 2004, 2006a, 2006b, 2008a, 2008b, 2011; Zhao and Zeng, 2006, 2007; Cipriani et al., 2012; Szeto and Wu, 2012; Chew et al., 2013; Camporeale et al., 2016), neighbourhood search (NS, also called local search) algorithm (e.g. Fan and Machemehl, 2004), Simulated Annealing (SA) algorithm (e.g. Fan and Machemehl, 2004, 2006b; Zhao, 2006; Zhao and Zeng, 2006, 2007; Yan et al., 2013), and Tabu Search (TS) algorithm (e.g. Fan and Machemehl, 2004, 2008a, 2008b, 2011; Roca-Riu et al., 2012). Each of these algorithms will be explained in detail in the following sub-sections, and Table 4-2 will compare their advantages and shortcomings at the end of this section.

4.5.2.3.1 Genetic Algorithm

Firstly introduced by Holland (1975), GA is the most widely used meta-heuristic algorithm in the literature for solving TNDP, based on natural evolution principle that genes can be transferred from a generation to its next generation in the form of inheritance and mutation. Details of applying GA technology in the optimisation models have been discussed in the published literature, such as Goldberg (1989), Chambers (1995) and Michalewicz (1999).

The GA starts with a population made up of a certain amount of individuals (sometimes called strings, or chromosomes). One individual represents one problem solution, thus the GA begins with a group of initial solutions. Each individual is associated with a fitness function. The fitness function judges how the individual performs in terms of the optimised objectives. The algorithm then uses the fitness function values to evaluate the survival capacity of each individual in the population, which then contribute to the generation of new populations by genetic operators (reproduction, crossover, and mutation).

- Reproduction (also named selection) is usually the first operator applied on a population. Reproduction is a process in which individuals are copied as parent individuals according to their fitness function values, which means that the individual with higher value has a higher probability of contributing one or more offspring in the next generation.

- Crossover: generate child individuals by combining sub-individuals from parent individuals. Good sub-individuals from either parent individual can be combined to form a better child individual if appropriate site is chosen. Since the knowledge of an appropriate site is usually not known, a random site is chosen.
- Mutation: generate child individuals by combining sub-individuals from parents, as well as randomly selected sub-individuals from the search space. The need for mutation is to keep diversity in the population.

The population is further evaluated and tested for termination. If the termination criteria are not met, the population is again updated using the three genetic operators and evaluated. In GA, a maximum number of generations is generally used as the termination criteria (see Figure 4-1).

When implementing GA in solving TNDP, the steps in the process can be described as follows:

- Step 1: generate initial population (a set of individuals) randomly, and evaluate every individual in the initial population by fitness function (objective function): one individual represent one possible bus network (i.e. a set of bus routes with associated frequencies), and the number of individuals involved in the initial population are decided by research objectives.
- Step 2: generate new (next) population by reproduction, crossover, and mutation.
    - Step 2.1: the reproduction procedure: select best two individuals (or best ones) from the initial population as parent individuals.
    - Step 2.2: the crossover procedure: sub-individuals (e.g. half number of total routes across the network) are randomly chosen from the parent individuals and are combined together to form child individuals.
    - Step 2.3: the mutation procedure: child individuals are generated by selecting part of routes (for example, half number of total routes across the network) from the parent individuals, and randomly selecting the remaining routes from the candidate route set.
    - Step 2.4: combine all the parent individuals selected from the reproduction procedure and child individuals generated from the crossover and mutation procedure together to form a new population.
- Step 3: update the new population as the initial population, and repeat step 2 until the maximum number of generations allowed in the model has been reached.

The mechanics of GA are very simple and involves nothing more than copying strings or swapping partial strings. The simplicity of the calculations and the ability to find good solutions are two characteristics that make the GA approach very attractive. However, the optimal solutions output from the GA are only the optima based on the initial population, the chief limitation of GA therefore is that it only outputs locally optimal solutions that may be far from the global optimum.

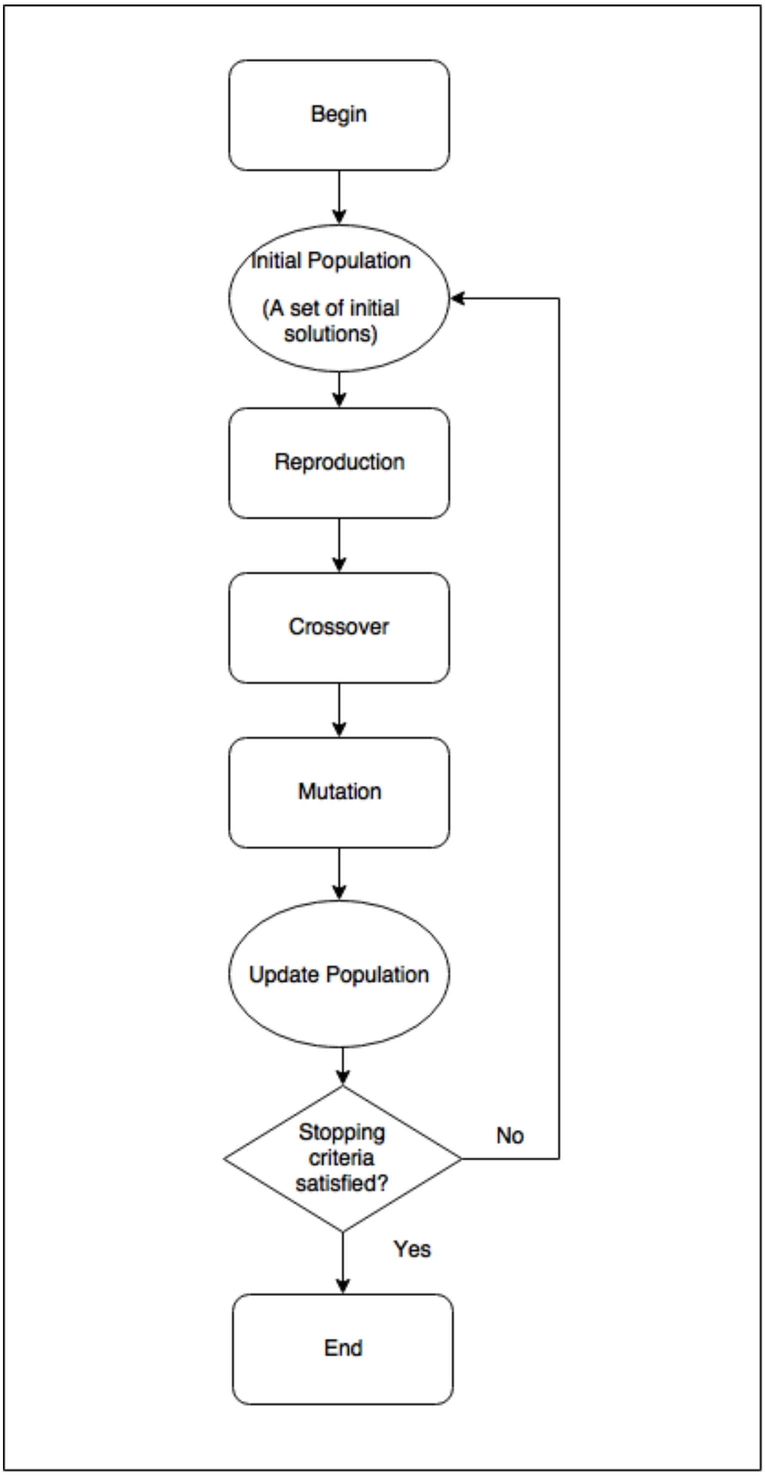

Figure 4-1 Workflow of Genetic Algorithm

4.5.2.3.2 Neighbourhood Search

In contrast to a set of initial solutions in the GA, the NS algorithm, begins the search procedure with one single initial solution, and explores the solution space by moving from the input initial solution to the solution with the best objective function value in its neighbourhood at each iteration (see Figure 4-2 and Figure 4-3). The neighbourhood of the initial solution is defined as a set of solutions which are similar with the initial solution except for minor details, such as having several different variables. Moves are defined as the sequences that lead from the initial solution to another solution in the neighbourhood. For example, the standard swap (or add/drop) move transforms the current solution into a new one by replacing one variable in the current solution by another one in search space (e.g. in TNDP, the standard swap move produces a new possible bus network by replacing only one bus route of the current bus network). Based on the 'small' swap moves, NS algorithm is able to investigate a huge number of solutions in a short time, but all examined solutions are similar just with minor difference, thus the algorithm is easily trapped in the local optima (Michalewicz and Fogel, 2004; El-ghazali, 2009). In order to overcome the limitations of the NS, large neighbourhood search (LNS) algorithm was introduced by Shaw (1997). Instead of 'small' moves, LNS adopts 'large' moves in the algorithm, which means pre-set parameter *q* decides *q* variables in the current solution will be replaced to form a new one. The larger number of *q* will contribute to a larger neighbourhood, more global optima, and longer calculation time needed for evaluation (Ropke and Pisinger, 2006; Pisinger and Ropke, 2010).

The iterations will continue until the termination criteria are met. There are mainly three categories of criteria implemented in the literature: 1) a maximum number of iterations (or a maximum length of calculation time); 2) no improvement is seen in the value of the objective function value after some number of consecutive iterations; 3) a pre-specific threshold value is reached by the objective function (Michalewicz and Fogel, 2004; El-ghazali, 2009).

When implementing NS in solving TNDP, the steps in the process can be described as follows:

- Step 1: generate initial solution (i.e. a set of bus routes with associated frequencies) randomly, evaluate it by objective function, and save it as the current best solution.
- Step 2: generate the set of feasible neighbours by randomly replacing one (or several) bus route in the current best solution by a new route (routes), and evaluate each solution in the set by objective function.
- Step 3: compare the best neighbour solution with the current best solution:
    - If the best neighbour is better than the current best solution: update it as the current best.

  - If the best neighbour is worse than the current best solution: directly go to next step.
- Step 4: repeat step 3 until the maximum number of generations allowed in the model has been reached.

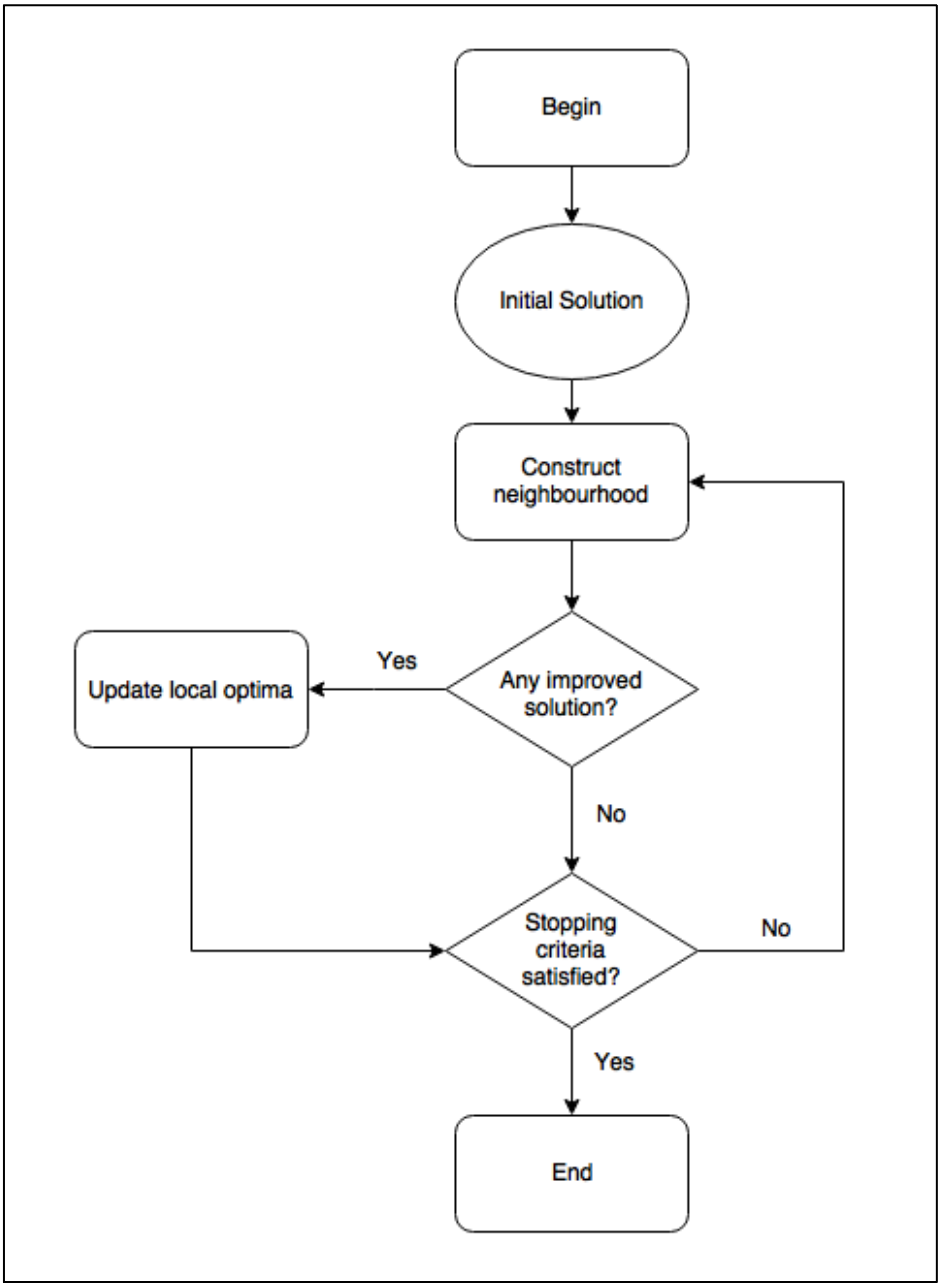

Figure 4-2 Workflow of Neighbourhood Search

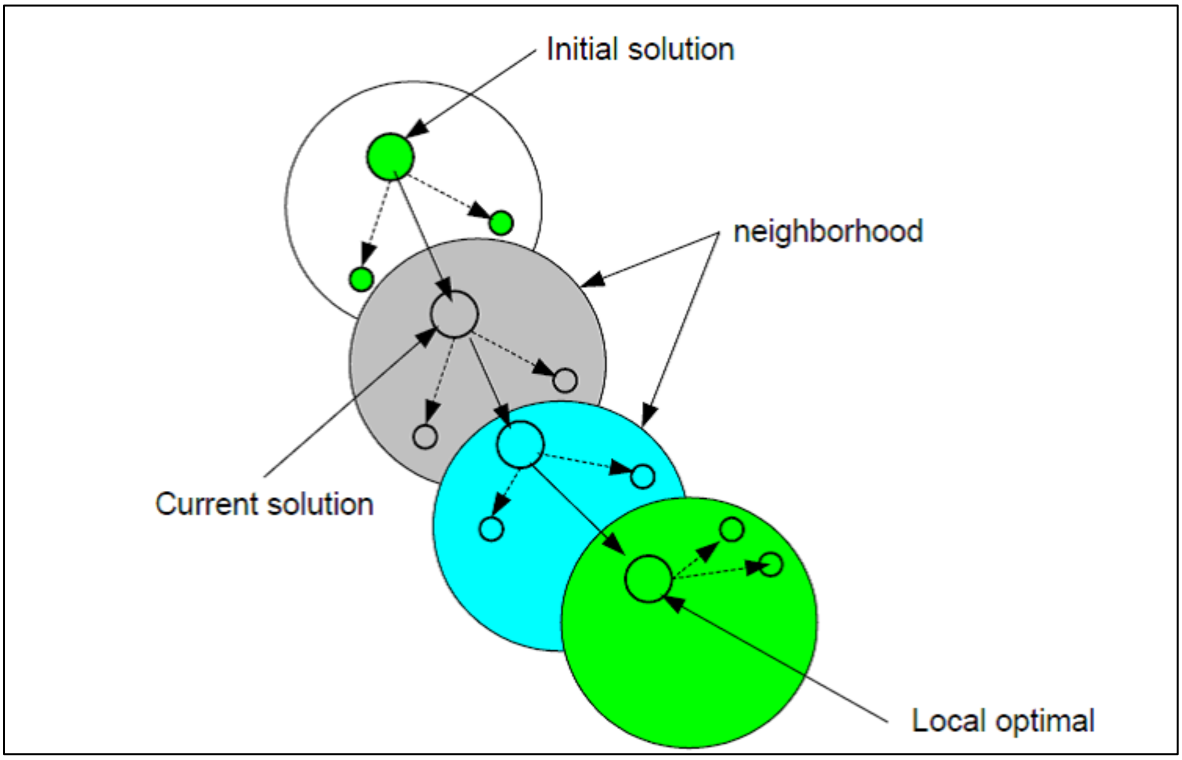

Figure 4-3 Graphical Representations for Neighbourhood Search (Fan and Machemehl, 2004)

4.5.2.3.3 Simulated Annealing

The term 'simulated annealing' is derived from the process of heating and then cooling a substance slowly to finally arrive at the solid state, and the method has been displayed in detail by Eglese (1990) and Koulamas et al. (1994).

Similar to the traditional neighbourhood search procedure, the SA starts the search procedure with an initial solution and searches optimal solutions in the neighbourhood by moves. Furthermore, the SA adopts an important concept, called 'temperature', in the algorithm. The value of the temperature represents which iteration the current calculation is on, and will be decreased by cooling function. For example, the initial temperature is set as 1.0 and decreases at the end of each iteration by multiplying it by a constant parameter (α), which is set between 0 and 0.99. The calculation will iterate until the current temperature is cool enough (the stopping criteria).

Compared with the NS, the performance of the SA is improved by adopting an acceptance probability function, which judges whether worse moves could be accepted in the process of exploring the solution space or not. The function is decided by two factors: 1) how much worse the neighbourhood solution is; 2) how high the current 'temperature' is. Basically, the better the neighbourhood solution is and the higher the current temperature is, the SA has larger probability to accept this worse solution.

The workflow of SA is illustrated in Figure 4-4. A slower cooling procedure and more iterations at each temperature level will contribute to a greater probability of achieving a more global optimum, but at the expense of a longer calculation time and longer execution time.

When implementing SA in solving TNDP, the steps in the process can be described as follows:

- Step 1: generate initial solution (i.e. a set of bus routes with associated frequencies) randomly, evaluate the initial solution by objective function, and save it as the current best solution.
- Step 2: select an initial temperature, and save the initial temperature as current temperature.
- Step 3: generate the set of feasible neighbours by randomly replacing one (or several) bus route in the current best solution by new route (routes), and evaluate each solution in the set by objective function.
- Step 4: compare the best neighbour solution with the current best solution:
    - If the best neighbour is better than the current best solution: update it as the current best.
    - If the best neighbour is worse than the current best solution:
        - If the worse move is accepted by the acceptance probability function: update the best neighbour as the current best.
        - If the worse move is refused by the acceptance probability function: directly go to next step.
- Step 5: update current temperature by the cooling function, and repeat step 4 until the current temperature is cool enough.

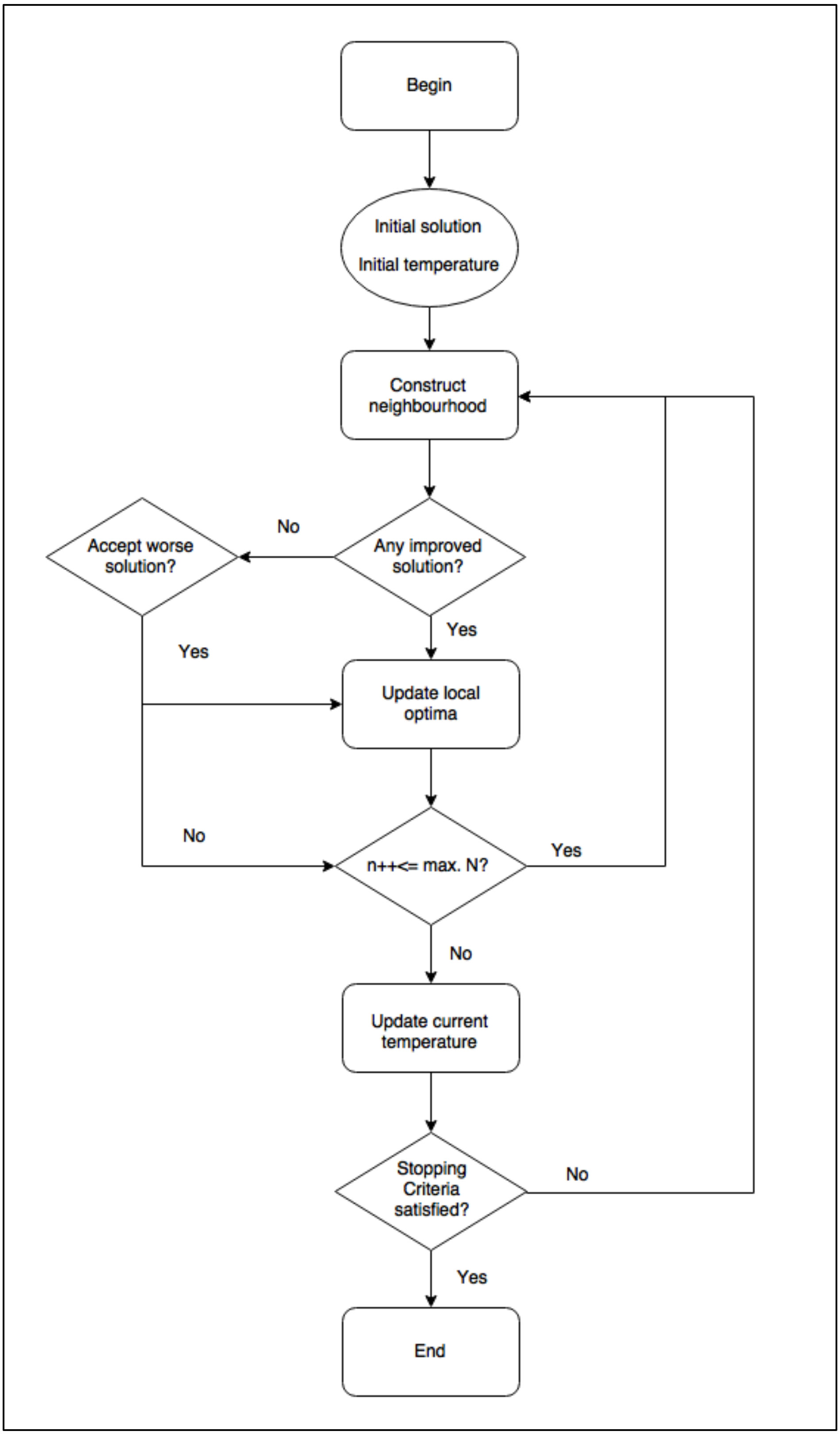

Figure 4-4 Workflow of Simulated Annealing

4.5.2.3.4 Tabu Search

The tabu search (TS) algorithm was designed by Glover (1977), and it is now one of the most successful meta-heuristic algorithms used for solving optimisation problems. Descriptions of both basic and advanced versions of tabu search can be found in Glover and Laguna (1997).

Similar to the NS and SA algorithms, the TS algorithm begins with one initial solution and searches optimal solutions in the neighbourhood by moves. However, the TS algorithm implements the 'memory', which makes it more talented than other meta-heuristic algorithms. Tabu lists used by the algorithm form the tabu search memory, which can be cleaned out after a certain number of iterations (short-term memory) or can be permanent throughout the entire process (long-term memory). Using short-term memory, solutions that were recently examined by the TS algorithm are declared forbidden or 'tabu' for a certain number of iterations (tabu tenures), thus avoiding duplicate calculations occurring in later iterations. The tabu status of a solution might be overridden if it is better than the current best solution, which is called 'aspiration'. In other words, TS algorithm makes the best available move at each step. Furthermore, the TS algorithm will output more global optima by adding intensification and diversification strategies based on the long-term memory. Intensification strategies focus on examining neighbours of the good solutions, which may initiate a return to attractive regions to search them more thoroughly. Diversification encourages the search process to examine unvisited regions and to generate solutions that differ in various significant ways from those seen before (see Figure 4-5).

When implementing TS in solving TNDP, the steps in the process can be described as follows:

- Step 1: generate initial solution (i.e. a set of bus routes with associated frequencies) randomly, evaluate the initial solution by objective function, and save it as the current best solution.
- Step 2: set the set of tabu neighbours to be empty.
- Step 3: generate the set of feasible neighbours by randomly replacing one (or several) bus route in the current best solution by new route (routes), and evaluate each solution in the set by objective function.
- Step 4: define the set of non-tabu neighbours as the difference between the set of feasible neighbours and the set of tabu neighbours.
    - If the best neighbour from the set of non-tabu neighbours is better than the current best solution, update it as the current best solution and add it to the set of tabu neighbours.

    - If the best neighbour from the set of non-tabu neighbours is worse than the current best solution, compare the best neighbour from the set of feasible neighbours and the current best solution.
        - If the best neighbour from the set of feasible neighbours is better than the current best solution, update it as the current best solution and add it to the set of tabu neighbours (tabu search aspiration process).
        - If the best neighbour in the set of feasible neighbours is worse than the current best solution, update the best solution from the non-tabu neighbours as the current best solution and add all neighbours in the set of feasible neighbours to the set of tabu neighbours.
- Step 5: apply the diversification and intensification procedure to the current best solution.
- Step 6: repeat step 3 - step 5 until the maximum number of generations allowed in the study has been reached.

Although the tabu search memory helps to build a more efficient search procedure and output more global optima results, the performance of TS algorithm is heavily dependent on the self-set parameters: such as iteration number, tabu tenures, and initial solution. Good parameter settings could output satisfactory results, while poor ones would reduce the speed of convergence and lead to a failure (Glover, 1989, 1990; Morz, 2006; Gendreau and Potvin, 2010).

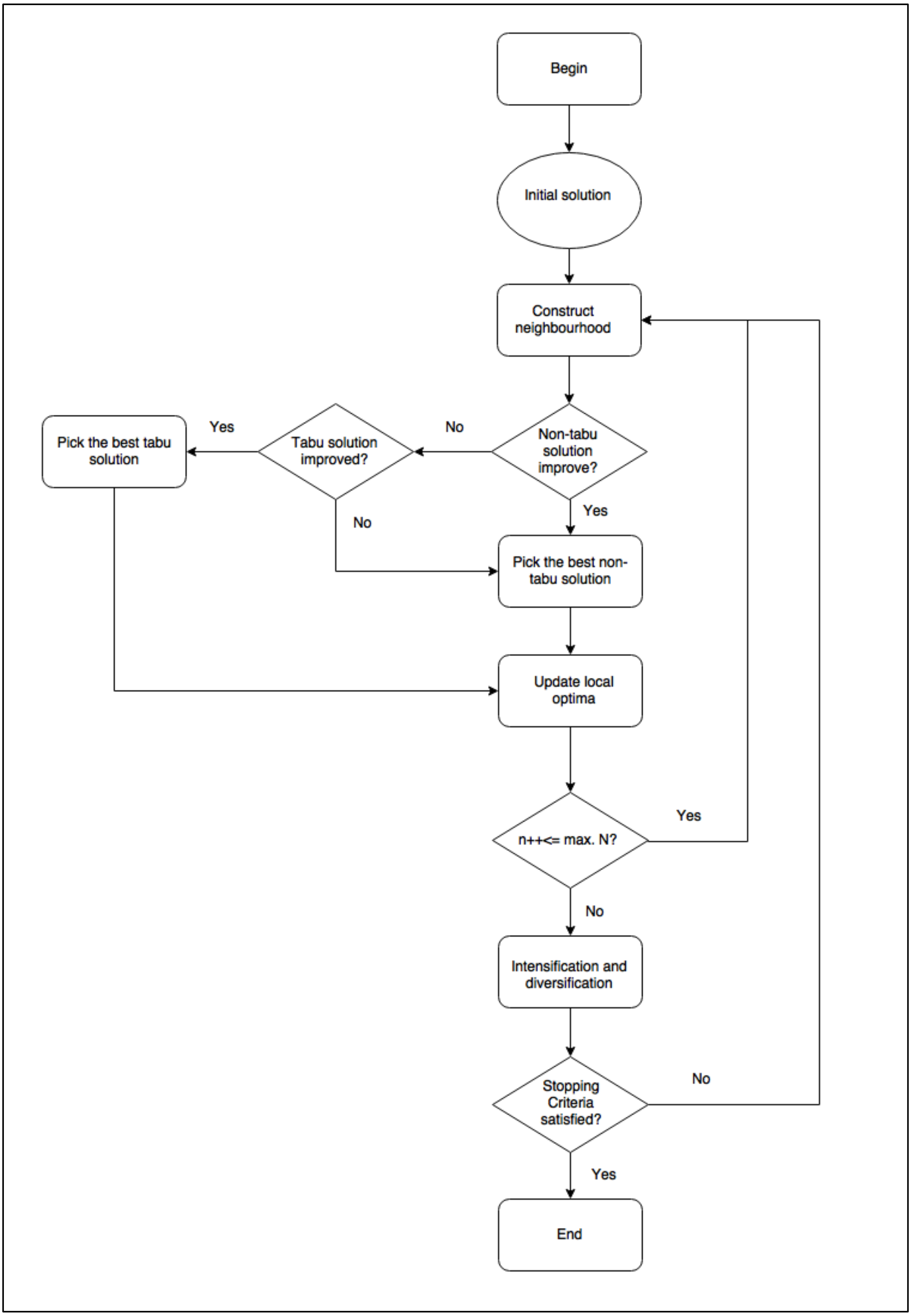

Figure 4-5 Workflow of Tabu Search

4.5.2.3.5 Summary

Four meta-heuristic approaches, GA, NS, SA, and TS, have been summarized and compared in Table 4-2, and can be categorized into two sub-categories: population based and single-solution based algorithms. The population based algorithms search for optimal solutions based on a set of initial solutions, and only GA belongs to this category. The remaining three algorithms are single-solution-based algorithms, which begin the search procedure by one single initial solution, and explore the solution space using the definitions of 'neighbourhood' and 'moves'.

Although GA and NS are simple and can be easily implemented in practice, the chief limitation of them is that they only output locally optimal solutions that may be far from the global optimum. In order to overcome this limitation, more advanced algorithms, SA and TS, were designed. Both algorithms share similar neighbourhood search procedures with the NS algorithm, but reduce the probability of being stuck in local optimum. The SA improves the quality of final results by accepting temporarily worse moves in the search procedure. While in TS algorithm, both short-term and long-term memory help to build a more efficient search procedure and output more global optima results.

Despite its known shortcomings, published studies mainly focus on GA, whereas other potential meta-heuristic algorithms, such as SA and TS algorithms, are seldom used to solve the TNDP (Desaulniers and Hickman, 2007; Guihaire and Hao, 2008; Kepaptsoglou and Karlaftis, 2009; Ibarra-Rojas et al., 2015). The numerical results from the papers by Fan and Machemehl (2004, 2008a, 2008b) compared TS with other meta-heuristic algorithms (i.e. GA, NS, and SA), and clearly indicate that the TS algorithm outperforms the others in solving the TNDP for a case study network with 160 nodes and 418 links. Based on the literature review and the research aim, an adapted TS algorithm was chosen as the methodology for optimising the bus network in this thesis.

Table 4-2 Comparison of Meta-heuristic Algorithms

Category	Characteristics	Advantages	Shortcomings
Genetic Algorithm	• Population-based algorithm; • Based on selection, crossover, and mutation.	• Simple algorithm and easy to implement; • Quick to converge.	• Only output locally optimal solutions.
Neighbourhood Search	• Single-solution based algorithm; • Based on neighbourhood search.	• Simple algorithm and easy to implement; • Quick to converge.	• Only output locally optimal solutions.
Simulated Annealing	• Single-solution based algorithm; • Accept temporary worse moves.	• Output more global optimum, compared with NS.	• Longer calculation time.
Tabu Search	• Single-solution based algorithm; • Accept temporary worse moves; • Add 'memory', both short and long term.	• Output more global optimum; • Avoid duplicate calculations in iterations.	• Longer calculation time; • Sensitive to self-set parameters.

4.6 Applying Meta-Heuristics to Solve the TNDP

According to the literature, such as Desaulniers and Hickman (2007), Guihaire and Hao (2008), Kepaptsoglou and Karlaftis(2009), and Ibarra-Rojas et al. (2015), there are three stages which are involved in solving TNDP using meta-heuristic approaches, they are candidate route generation procedure, selection procedure, and evaluation procedure (see Figure 4-6).

In candidate route generation procedure, all potential candidate routes are generated, relying on shortest path algorithms, such as Dijkstra's shortest path algorithm (Ahuja et al., 1993) and Yen's shortest path algorithm (Yen, 1971). Then, all candidate routes should to be filtered through some user-defined constraints, such as minimum and maximum route length constraints. Based on this generated candidate route set, a possible optimum set of routes (potential solution) could be selected by meta-heuristic algorithms in the selection procedure. Each potential solution is then evaluated in the evaluation procedure which assigns the OD demand data, determines frequency on each route, and calculates values for the objective function. The choice of planning objective will differ when varying the priority given to the conflicting interests of passengers and operators. Iteration will continue between the selection and evaluation procedure until a pre-specified calculation time or number of solutions has elapsed. The final output of this optimisation model is then an optimal bus network as measured by objective function, consisting of a set of bus routes with associated frequencies.

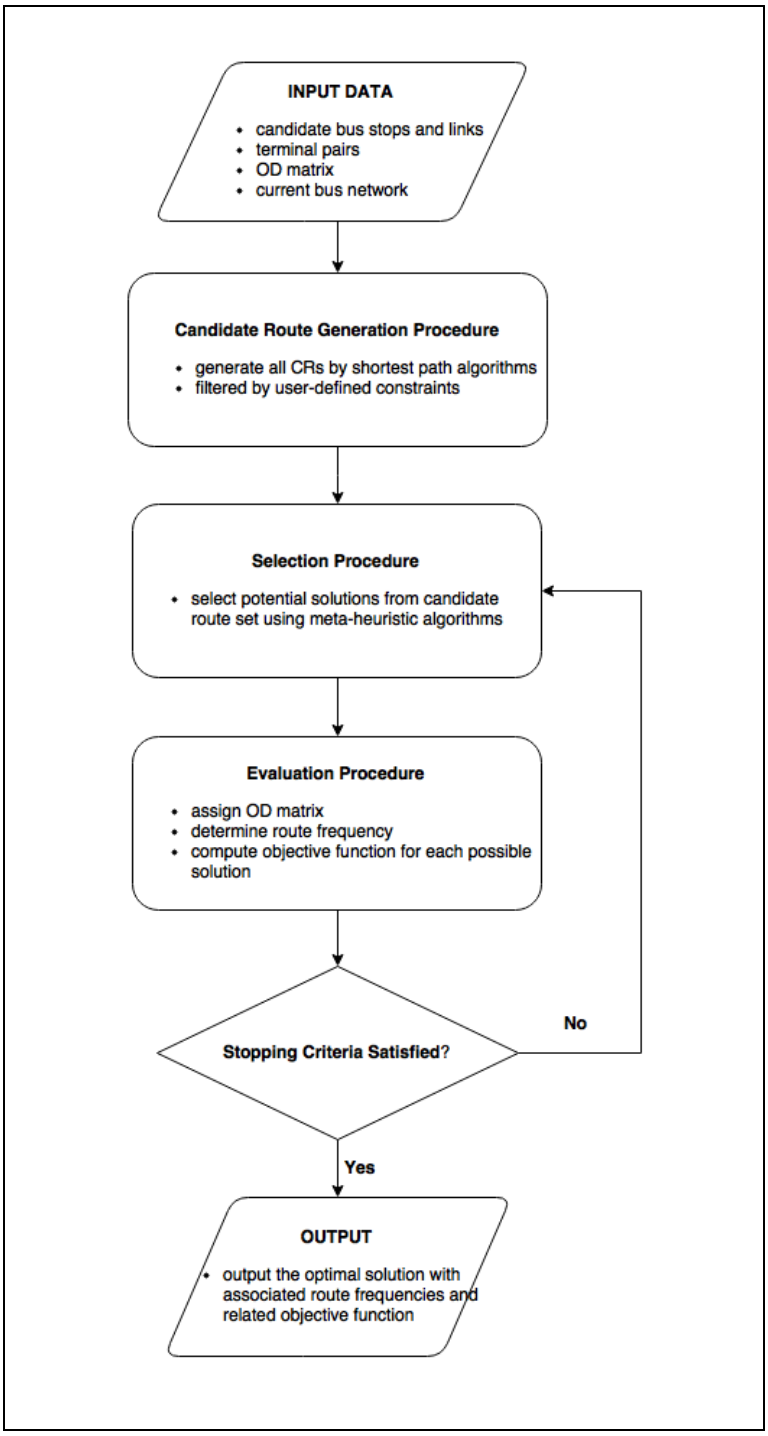

Figure 4-6 Procedures of TNDP

4.7 Deficiencies of Current Studies

Table 4-3 summarises and compares recent published studies for solving TNDP using meta-heuristic methods based on objective function, constraints, solution techniques and case study application. In summary, these approaches have following shortcomings:

1) Complicated but impractical methodologies: Many studies focus on using complicated methodologies to improve small-scale networks. For example, the Swiss road network (a small network with 15 nodes and 21 links) designed by Mandl (1979) is widely used by many studies, such as Chakroborty and Dwivedi (2002), Chakroborty (2003), Zhao (2006), Zhao and Zeng (2006, 2007), Chew et al. (2013), and Yan et al. (2013). These small networks are an order of magnitude smaller than a real life bus network in anything other than the smallest of urban areas, and therefore the approaches described in these papers could not be directly applied to the city-scale bus network being considered in this research.
2) Data demanding: An OD matrix is used to provide the input demand data for all studies listed in Table 4-3, and is essential for the route planning and frequency setting associated with the assignment sub-model of studies. However, comprehensive OD matrices are unavailable for British bus networks outside London due to commercial confidentiality under the current deregulated environment where multiple operators run (or could in theory run) services in a particular urban area. While mode-specific OD data is available from the 2011 Census for commuting trips, there is no corresponding demand data for other travel purposes making it impossible to construct a comprehensive OD matrix without carrying out extensive survey work.
3) Limited range of methodologies: Previous studies mainly focus on GA, despite their known shortcomings, whereas other potential meta-heuristic algorithms, such as TS, are seldom used to solve the TNDP, with the papers by Fan and Machemehl (2004, 2006a, 2006b, 2008a, 2008b, 2011) the only ones which are known to the author.
4) Lack of intermodal integration: The published studies only focus on the improvements of single mode transit networks (for all studies listed in Table 4-3, only bus and walking were considered as available travel modes), and there is less consideration of integrated improvements of multi-modal public transport networks, which might in practice be expected to form the basis of a regulated transit system.

Table 4-3 Current TNDP Studies Using Meta-heuristics

Authors (year)	**Objective function**	**Constraints**	**Solution technique**	**Application**
Pattnaik et al. (1998)	Min. weighted sum of operator cost and user cost	• Frequency feasibility • Load factor	GA	Small network with 25 nodes and 39 links.
Chakroborty and Dwivedi (2002)	Min. weighted sum of unsatisfied demand, total travel time, and passengers with more than two transfers	• Route length feasibility	GA	Mandl's (1979) Swiss road network: small network with 15 nodes and 21 links.
Chakroborty (2003)	Min. user transfer time and waiting time	• Fleet size • Load factor • Frequency feasibility • Maxi. transfer time	GA	Mandl's (1979) Swiss road network: small network with 15 nodes and 21 links.
Ngamchai et al. (2003)	Min. weighted sum of operator cost, user in-vehicle cost, and user waiting cost	• Demand satisfaction	GA	Small network with 13 nodes and 13 links
Tom and Mohan (2003)	Min. weighted sum of operator cost and user travel cost	• Frequency feasibility • Load factor	GA	Medium network with 75 nodes and 125 links
Argwal and Mathew (2004)	Min. weighted sum of operator cost and generalized travel cost (user cost)	• Frequency feasibility • Load factor • Demand satisfaction	GA	Real-world size network (Delhi, India)
Fan and Machemehl (2004, 2006a, 2006b, 2008a, 2008b, 2011)	Min. weighted sum of operator cost , user cost, and unsatisfied demand	• Route length feasibility • Maxi. Route number • Frequency feasibility • Fleet size • Load factor	GA / NS/ TS/ SA	Medium network with 160 nodes and 418 links
Zhao (2006)	Min. user cost	• Route length feasibility • Frequency feasibility • Fleet size	SA	Mandl's (1979) Swiss road network: small network with 15 nodes and 21 links.

Authors (year)	Objective function	Constraints	Solution technique	Application
Zhao and Zeng (2006, 2007)	Min. weighted sum of operator cost and user cost	• Frequency feasibility • Load factor • Fleet size • Route length feasibility	GA/ SA	Mandl's (1979) Swiss road network: small network with 15 nodes and 21 links.
Cipriani et al., (2012)	Min. weighted sum of operator cost , user cost, and unsatisfied demand	• Load factor • Route length feasibility • Frequency feasibility	GA	Real-world size network (the urban area of Rome)
Szeto and Wu (2012)	Min. weighted sum of the number of transfers and user travel time	• Frequency feasibility • Fleet size • Number of transfer stops • Max. travel time	GA	Real-world size network (Tin Shui Wai, Hong Kong)
Roca-Riu et al. (2012)	Min. weighted sum of operator cost and user cost	• Demand satisfaction	TS	Real-world size network (City of Barcelona, Spain)
Chew et al. (2013)	Min. weighted sum of operator cost and user cost	• Number of stops along route • Max. routes number • Demand satisfaction	GA	Mandl's (1979) Swiss road network: small network with 15 nodes and 21 links.
Yan et al. (2013)	Min. operator cost	• Fleet size • Frequency feasibility • Route length feasibility • Load factor • Demand satisfaction • Travel time reliability	SA	Mandl's (1979) Swiss road network: small network with 15 nodes and 21 links.
Camporeale et al. (2016)	Min. weighted sum of operator cost , user cost, and unsatisfied demand	• Route length feasibility • Max. routes number • Frequency feasibility • Fleet size • Demand satisfaction • Equity	GA	Small network: 10 nodes and 19 links

4.8 Conclusion

Chapter 4: Review of Optimisation Models

This chapter reviewed published literature on solving the TNDP, and mainly focused on discussing three essential components, objective function and constraints (in section 4.3), demand and assignment sub-model (in section 4.4), and solution techniques (in section 4.5), of modelling it. Based on the research aim and available input data, a practical optimisation model based on a Tabu-Search methodology was developed following the three-stage methodology described in section 4.6. Detailed model building processes, including data preparation, model formulation, and methodology, are described in Chapter 6.

Chapter 5: Accessibility Model

5.1 Introduction

In this chapter, an accessibility model was developed to measure the performance of the current bus networks by calculating gravity-based accessibility levels from population-weighted centroids of postcodes to key services (including education, health, city/town/district centres, employment centres, and open spaces). This model is based on the findings from the review of evaluation methods for bus network performance described in Chapter 3. There are four steps involved in the calculation process, which are calculation of travel costs, calculation of service-specific accessibility index using gravity-based measures, calculation of composite accessibility index, and visualization of final results. Among them, the first step, calculation of travel costs for each potential OD pairs, is crucial, and an integrated ArcGIS model was therefore developed using ArcObjects for Java. Compared with other published models, this self-built ArcGIS model has following characteristics:

- By applying the 3D capability of ArcGIS, the model is designed for multimodal public transport systems: three modes, bus, walking and rail services, are considered in the model. Walking is considered to be the only available access and egress mode for bus services. Rail services are considered in the model alongside bus and walk options in order to develop an integrated and realistic representation of accessibility levels based on the public transport network.
- Four attributes which contribute to the travel cost are included in this model, including walking time (consisting of access time, egress time, and transfer walking time between public transport stops), waiting time (both origin and transfer waiting time), in-vehicle time, and transfer penalties.
- The calculation is based on the real public transport timetable: In order to improve the accuracy of the final results, both in-vehicle time and waiting time are calculated based on the real timetable in this model. The value of in-vehicle time is the difference between the time the bus/train arrives at the destination stop and the time the bus/train departs from the origin stop; and waiting time is modelled as the difference between the next available departure time and the time the passenger arrives at this stop.

The remainder of this chapter is divided into four sections. Section 5.2 lists the input data required by the accessibility model. The four-step methodology follows in section 5.3. Steps in building the ArcGIS model for travel costs calculation were described in detail in section 5.4. The final section summarises and discusses the whole chapter.

5.2 Model Requirements

Three categories of input data are required in the accessibility model: road network, routes and timetable data of the current public transport networks, and possible origin-destination (OD) pairs. While the data collection and preparation process described here focuses on the British context, the general principles could be applied equally well in other contexts around the world.

5.2.1 Road Network

The Ordnance Survey's (OS) Integrated Transport Network (ITN) is used to represent the road network in this research, and can be directly downloaded from the Digimap website (http://digimap.edina.ac.uk/) by academic users. ITN contains details of the road network for Great Britain and is continuously updated by the Ordnance Survey. It covers details about each link of the network such as the road class (A roads, B roads, minor roads, local streets and private roads), nature of road (e.g. single carriageway, dual carriageway) and the road routing information (route restriction information such as banned turns, one-way restrictions and so on) (Ordnance Survey, 2007).

5.2.2 Public Transport Network Data

Starting in 2004, Department for Transport (DfT) yearly published the National Public Transport Data Repository (NPTDR), which is a snapshot of route and timetable data for all public transport services in Great Britain. The week was normally the first or second complete week in October to ensure that it avoids school holidays or other seasonal variations and to achieve consistency from one year to the next. From 2011, the NPTDR was replaced by Traveline National Dataset (TNDS), which is updated weekly by Traveline Information Limited. Both datasets are free and can be download from the website www.data.gov.uk. All of the route and timetable data is referenced to stops coded using the National Public Transport Access Nodes (NaPTAN) database, available from the same website.

Both NPTDR and TNDS are supplied in TransXChange (TXC) format, which is a general purpose interchange format for timetable information and can be applied to any mode of public transport. Although the TXC files provide a highly adaptable transfer format for timetable information, they are verbose and unsuitable for direct analysis by most software packages, including ArcGIS. This problem was solved by linking Python to ArcGIS to convert TXC format files to Geodatabase format. This involved using the Python ElementTree module (xml.etree.ElementTree) to parse the TXC files into CSV (comma-separated values) files, and applying geocoding functions in ArcGIS to geo-locate them (See Figure 5-1).

Based on the research objectives, stops, routes and timetable data of public transport networks are essential input data for the accessibility model. The following three CSV files were therefore output from the Python conversion process, and the Python codes used can be found in Appendix A:

- Stops file: details of all stops included in the schedules are listed, including stop name and NaPTAN ATCO code. The ATCO codes are identifier for bus stops in the NaPTAN dataset, and each bus stop has a unique ATCO code to differentiate them from each other. By linking to the NaPTAN dataset, XY location data is added to the stop file for each ATCO code, and then the file is well-prepared for the afterward geocoding process in ArcGIS.
- Routes file: services are identified by service code (service number), with the file also including information on its operator name, direction (in/outbound) and a unique sequence of stops.
- Timetable file: a sequence of arrival and departure times is associated with each service.

Based on the CSV files output from the Python parse process, the next step is to apply the geocoding functions in ArcGIS to geo-locate the stops and routes:

- Stops feature class (point feature class): based on the XY location data saved with the stops file in CVS format, the file was converted into geodatabase format (point feature class) in ArcGIS using the tool 'Display XY Data'.
- Routes feature class (polyline feature class): each bus route was delineated by its unique sequences of stops based on the available ITN road layers and the embedded network analysis functions (ArcGIS. Network Analyst. New Route) in ArcGIS. Thus, each bus route was saved as a polyline feature, and all of them merged together to form the route feature class.

Hence, stops and route information provided in TXC format by NPTDR and TNDS were transferred into geodatabase format and can be directly used by ArcGIS for data display and further analysis. While the non-geometrical data, timetable data, was stored in CSV files and ready for usage by linking to the tools of Network Analyst for real-time calculation.

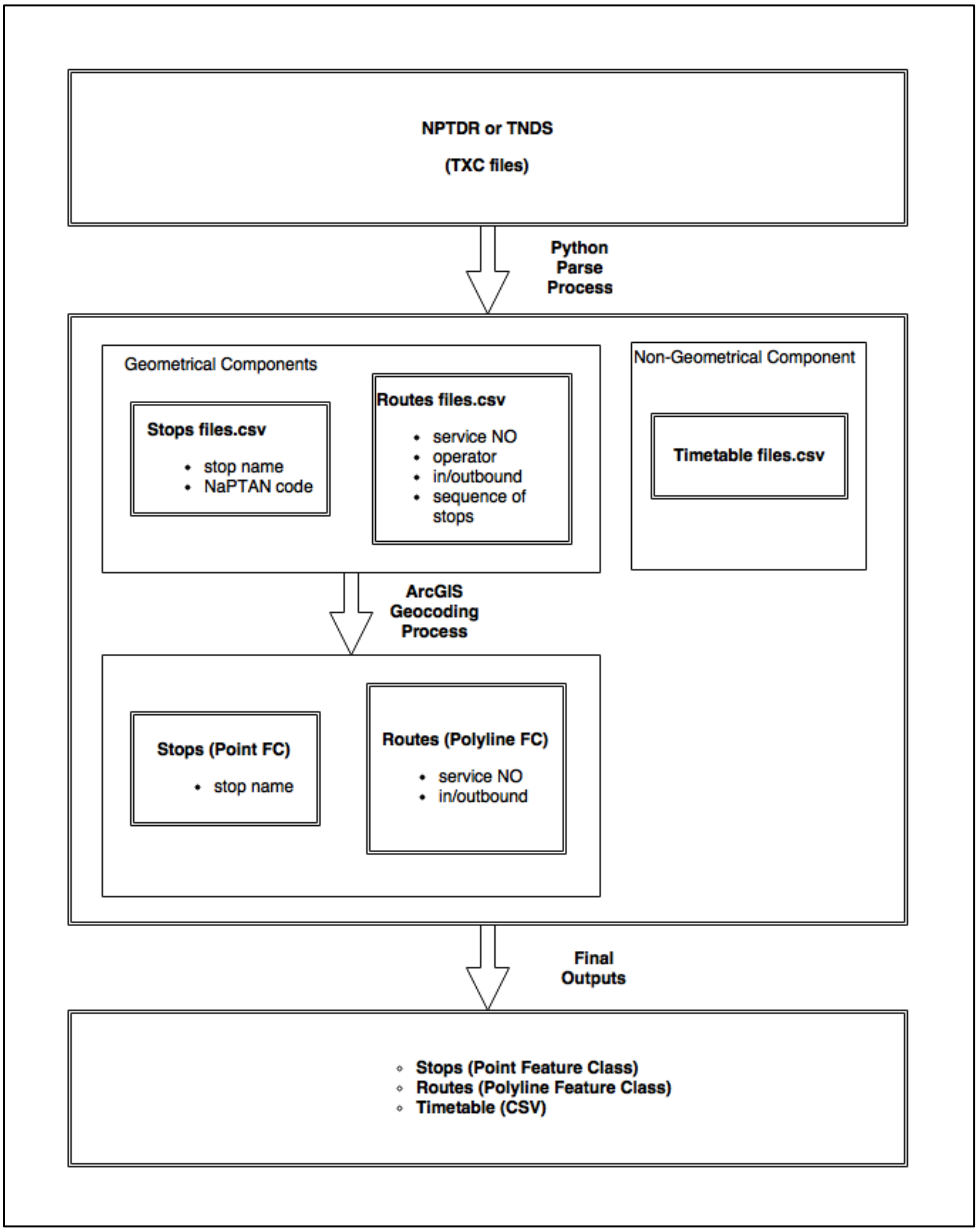

Figure 5-1 Public Transport Network Data Preparation

5.2.3 Origin-Destination Pairs

The possible OD pairs are generated by matching each possible origin point with each possible destination point. The definitions of the potential origins and destinations adopted in this accessibility model are listed below.

5.2.3.1 Set of Origin Points

The population centroids of six/seven digit postcode units (which typically contain 10 households) are defined as the set of possible origin points. Compared with the smallest geographic unit for the UK 2011 Census outputs, the Output Area (OA) which was designed to have at least 40 households, the postcode points give more details of population distribution in reality. The locations of postcode points were downloaded from the Digimap website (www.edina.ac.uk/digimap). However, this service does not provide any associated data on the number of household in each postcode. The spatial data therefore had to be joined to statistical data from the UK 2011 census at postcode level which was downloaded from the Nomis website ('Headcounts and household estimates for postcodes in England and Wales' http://www.nomisweb.co.uk).

5.2.3.2 Set of Destination Points

According to the guidelines provided by available models in network accessibility measurement, such as *Accessibility Statistics* by Department for Transport (2012) and *Access to Opportunities and Services (ATOS)* by Transport for London (2009), five categories of key services are defined as possible destination points in the process of calculating the gravity-based accessibility index, they are:

- Educational establishments: includes primary schools, secondary schools, colleges and universities.
- Health services: this accessibility model measures access to General Practitioners (GPs) surgeries, based on the assumption that this can provide a reasonable representation of access to primary health care in general.
- Employment centres: defined as locations which provide more than 1000 employment opportunists within the research area.
- City/ town/ district centres: provide the main shopping, leisure and entertainment destinations, and learning institutions.
- Open spaces: defined as locations which are freely accessible and suitable for children's play, exercise and social interaction (Wright and Cooper, 2009).

The point locations of these destinations, such as educational establishments and GPs, were directly extracted from the PointX National Points of Interest database (available from the Digimap website: www.edina.ac.uk/digimap), and ArcGIS was used to geocode them. For the remaining polygon destinations, their boundaries were extracted from the following sources:

- For employment centres: from *Business Register and Employment Survey (BRES)* (http://www.ons.gov.uk/).

- For city/town/district centres: from *Local Development Framework*, available at the websites of local authority[8].
- For open spaces: available from the OS's boundary maps (named as 'Boundary-Line' category in the list of 'Boundary and Location Data') at Digimap website.

In order to improve the accuracy of the final results, alternative point locations were selected as the locations of these polygon destinations in the calculation:

- For employment centres and open spaces: the locations of each entry/exit points as well as all bus stops located in them were selected as alternative point locations (see Figure 5-2).
- For city/town/district centres: the points where roads intersect with the boundary of city/town/district centres as well as the locations of bus stops located in them were selected as alternative point locations (see Figure 5-3).

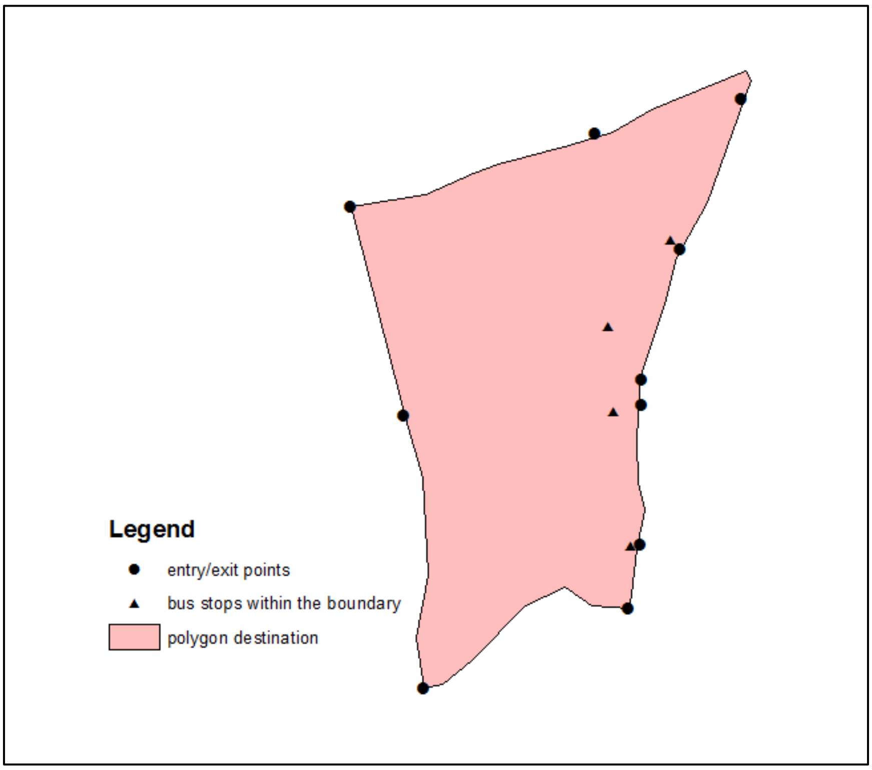

Figure 5-2 Definition of Point Locations for Employment Centres and Open Spaces

[8] Local Development Frameworks are spatial planning strategies introduced in England and Wales, and the documents are always available at the website of local authorities. For the case study of this research, the boundary of city/town/district centres of Southampton were defined in the Southampton Local Development Framework, available at https://www.southampton.gov.uk/planning/planning-policy/emerging-plans/local-development-scheme.aspx.

Figure 5-3 Definition of Point Locations for City/Town/District Centres

5.3 Methodology

The methodology for calculating the gravity-based accessibility index is as follows:

5.3.1 Step 1: Calculation of Travel Costs

For each category of destinations, the travel cost (C_{ij}) between each origin and each destination point within this category was calculated. The model assumed that all passengers share a perfect and equal perception of the travel cost to their destinations and all choose the cheapest option (all-or-nothing assignment approach). Travel costs were calculated based on the *WebTAG*[9] *Public Transport Assignment* methodology (Department for Transport, 2014a), which states that the travel cost (C_{ij}) from origin point i to destination point j comprises a weighted sum of the walking time (WKT), waiting time (WTT), in-vehicle time (IVT), transfer penalty ($T_{penalty}$) and fare. According to the research aim and objectives, the bus network improvement methods considered in this research only include route planning and frequency setting, while fare system remains at current levels. Hence, the differences in travel cost between the current and optimised network

[9] WebTAG remains the leading model of open documentation of appraisal guidance and is frequently used as a benchmark by other countries, such as Germany, Netherlands, Sweden, USA, Australia, New Zealand, and so on (Mackie and Worsley, 2013).

are from the WKT, WTT, IVT and $T_{penalty}$, not from fare. The fare attribute therefore was excluded in the calculation of travel cost in this research. The attributes which contribute to the travel cost in the model were defined as follows:

- Walking time (WKT): walking is considered to be the only available access and egress mode for bus services, and maximum permitted walking time is always set as an essential constraint in models. The value of the maximum permitted walking time varies between 5 minutes and 24 minutes in the published literature, such as 5 minutes (O'Neill et al., 1992; Hsiao et al., 1997; Phillips and Edwards, 2002; Biba et al., 2010; Foda and Osman, 2010; Langford et al., 2012), 8 minutes (Transport for London, 2010), 10 minutes (Transport for London, 2009), 15 minutes (Transport for South Hampshire, 2011) and 24 minutes (Department for Transport, 2012). The value of 15 minutes was chosen and applied in this accessibility model. In other words, passengers will walk no more than 1200 metres to access public transport services on average, based on the average walk speed (4.8 kilometres per hour) advised by *WebTAG Public Transport Assignment* (Department for Transport, 2014a).
- Waiting time (WTT): WTT is calculated based on the real bus timetable, and its value is the difference between the next available departure time and the time the passenger arrives at this stop.
- In-vehicle time (IVT): IVT is calculated based on the real public transport timetable, and its value is the difference between the time the bus/train arrives at the destination stop and the time the bus/train departs from the origin stop.
- Transfer penalty ($T_{penalty}$): a fixed value of time penalty for each transfer. Based on *WebTAG Public Transport Assignment* (Department for Transport, 2014a), a transfer penalty of 7.5 minutes of IVT per interchange was applied.

Hence, travel cost (C_{ij}) can be calculated using the following function:

$$C_{ij} = C_{ivt}\left(IVT + W_{wkt} \times WKT + W_{wtt} \times WTT + T_{penalty} \times T_n\right) \qquad (5.1)$$

Where:

W_{wkt} = Perception of a given unit of walking time compared to the same unit of in vehicle time, and value 1.75 was applied in this model based on *WebTAG Public Transport Assignment* (Department for Transport, 2014a).

W_{wtt} = Perception of a given unit waiting time compared to the same unit of in vehicle time, and value 2 was applied in this model based on *WebTAG Public Transport Assignment* (Department for Transport, 2014a).

T_n = number of transfers.

C_{ivt} = Value of passenger travel time (£ per hour). According to *WebTAG data book Table M 2.1* (Department for Transport, 2015a), the value of passenger travel time (for non-work purposes) is equal to £6.23 per hour (2010 market prices)[10] in the UK urban context. In this thesis, this developed accessibility model has been implemented based on a real-world size bus network, the current Southampton bus network. Compared with other urban areas in UK, the Southampton case study shows no difference, thus the value of passenger travel time in the UK urban context could be applied equally well in Southampton.

Although some commercial software packages, such as Visography TRACC, are available for calculating travel costs across multimodal networks, they lack flexibility in their custom settings and could not be easily adapted to fit the objectives of this research. In order to meet the kind of requirements here, ArcGIS was chosen as the main analysis software for this research. Compared with other available commercial software packages, ArcGIS has the ability to calculate large geographic datasets, has embedded efficient network-based analysis tools (ArcGIS Network Analyst extension) for solving complex routing problems, and provides high flexibility in custom settings using its developer interfaces (such as ArcObjects for Visual Basic, ArcObjects for C#, and ArcObjects for Java). An integrated ArcGIS model was therefore developed using ArcObjects for Java, step-by-step building procedures are described in section 5.4.

5.3.2 Step 2: Calculation of Service-Specific Accessibility Index

For each category of destinations, the accessibility index using gravity-based measures was calculated by following function:

$$A_{i_{service}} = \frac{W_i \sum_j B_j e^{-\alpha c_{ij}}}{\sum_j B_j} \tag{5.2}$$

Where:

W_i = population of origin point i.

α = distance decay parameter. According to the *WebTAG Wider Impacts Dataset* (Department for Transport, 2013a) and Graham et al. (2009), the value of α is 1.818 in UK urban areas. In this

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[10] The value of passenger travel time remains a crucial parameter for the economic appraisal of transport projects both because travel time savings tend to dominate the monetized benefits of most schemes and because other values such as reliability or public transport crowding are themselves multiples of the value of travel time savings (Mackie and Worsley, 2013). According to WebTAG, commuting time savings (£6.85 per hour) are valued 10% higher than other non-working journey purposes (£6.23 per hour) in England, based on original work by AHCG (1999).

thesis, this developed accessibility model has been implemented based on a real-world size bus network, the current Southampton bus network. Compared with other urban areas in UK, the Southampton case study shows no difference, thus the value of distance decay parameter in the UK urban context could be applied equally well in Southampton.

B_j = number of opportunities at destination point j. The definitions of the opportunities provided by destinations vary by destination category of them, and are listed below in Table 5-1.

Table 5-1 Definitions of Opportunities

Category of Services	**Definition of Opportunities**	**Data Source**
Educational establishments	Number of pupils	Edubase database from the Department of Education website (http://www.education.gov.uk/edubase/home.xhtml)
Health services	Number of registered patients	NHS website (http://www.nhs.uk/pages/home.aspx)
Employment centres	Number of jobs provided	Business Register and Employment Survey (BRES) (http://www.ons.gov.uk/)
City/town/district centres	Retail floor space (square metre)	'Town Centre and Retail Planning Statistics for England and Wales' dataset from Department for Communities and Local Government (DCLG) (http://www.planningstatistics.org.uk/)
Open spaces	Open spaces areas (square metre)	Calculated using ArcGIS.

5.3.3 Step 3: Calculation of Composite Accessibility Index

The composite accessibility index was computed by totalling the service-specific accessibility index by related service weightings ($W_{service}$). The weightings were based on data on the frequency of different trip purposes by bus from *Transport Statistics Great Britain 2014* (Department for Transport, 2014b). The weights used are as follows:

- Educational establishments - 0.21
- Health services – 0.10
- Open spaces - 0.10
- Employment centres - 0.19
- City/town/district centres - 0.40

Hence, the composite accessibility index can be calculated using the following function:

$$A_{i_{composite}} = \sum W_{service} \times A_{i_{service}} \tag{5.3}$$

5.3.4 Step 4: Visualization of the Results in ArcGIS

Group the composite accessibility index using ranges on the following criteria (see Table 5-2), where origin points in level A have the worst level of accessibility to the service and level E the best; a direct visualization of results using the coloured contour map by ArcGIS will be provided as well.

Table 5-2 Accessibility Levels and Related Ranges

Accessibility Level	**Range**
A	20% lowest values
B	Values between 20% and 40% lowest
C	Values between 40% and 60% lowest
D	Values between 60% and 80% lowest
E	20% highest values

5.4 Calculation of Travel Costs in ArcGIS

5.4.1 Network Analyst Extension in ArcGIS

Any network analyses with the ArcGIS Network Analyst extension are based on a network dataset, which is made up of network elements. Network elements are the source feature classes used to create the network dataset. For example, a line feature class representing pedestrian network is a network element. For a network dataset with multiple network elements, a concept of 'connectivity' is used to define how these network elements are connected each other. Network datasets connect features assigned to one connectivity group, while separating them within a different connectivity group. For instance, a network dataset involves two line feature classes: one represents bus network, another represents rail network. In order to connect line features within the same feature class and separate them within different feature classes, two connectivity groups need to be set in this network dataset: one for bus network, another for rail network. Network datasets calculate travel impedance by network attributes, and the most widely used travel impedance is travel distance or travel time. The following tools are available in the current ArcGIS Network Analyst extension:

- Find best route: the best route can be found between given OD pair. The best route can be the quickest, or shortest, depending on the chosen impedance.
- Closest facility: the closest facility can be found for a give location, such as fining the closest hospital to an accident, or the closest police cars to a crime scene.

- Service areas: find service areas around any location on a network. For instance, a 10-minutes walking buffer includes all streets that can be reached within 10 minutes from the origin point.
- OD cost matrix: calculate travel impedance from each origin to each destination.
- Vehicle routeing problem: determine solutions for complex fleet management tasks, including the demand satisfaction, routes design, and schedule assignment.
- Location-allocation: find the best locations for new facilities based on demand satisfaction, such as, find the best location for a new rail station within the city.

Based on those available tools in the Network Analyst extension, ArcGIS extends its ability in network analysis by developer interfaces, and available options are ArcObjects for Visual Basic, ArcObjects for C#, and ArcObjects for Java. These interfaces for developers contain all tools available in the normal customer interface, as well as providing more flexibility in custom setting and could easily develop specific tools or models to fit any research objectives. Detailed guidelines, as well as sample codes, can be found from the website of ArcGIS Resource Centre (http://help.arcgis.com/). In this research, ArcObjects for Java was chosen as the main developer tool, and has been proved to work efficiently for both model building and large-size datasets calculation.

5.4.2 3D Multi-modal Network Datasets

Alongside bus services, walking and rail services are also considered in this model, which therefore contributes to a complex multi-modal modelling problem. Although ArcGIS Online Help (http://resources.arcgis.com/en/help) provides detailed instructions in building multimodal network datasets based on its network analysis functions, it only focuses on modelling a simple case study with well-prepared input data. The main challenge for this research therefore was to build the complex multimodal network dataset based on the currently available input data. The overlapping problem of bus routes and pedestrian network posed a key challenge in the modelling process.

For simplicity, roads were represented as a set of line elements using the OS Mastermap ITN data in this model. As a result, pedestrian paths are not available separately, so that pedestrians are assumed to share the same roads with buses. Furthermore, all bus routes share the same road lines as well. Although rail services are operated on railway lines which will separate it with the pedestrian and bus network, all rail services are operated on the same railway lines and will cause overlapping problem as well. As a result, the problem of overlapping routes of both different modes and the same mode is present. The solution to the overlap problem is to use the 3D capability of ArcGIS. Each bus, rail and pedestrian line segment is assigned to an elevation value in order to separate it from the other routes vertically. For all walking line segments, the elevation value is zero; for each bus line segment, the elevation value is equivalent to the bus route number; for each rail line segment, the elevation value equals to the service number. Multi-modal systems require the model to deal with transfers, either between modes or between routes of the same mode (like the bus and rail). Transfer is seen in this model as the physical movement of a person from one mode or route to another and the associated impedance caused by this transfer. Therefore, the transfers are created as 'vertical' line features linking pedestrian, bus and rail networks with an attribute storing the associated transfer penalty in this model.

A similar approach, applying the 3D capability of ArcGIS to build a multi-modal network model, has previously been used in the work of Mandloi & Thill (2010) and Hahrous (2012). However, these published models are quite simple and are only applied to small-scale networks. Several improvements have been made in the model developed for this research compared to these published models:

- In the models developed by Mandloi & Thill (2010) and Hahrous (2012), travel cost is chosen as the travel impedance, and involves the following attributes: walking time (both access and egress time), waiting time (both origin and transfer waiting time), and in-vehicle time. Transfer time is ignored in their models, but is an essential component of in-direct journeys (the percentage of in-direct journeys by public transport network is quite high) and certainly will be considered by passengers when planning journeys. Therefore, alongside walking time, waiting time and in-vehicle time, transfer penalty was also considered as an attribute which contribute to the travel cost in the model described here.
- In order to improve the accuracy of the final results, both in-vehicle time (IVT) and waiting time (WTT) were calculated based on the real bus timetable in this model.
    - According to the published models by Mandloi & Thill (2010) and Hahrous (2012), IVT is calculated by converting the distance between service access point (such as bus stops, rail stations, etc.) and service egress point to a measure of time using an assumed average vehicle speed. In order to output exactly IVT for each journey, the difference between the time the public transport service (such as bus or train) arrives at the destination stop and the time the service departs from the origin stop was calculated as IVT in this model.
    - In the published models, WTT is defined as a function of headways, being calculated as half the headway for headways up to 15 minutes, and with the waiting time capped at 7.5 minutes for longer headways. In order to improve the

accuracy of the final results, WTT was calculated based on the real bus timetable in this model, and its value is the difference between the next available departure time and the time the passenger arrives at this stop.

Steps in building this ArcGIS model and calculating travel costs are described below in detail, including following three steps: data preparation procedure for pedestrian, bus, and rail sub-networks, the multi-modal network dataset development procedure using ArcGIS Network Analyst extension, and travel cost calculation procedure for each OD pair (see Figure 5-4).

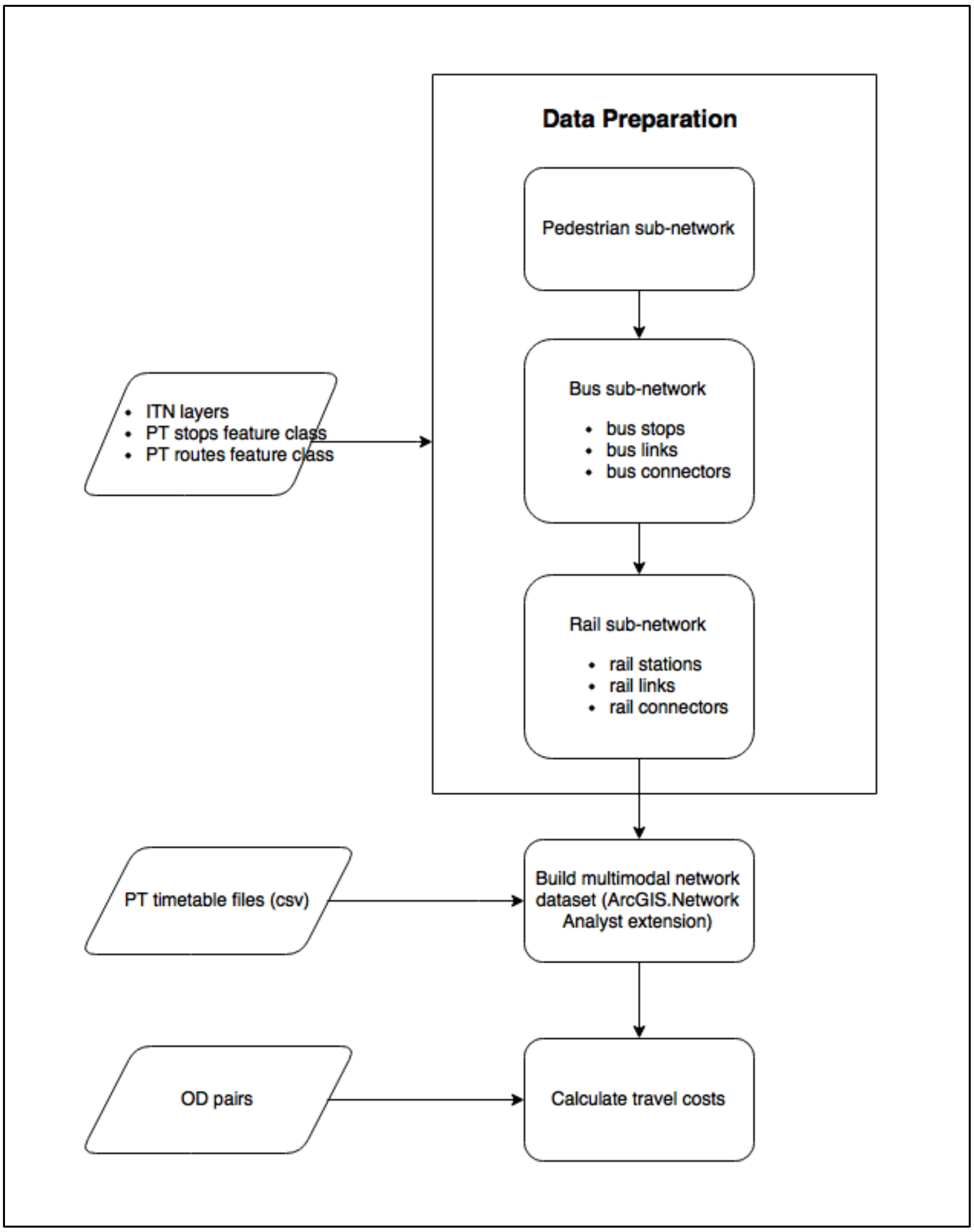

Figure 5-4 Workflow of 3D ArcGIS Model

5.4.3 Data Preparation

5.4.3.1 Pedestrian Sub-network Preparation

Figure 5-5 shows the details of preparing a separate dataset for pedestrians from the existing roads dataset (ITN layers). By excluding motorways, an assumption is made that all the rest of roads are available for walking. Required attributes were added to each pedestrian link, including walking time and elevation value. After that, the prepared pedestrian lines dataset was transformed to 3D features by being assigned zero elevation.

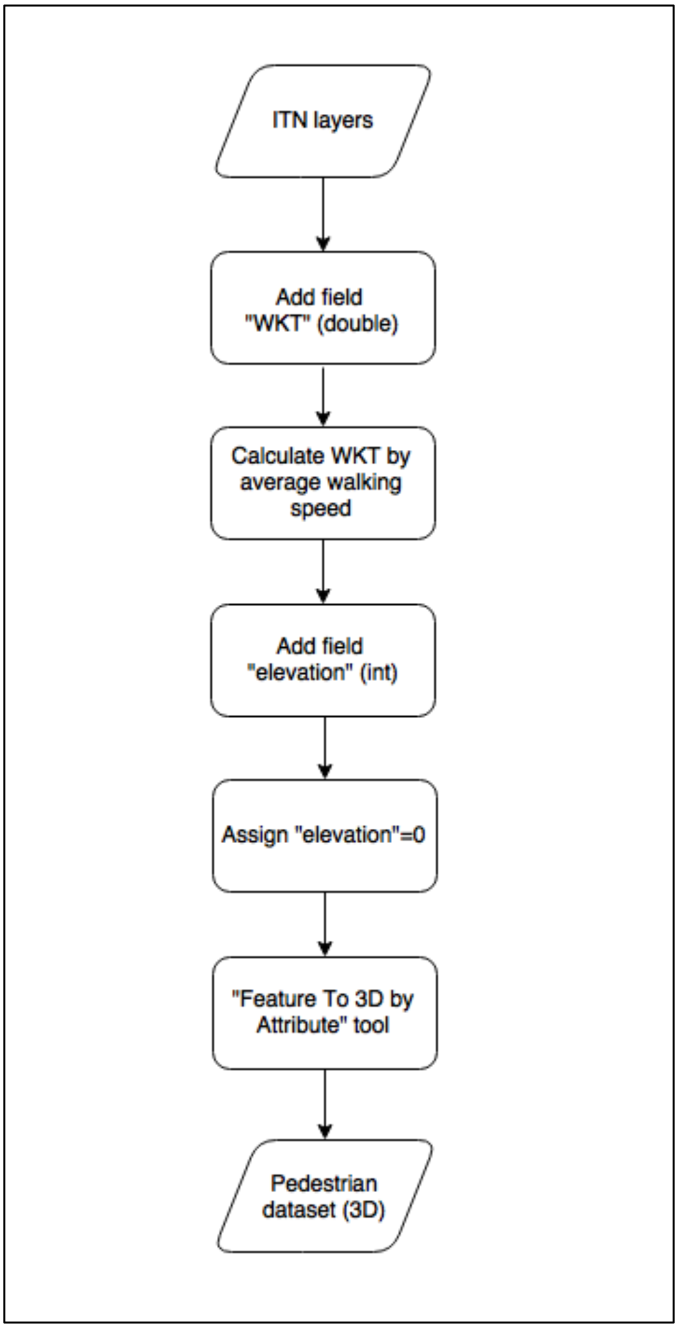

Figure 5-5 Pedestrian Paths Data Preparation

5.4.3.2 Bus Sub-network Preparation

Bus is in some ways a restricted mode of transport. It has fixed routes, bounded by time schedules and can be accessed only at specific locations (bus stops). From this, the bus network can be identified by its main geometrical components as bus routes and bus stops and other non-geometrical information needed such as bus schedule. Based on this classification, each bus route needs to have a set of lines representing its links (a link is a connection between two bus stops), bus stops that serves this bus lines, and the schedule of this bus line. The non-geometrical information (bus schedule) has been extracted from the TNDS 2016. This section is about preparing all required geometrical information for the bus network, including bus links, bus stops and transfer connectors.

5.4.3.2.1 Bus Links Datasets

The bus links datasets were built based on the input bus routes features. The following steps need to be repeated for each bus route feature (see Figure 5-6):

1) Split each input bus route polyline feature into bus links, defined as polyline features between two bus stops, using ‘Split Line at Point’ tool.
2) Add and calculate needed attributes to each bus link feature, such as bus route number, elevation (the value of elevation equals its unique bus route number), in/outbound direction information.
3) Transform this 2D bus link dataset to 3D by the elevation value.

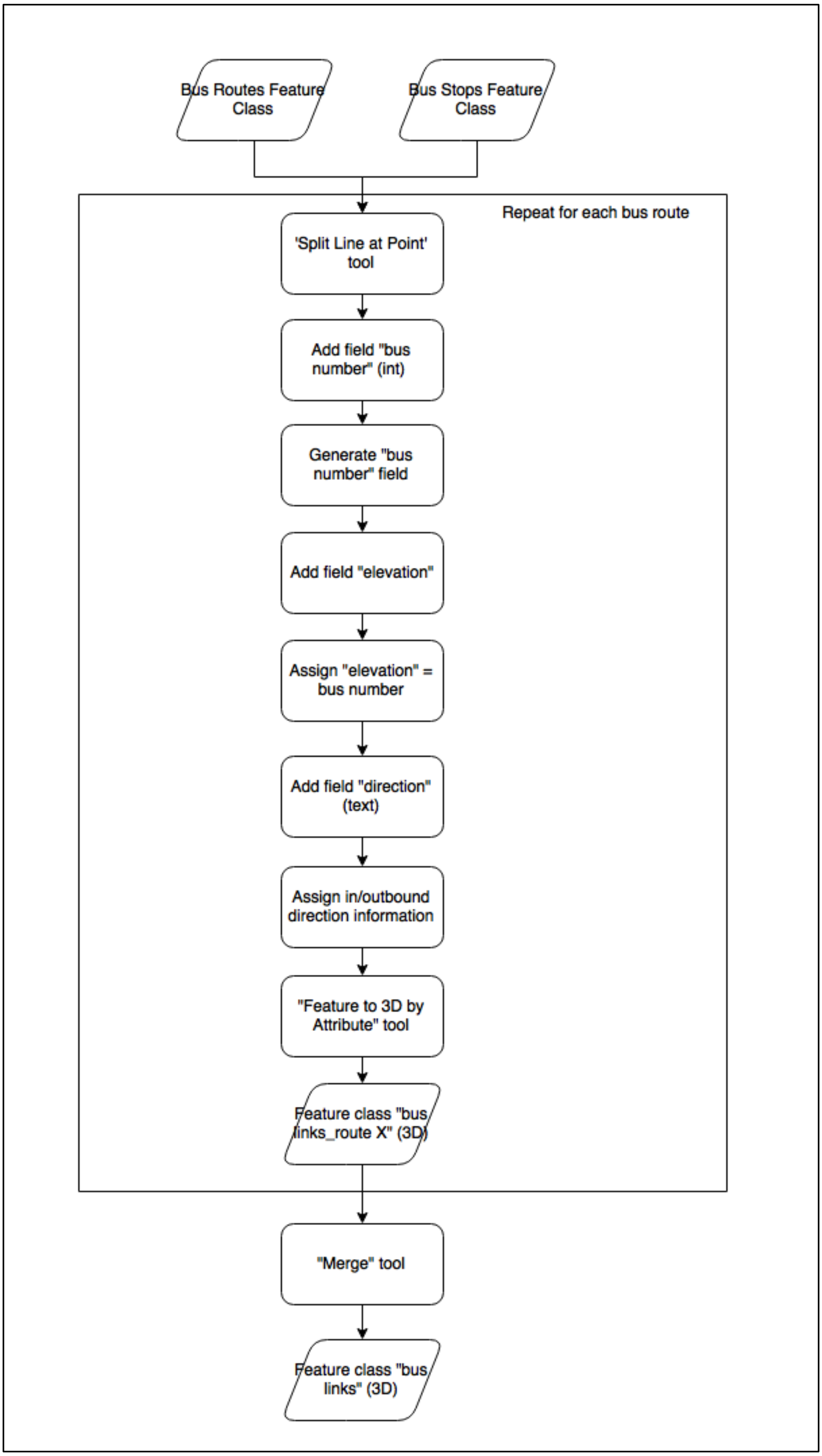

Figure 5-6 Bus Links Dataset Preparation

5.4.3.2.2 Bus Stop Datasets

Bus stop locations and names are available from the National Public Transport Access Nodes (NaPTAN) 2011 database, and ArcGIS has assigned them to their spatial location using the geocoding function in the preparation process of input data for the model. Based on the available bus stops feature class, the first step of creating the bus stop dataset is to snap these bus stop features to the pre-prepared pedestrian paths. In real life, a bus stop is usually on the pavement so that passengers can wait there safely and also reach it on foot. Only at the moment when the bus arrives, passengers move from the pedestrian network to the bus network through bus stops. From that concept, bus stops should be geometrically coincident with pedestrian paths.

There are two categories of bus stops involved in this model: real and projected bus stops (see Figure 5-7). Real bus stops are point features coincident with the pedestrian network (elevation value is zero) representing real bus stops that enable the transfer between walking and bus modes. These differ from projected bus stops, which are point features coincident with related bus routes as represented in ArcGIS (with elevation values equivalent to the related route number), representing the projection of real bus stops onto the bus route located at a different elevation to the pedestrian route. In other words, real and projected bus stops are stops sharing the same XY location but with different elevations. Real and projected bus stops are linked by vertical transfer connectors, which connect pedestrian and bus routes with an attribute storing the associated transfer penalty. The process of creating bus connectors and the way of modelling transfers between bus and pedestrian network and between different bus routes is represented in the next section (section 5.4.3.2.3).

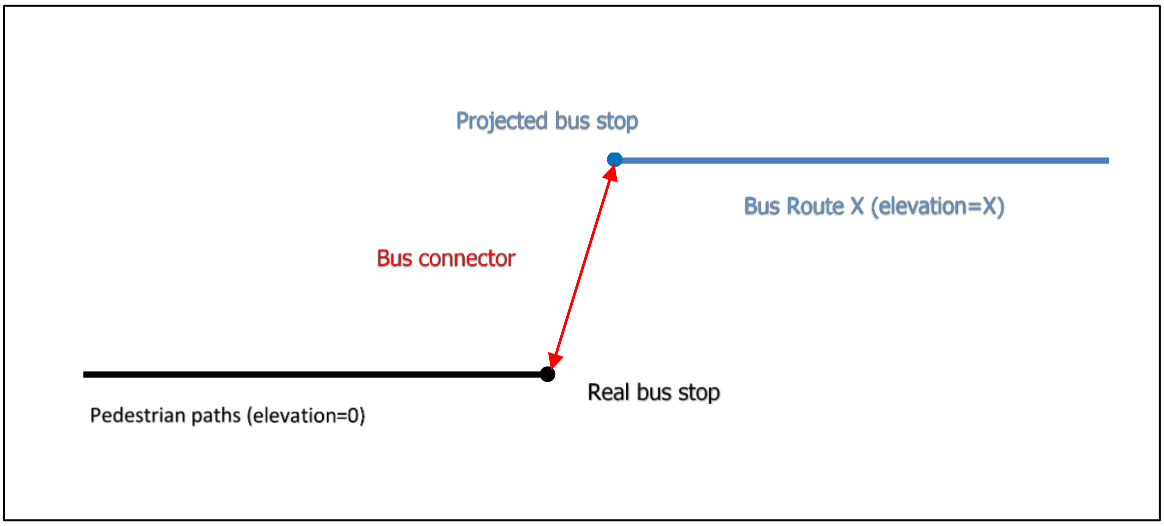

Figure 5-7 Real v.s. Projected Bus Stop (side view)

Figure 5-8 and Figure 5-9 lists detailed steps of preparing real and projected bus stop dataset, as follows:

- Real bus stop dataset preparation process
    1) Coincide bus stops on pedestrian network representing real bus stops that enables the transfer between walking and bus mode.
    2) Add elevation field with value equal to zero.
    3) Transform the dataset to 3D based on elevation value.
- Projected bus stop dataset preparation process
    1) Coincide bus stops on related bus routes, representing the projection of real bus stops on bus routes.
    2) Add elevation field with value equal to the bus line number.
    3) Transform the dataset to 3D based on elevation value.

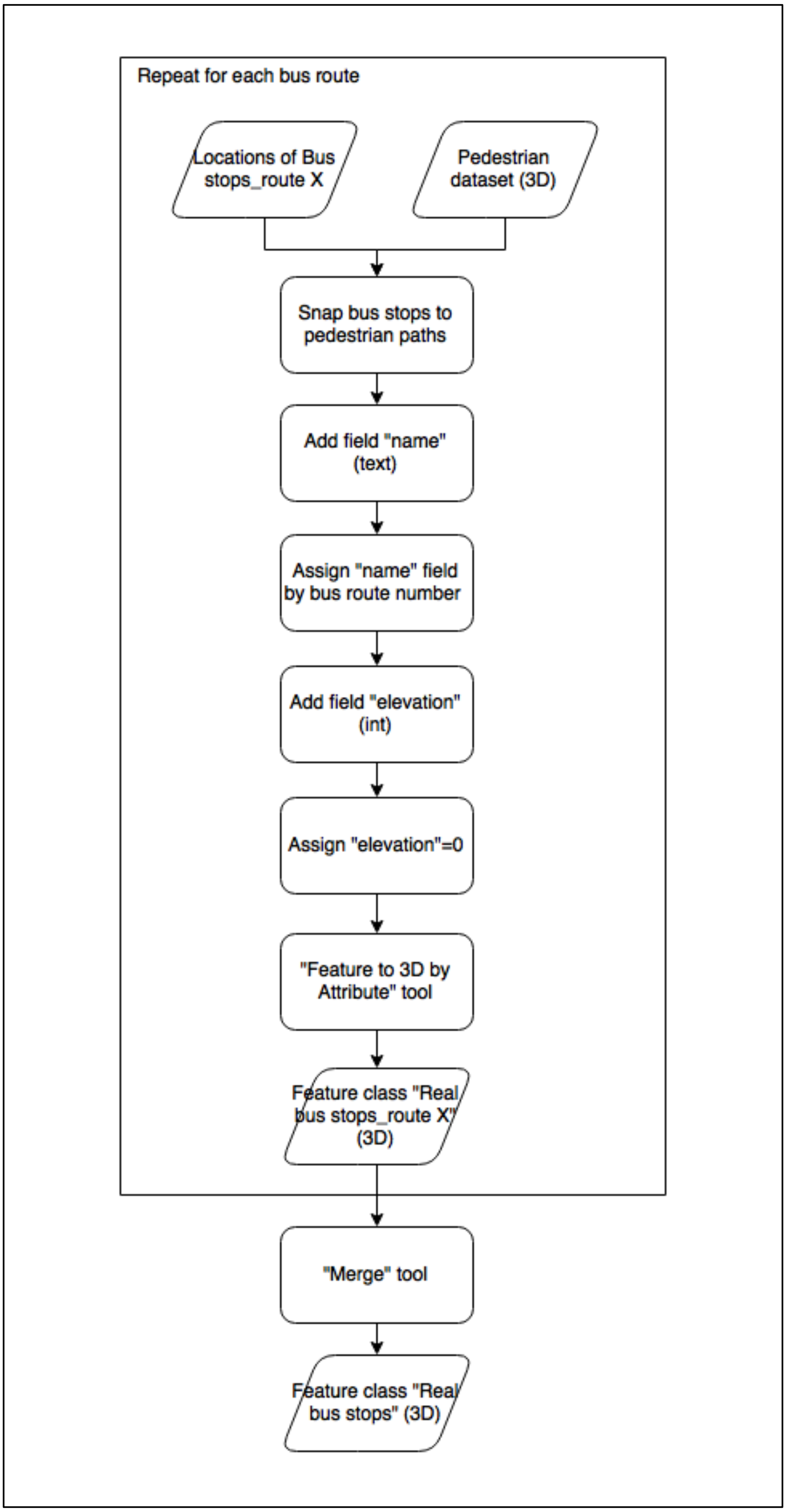

Figure 5-8 Real Bus Stops Dataset Preparation

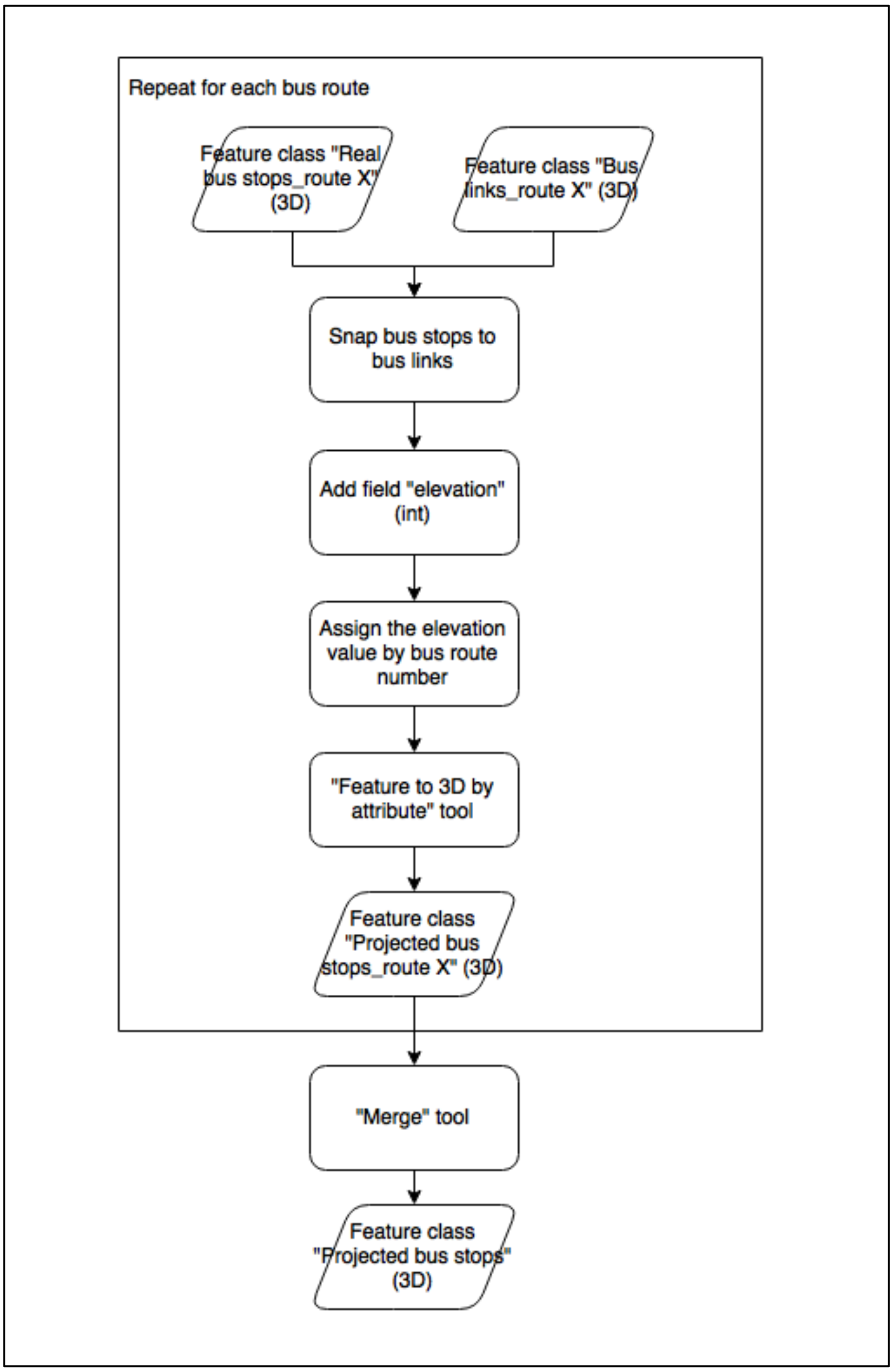

Figure 5-9 Projected Bus Stops Dataset Preparation

5.4.3.2.3 Bus Connector Datasets

This section is to generate transfer connectors between real and projected bus stops that model the physical movement of a passenger to or from the bus. Using the ArcGIS 'point to line' tool, a 'vertical' line was drawn between each pair of real and projected bus stops at the same location. All the connectors were afterwards collected in one feature class representing the bus connectors between real bus stops on pedestrian paths and the different projected bus stops of the different bus routes (see Figure 5-10).

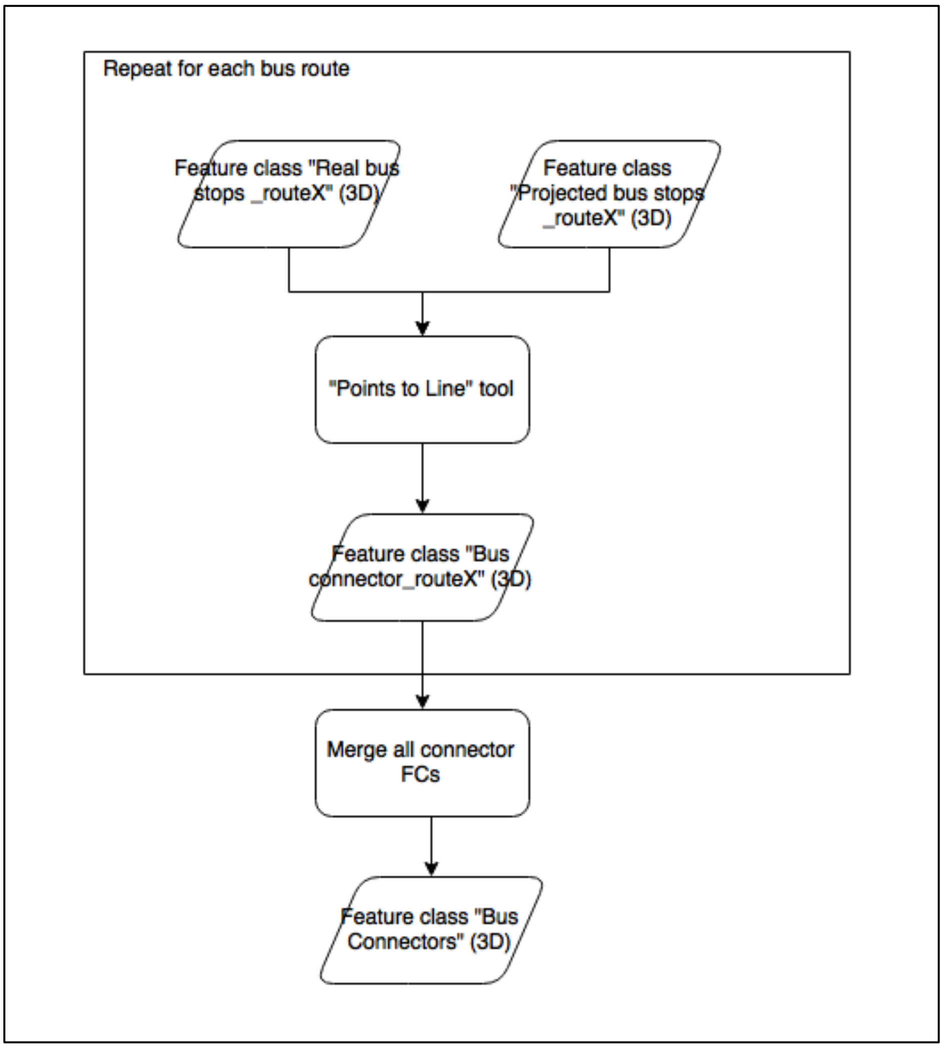

Figure 5-10 Bus Transfer Connectors Preparation

Using this output bus connector dataset, all bus routes were linked to form the bus sub-network, and they were linked to the pedestrian network as well. The transfer connectors between bus and pedestrian network, as well as between different bus routes were represented as follows, while the travel costs associated with these transfer connectors were detailed in section 5.4.4.4.1.

For walking-bus transfer connectors (see Figure 5-7):

- The path of boarding a bus: Pedestrian network>>real bus stop>>bus connector>>projected bus stop>>desired bus line
- The path of alighting from a bus: Bus line>>projected bus stop>>bus connector>>real bus stop>>pedestrian network

The path of bus-bus transfer connectors (see Figure 5-11): starting bus line (route X)>>projected bus stop (at the starting bus route X)>>bus connector (link projected bus stop at route X and real bus stop)>>real bus stop>>bus connector (link projected bus stop at route Y and real bus stop)>>projected bus stop (at the targeted bus route Y)>>the targeted bus line (route Y)

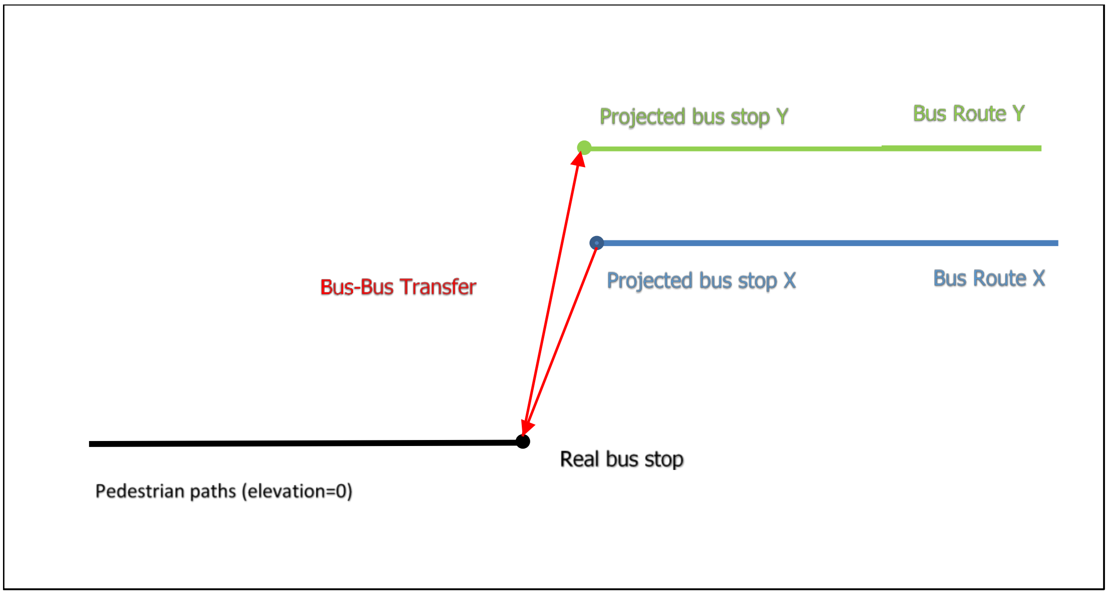

Figure 5-11 Bus-Bus Transfer (side-view)

5.4.3.3 Rail Sub-network Preparation

Similar to the bus networks, three geometrical components are required to represent rail networks: rail links, rail stations and related transfer connectors; and the detailed preparation process for them can be found in this section. Although rail services are operated on railway lines which will separate it with the pedestrian and bus network, all rail services are operated on the same railway lines and will cause overlapping problem as well. The 3D concept adopted in modelling bus services therefore was also applied at here.

5.4.3.3.1 Rail Links Datasets

The rail links datasets were built based on the rail network can be directly extracted from the railway layer of the ITN data. For each rail service, the rail service number was assigned as the name of this service and the evaluation value of it. Afterward, the dataset was transformed to 3D by the elevation value (see Figure 5-12).

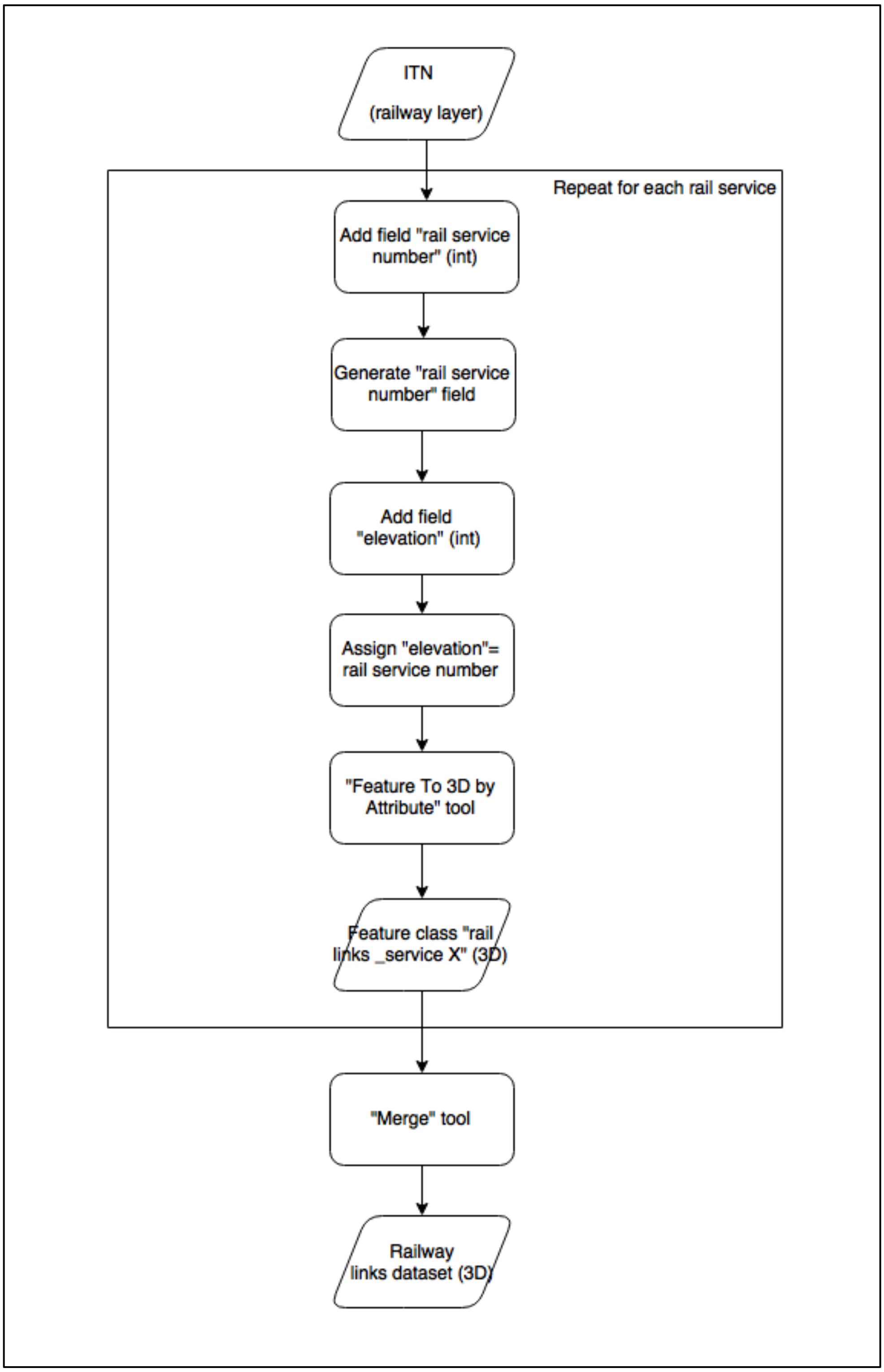

Figure 5-12 Railway Links Dataset Preparation

5.4.3.3.2 Rail Station Datasets

Followed by the methodology of building bus stops datasets in section 5.4.3.2.2, Figure 5-13 illustrates the process of building rail station datasets, involving both real and projected rail stations datasets.

- Real rail station dataset preparation process
  1) Coincide rail stations on pedestrian network representing real rail stations that enables the transfer between walking and rail mode.
  2) Add elevation field with value equal to zero.
  3) Transform the dataset to 3D based on elevation value.
- Projected rail station dataset preparation process
  1) Coincide rail stations on related rail links, representing the projection of real rail stations on rail links.
  2) Add elevation field with value equal to the rail service number.
  3) Transform the dataset to 3D based on elevation value.

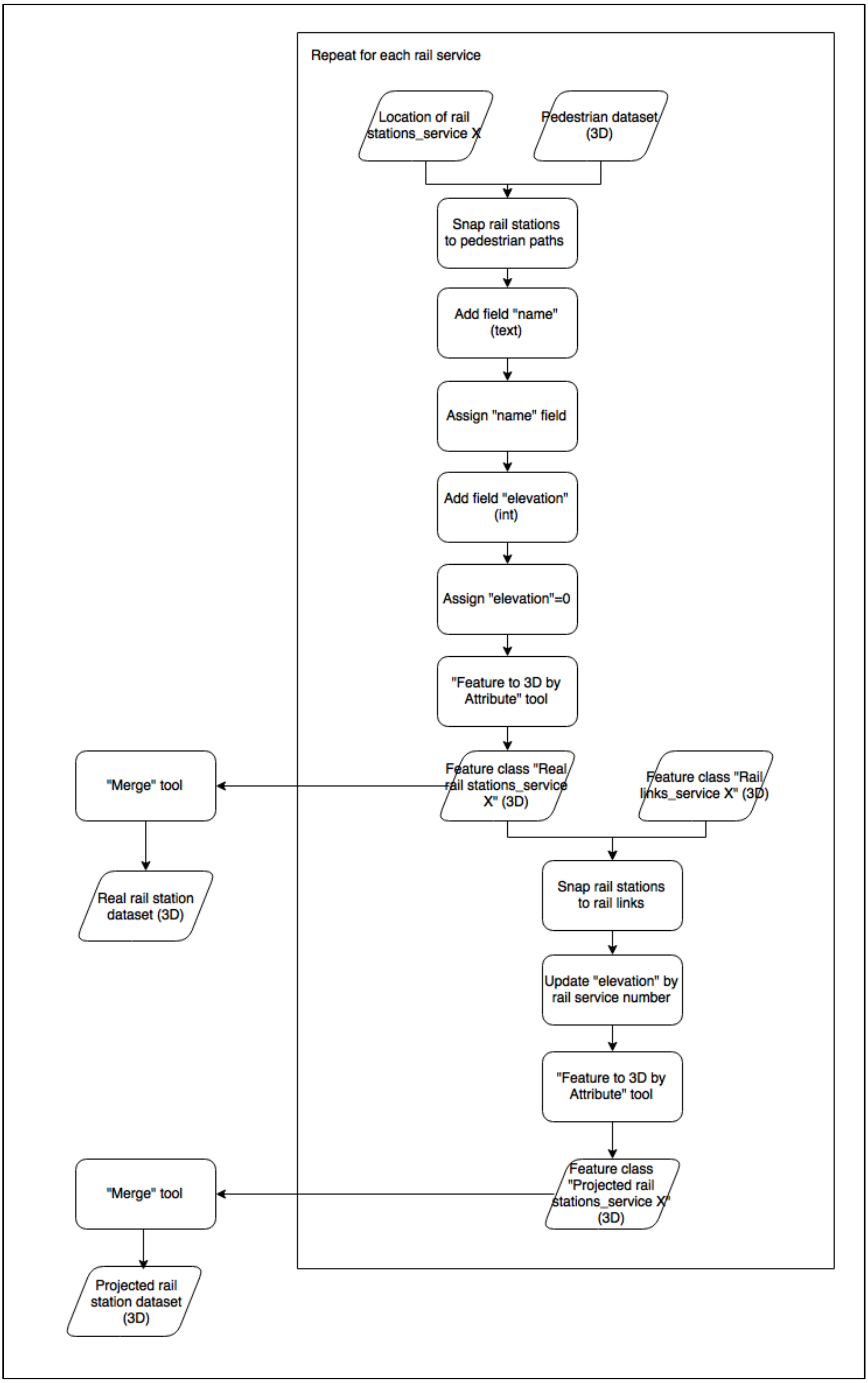

Figure 5-13 Rail Stations Dataset Preparation

5.4.3.3.3 Rail Connector Datasets

Using the ArcGIS 'point to line' tool, 'vertical' rail connector was drawn to link each pair of real and projected rail stations at the same location. Then all the connectors were collected in one feature class representing the rail connectors between real rail stations on pedestrian paths and the different projected rail stations of the different rail services (see Figure 5-14).

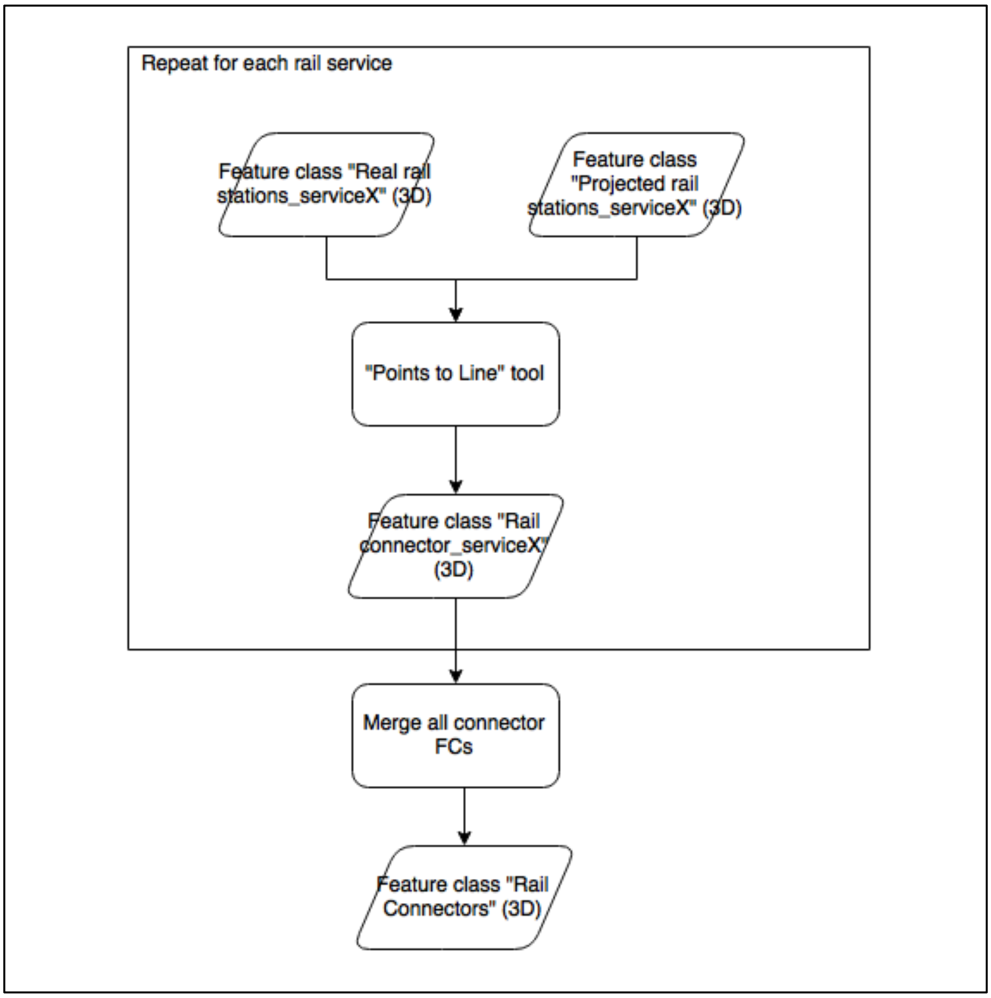

Figure 5-14 Rail Transfer Connectors Preparation

Based on the output rail transfer connector dataset, all rail services were connected together to form the rail sub-network, as well as linked to the pedestrian and bus sub-network. The transfer connectors between different rail services, as well as between rail and other sub-networks (pedestrian and bus sub-networks) were represented as follows. While the travel costs associated with these transfer connectors were detailed displayed in section 5.4.4.4.1.

The path of rail-rail transfer connectors (see Figure 5-15): starting rail line (service X)>>projected rail station (at the starting rail service X)>>rail connector (link projected rail station at service X and real rail station)>>real rail station>>rail connector (link projected rail station at service Y and real rail station)>>projected rail station (at the targeted rail service Y)>>the targeted rail line (service Y)

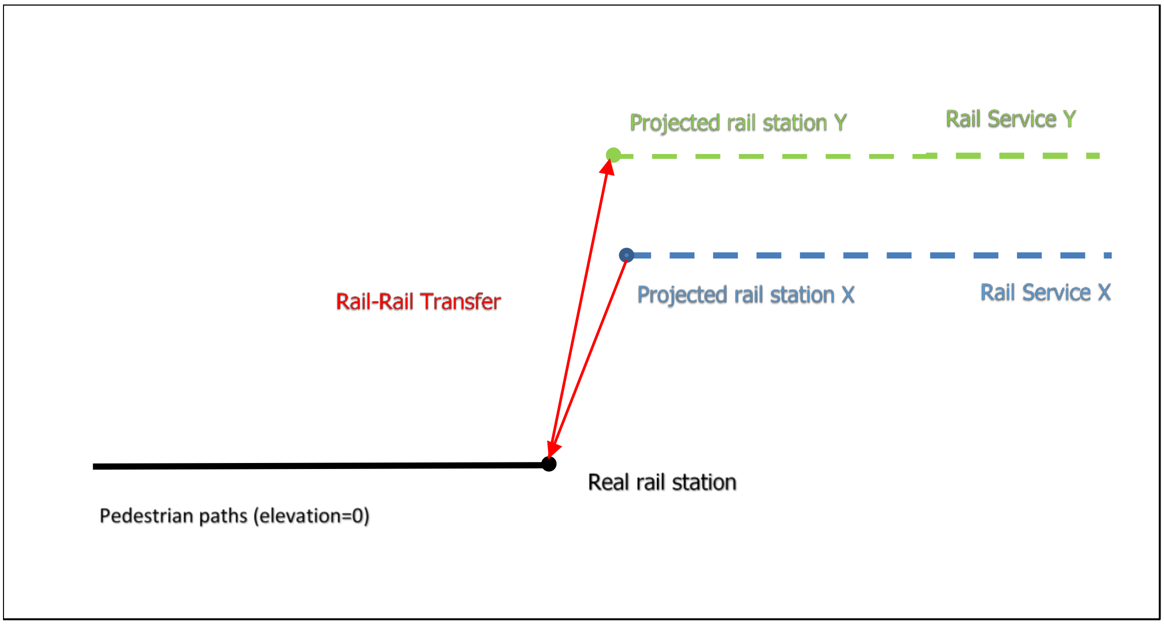

Figure 5-15 Rail-Rail Transfer (side-view)

For walking-rail transfer connectors (see Figure 5-16):

- The path of boarding a train: Pedestrian network>>real rail station>>rail connector>>projected rail station>>desired rail line
- The path of alighting from a train: rail line>>projected rail station>>rail connector>>real rail station>>pedestrian network

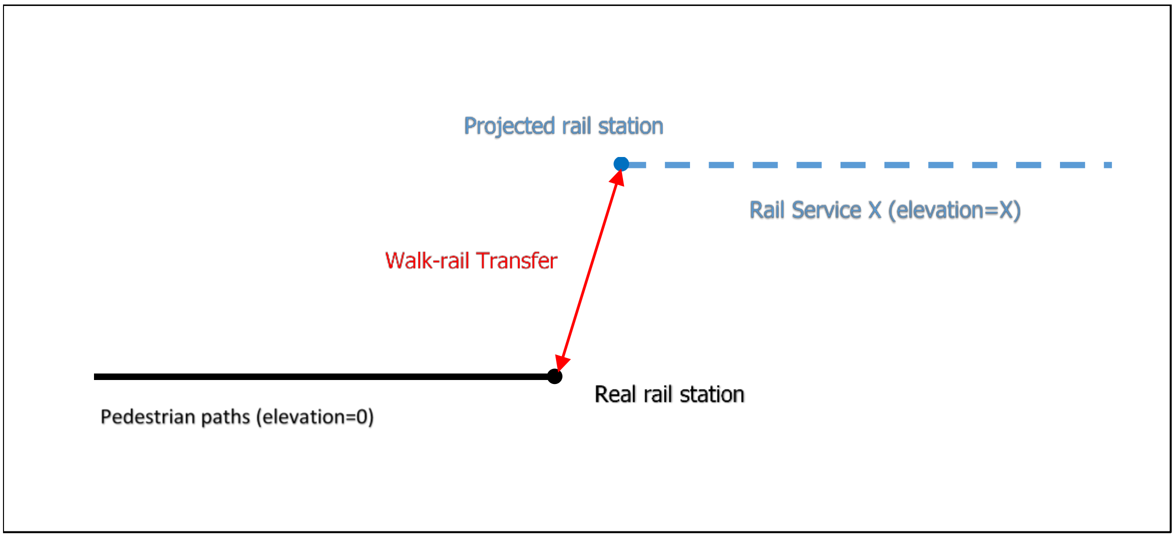

Figure 5-16 Walk-Rail Transfer (side-view)

For rail-bus transfer connectors (see Figure 5-17):

- The path of boarding a train having accessed the station using bus services: starting bus line>>projected bus stop>>bus connector>>real bus stop>>pedestrian network>>real rail station>>rail connector>>projected rail station>>rail network
- The path of boarding a bus after alighting from a rail services: starting train network>>projected rail station>> rail connector>> real rail station>>pedestrian network>> real bus stops>> bus connector>> projected bus stops >>the targeted bus line

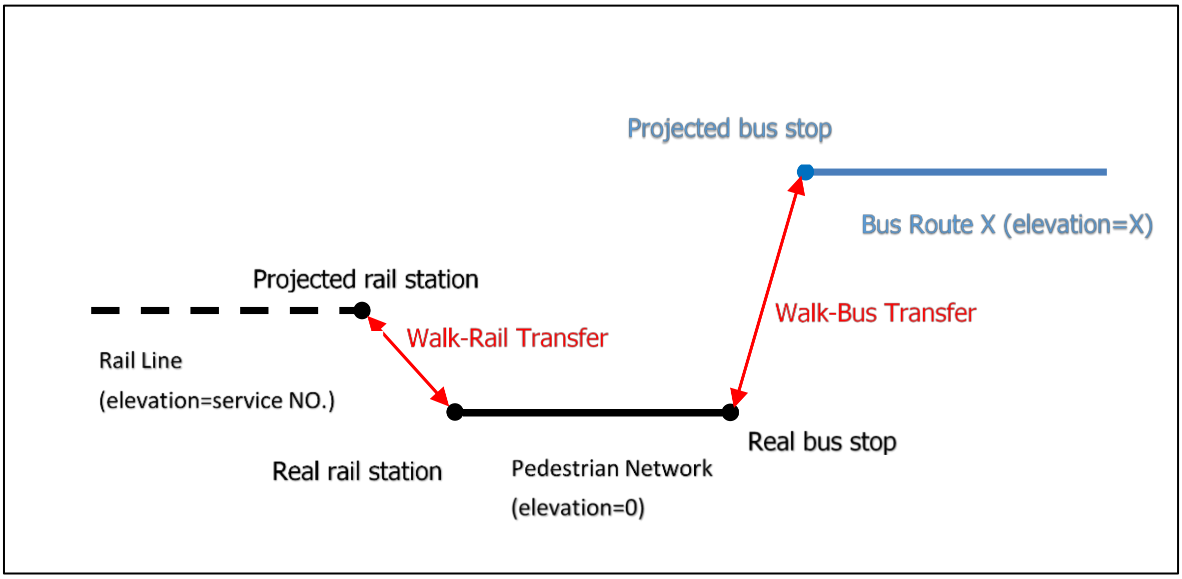

Figure 5-17 Rail-Bus Transfer (side view)

5.4.4 Build Multimodal Network Dataset

Based on the well-prepared source data from the preparation procedure, it is feasible to create a multimodal network dataset using the Network Analyst extension in ArcGIS. Detailed instructions have been provided by ArcGIS Online Help (http://resources.arcgis.com/en/help), and key steps of building multimodal network dataset were represented below.

5.4.4.1 Step 1: Select Network Elements

Network datasets are made of network elements. Network elements are generated from the source feature classes used to create the network dataset, and can be categorised by two groups: edges (polyline feature classes) and junctions (point feature classes). Nine 3D feature classes were selected as network elements for this multimodal model, they are (see Figure 5-18):

- Edges: pedestrian links, bus links, bus connectors, rail links, and rail connectors.
- Junctions: real bus stops, projected bus stops, real rail stations, and projected rail stations.

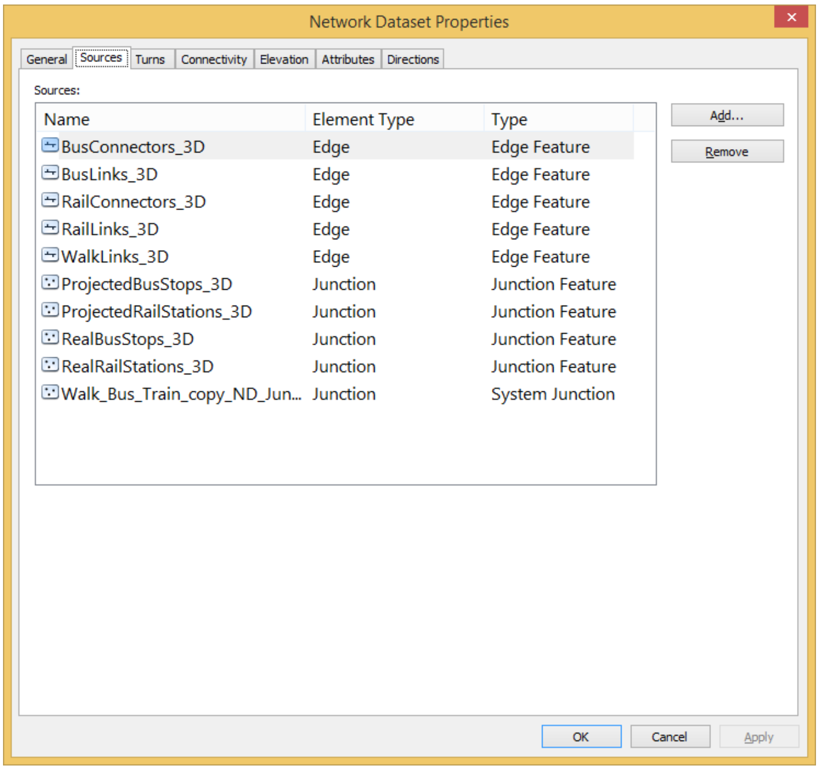

Figure 5-18 Multimodal Network Dataset: Select Elements

5.4.4.2 Step 2: Set Connectivity

Connectivity was set using the connectivity groups of ArcGIS, which is an essential step in modelling multi-modal transportation networks by ArcGIS Network Analyst extension. Each edge source can be only assigned to one connectivity group, while each junction source can be assigned to multiple connectivity groups. In other words, a connectivity group is a group of one edge element and multiple junction elements. Two edges in separate connectivity groups cannot connect each other unless they are joined by a junction that participates in both connectivity groups. Following this connectivity group concept, Figure 5-19 shows how the pedestrian, bus, and rail sub-network were connected each other to form a multimodal network.

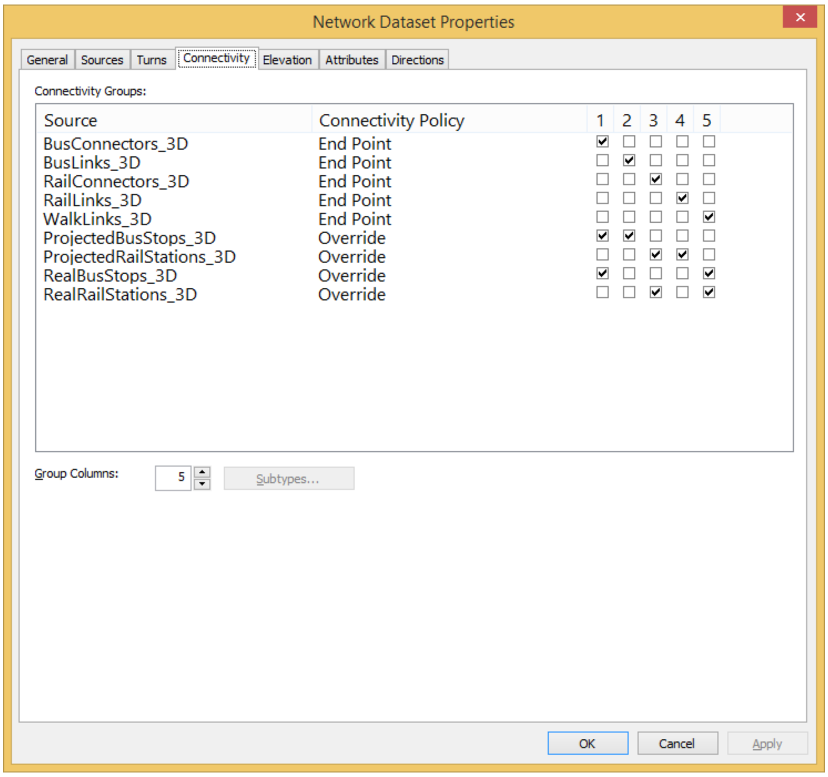

Figure 5-19 Multimodal Network Dataset: Set Connectivity

5.4.4.3 Step 3: Set Elevation

This model's main idea is the use of 3D capabilities of ArcGIS to overcome the problem of overlapping routes. All the features participating in the network are 3D features having an elevation value even if it is zero like walking links, real bus stops, and real rail stations. So all feature classes have an elevation field and the elevation connectivity would be modelled on these elevation fields (see Figure 5-20).

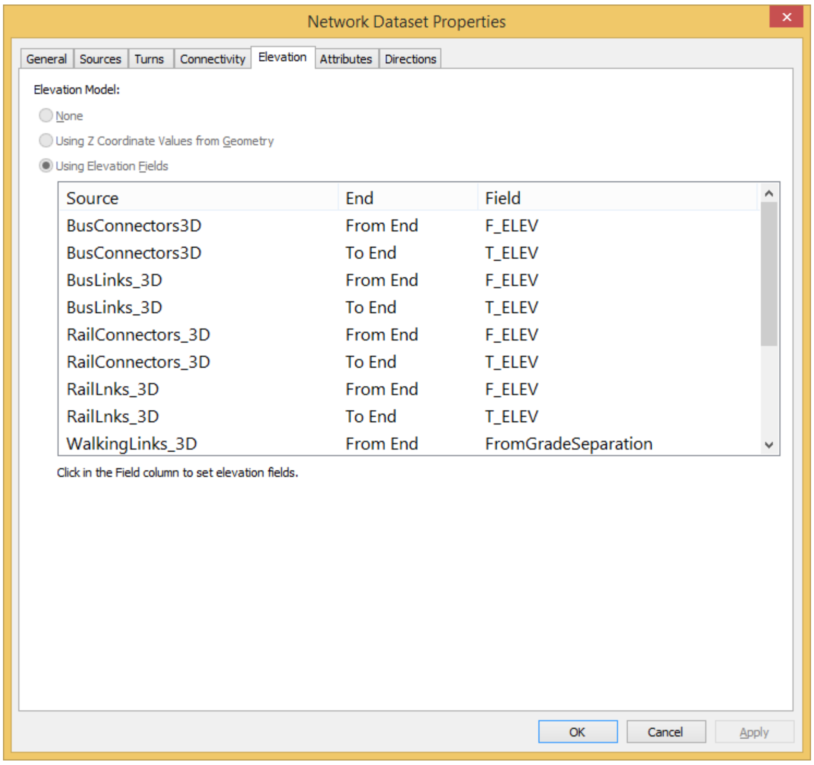

Figure 5-20 Multimodal Network Dataset: Set Elevation

5.4.4.4 Step 3: Set Attributes

There are three categories of attributes involved in this model: cost, restriction and descriptor attributes (see Figure 5-21). Each category of attributes assigns their values by evaluators, and there are mainly four types of evaluators:

- Field evaluator: to assign values from a field of one network element, which is also the most widely used category of evaluators.
- Constant evaluator: to assign a constant value.
- Function evaluator: by performing a multiplicative or logical function on another attribute value or parameter value.
- Script evaluator: provides a way to model complex attributes, using VB script or Python script.

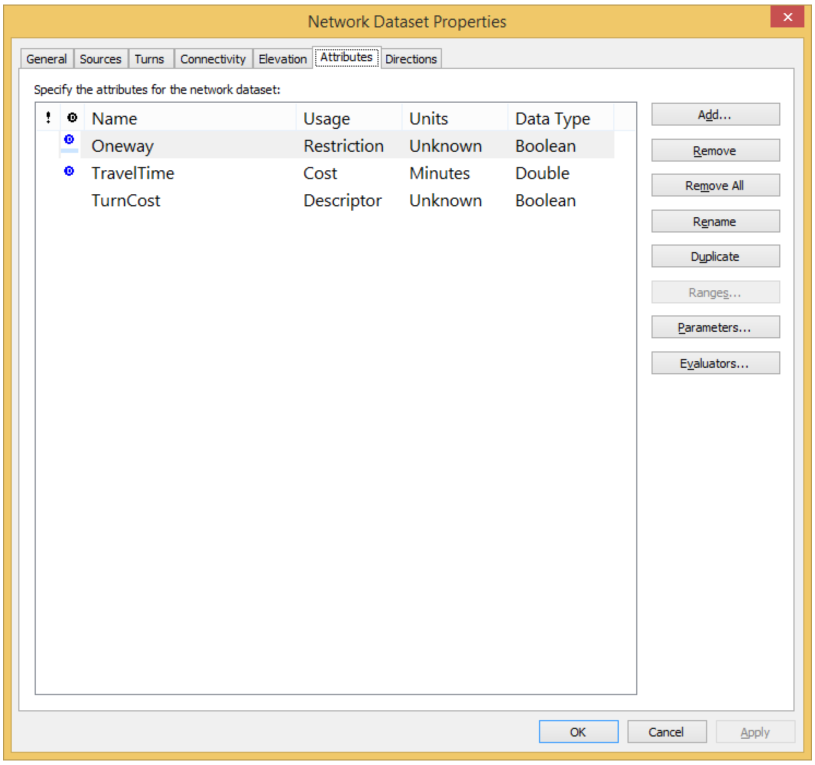

Figure 5-21 Multimodal Network Dataset: Set Attributes

5.4.4.4.1 Set Up of Cost Attribute

Cost attributes are used to measure travel impedances, such as travel length or travel time. In this model, minimum travel time of each OD pair was selected and considered as the travel impedances. Based on the methodology in Section 5.3.1, travel cost for each OD pair is defined by four components: WKT, WTT, IVT and Transfer penalty. Table 5-3 describes how cost attribute is assigned to each input network elements.

- WKT: based on the 'WKT' field of the pedestrian links source element.
- WTT: based on the timetable data, script evaluator was assigned to the from-to direction of the bus and rail connector elements. When a from-to direction bus or rail connector is traversed, this WTT script evaluator is called and will search for timetable data stored in a CSV file, and returns the next available departure time based on the current time (the time the passenger arrives at the departure bus stops). As a result, the value of WTT is equivalent to the difference between the current time and departure time of next available public transport services.
- IVT: based on the timetable data, script evaluator was assigned to both bus and rail links elements. When a bus or rail link is traversed, this IVT script evaluator is called and will search for timetable data, and returns the next arrival time and departure time of this public transport link. Hence, the value of IVT is the difference between them.

- Transfer penalty: based on the methodology described in section 5.3.1, transfer penalty is modelled as a fixed value of penalty (7.5 minutes of IVT per interchange) for each transfer. The calculation of transfer penalty therefore was based on the number of transfers for each journey. In conjunction with descriptor attributes (details see section 5.4.4.4.2), the number of transfer was counted for each journey and the corresponding transfer penalty was added as a component of the travel cost.

Table 5-3 Travel impedances as assigned to input elements

Network Elements	Element Type	Direction	Evaluator Type	Value
Pedestrian links	Edges	From_To	Field	WKT
		To_From	Field	WKT
Bus Links	Edges	From_To	Script* (linking timetable data)	IVT
		To_From	Script* (linking timetable data)	IVT
Bus connectors	Edges	From_To	Script* (linking timetable data)	WTT
		To_From	Constant	0
Rail links	Edges	From_To	Script* (linking timetable data)	IVT
		To_From	Script* (linking timetable data)	IVT
Rail connectors	Edges	From_To	Script* (linking timetable data)	WTT
		To_From	Constant	0
Real bus stops	Junctions			
Projected bus stops	Junctions			
Rail stations	Junctions			

*the scripts for WTT and IVT calculation based on timetable data are represented in Appendix C.

5.4.4.4.2 Set Up of Descriptor Attributes

Descriptors are attributes that describe characteristics of the network or its elements, such as the number of lanes and speed limit on a road system. Although descriptors could not be directly used as a travel impedance, they can be used in conjunction with cost attributes.

In this model, a descriptor attribute was created for describing bus routes used to model transfer penalties when transferring between them (see Figure 5-22). This 'Turn Cost' descriptor characterized bus routes by the elevation attribute field and was used to apply an appropriate transfer penalty. Since all bus routes were included in one connectivity group and there was overlap between them, there was a tendency for Network Analyst to switch between bus routes in order to produce journey path with the shortest travel time. As a result, a turn cost was created that would add 7.5 minutes every time a journey path switched from one bus route to another as distinguished in the 'Turn Cost' descriptor. This was implemented as a default turn value for all bus-related costs.

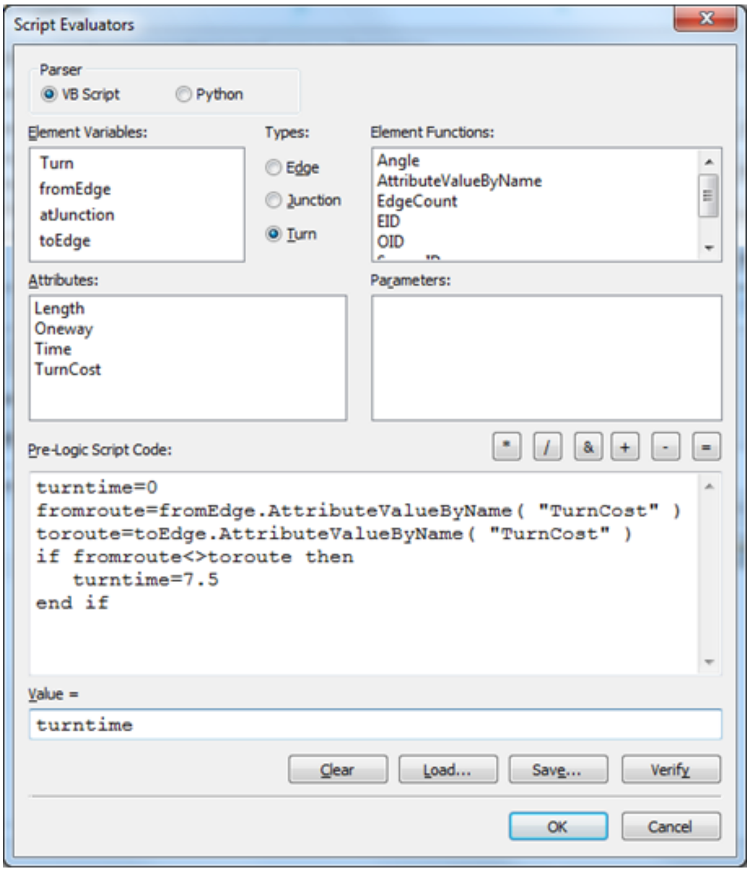

Figure 5-22 Multimodal Network Dataset: Descriptor Attribute

5.4.4.4.3 Set Up of Restriction Attribute

Restrictions are used for restricting travel across elements, and the most widely used example is the 'one-way' restriction. In this model, the 'direction' field of the bus link element stores in/outbound information for each bus link:

- Value 'FT' means outbound direction of this bus link is available.
- Value 'TF' means inbound direction of this bus link is available.
- Value 'Both' means both directions of this bus link are available.

Therefore, the one-way' restriction attribute were set by VB script, as follows (see Figure 5-23):

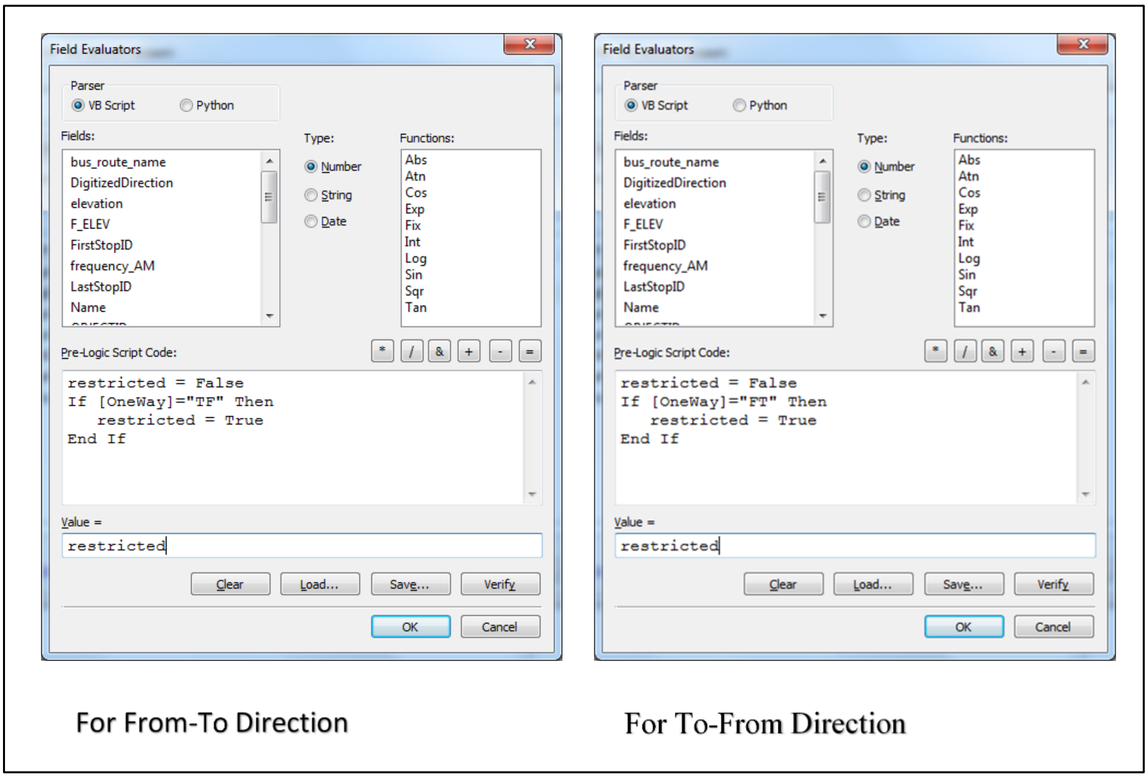

Figure 5-23 Multimodal Network Dataset: Restriction Attribute

5.4.5 Calculate Travel Costs

The final stage is to input all potential OD pairs into ArcGIS, and to calculate travel costs based on the multimodal network dataset built in the previous step. Using the 'New Route' tool available in the ArcGIS Network Analyst package, minimum travel time of each OD pair was selected and considered as the final result.

5.4.6 Automating the Travel Cost Calculation Model

Although this 3D ArcGIS model could be modelled under the ArcGIS user interface, it is clear that the data preparation process of the model is lengthy and in some parts repetitive. For example, the steps of creating bus stops, routes and transfer connectors datasets need to be repeated for each bus route. Based on the research objective, this travel costs calculation model is designed for city-size bus networks, which means large number of available bus routes and huge size of potential OD pairs. With such a large dataset, both the data preparation and travel costs calculation process become even more time-consuming. The whole model was therefore automated using the developer interface of ArcGIS: ArcObjects for Java (see Appendix D). As a result, the data preparation process would run automatically, and the calculation time has been significantly reduced.

5.5 Conclusion

This chapter developed a methodology to measure the performance of the current bus networks by calculating gravity-based accessibility levels from population-weighted centroids of postcodes to a set key services, including education, health, city/town/district centres, employment centres, and open spaces. Compared with other published models, this ArcGIS-based model was designed for real-world size public transport networks, and will output more realistic results based on the available public-source input data. Based on the methodology described here, an automated accessibility model has been built under the environment of ArcObjects for Java, and will be implemented to a city-size public transport network, the current Southampton bus network, in Chapter 7.

Chapter 6: Optimisation Model

6.1 Introduction

In this chapter, a practical optimisation model has been developed to explore the potential improvements, including both route planning and frequency setting, which could be achieved with centralised planning of bus networks using an adapted tabu search algorithm. The methodology of the improvement approach is to minimise total social cost subject to a variety of constraints which reflect system performances and/or resource limitations. This optimisation model has been developed under the environment of ArcObjects for Java. Compared with other published models, this optimisation model has the following characteristics:

- It is designed to work for real-world size bus networks based on complex road network topology.
- The multi-objective function of this optimisation model is to minimise total social cost (TSC), which is defined as the weighted sum of total operator cost (TOC), total user cost (TUC) and total external cost (TEC). In order to evaluate all costs involving in providing public transport networks, the impacts to external environment should also be considered, as well as the TOC and TUC that considered by published models.
- Multimodal public transport system: rail services were considered in the model alongside bus and walk options in order to develop an integrated improvement of the public transport network.
- Using possible OD pairs instead of an OD matrix to calculate user cost: Because of the difficulties in obtaining OD matrices for British urban areas, alternative ways of estimating user cost across a network were considered.
- Tabu Search-based methodology: because of its advantages in both theory and practice compared with other meta-heuristic algorithms, an adapted tabu search algorithm was applied in this optimisation model.

The remainder of this chapter is divided into 4 sections. Section 6.2 lists the input data required by the optimisation model. Mathematical formulation of the model is displayed in section 6.3. A detailed methodology follows in section 6.4, consisting of three main components: the candidate route set generation procedure, the solution evaluation procedure, and the optimal solution search procedure. The final section summarises and discusses the whole chapter.

6.2 Model Requirements

There are three categories of input data required in this optimisation model: candidate bus stops and links, possible origin-destination (OD) pairs, and the possible terminal set.

6.2.1 Candidate bus stops and links

Candidate bus stops are created based on the current bus stops and their locations, and any additional bus stops can also be added depending on research objectives. Between each two adjacent bus stops, a candidate bus link was delineated based on the available ITN road layers.

6.2.2 Possible OD pairs

Possible OD pairs have been extracted from the accessibility model (see section 5.2.3): the population centroids of six/seven digit postcode units are defined as the set of possible origin points; key services, including educational establishments, health services (GPs), employment centres, city/ town/ district centres and open spaces, are defined as possible destination points.

6.2.3 Candidate Terminal Set

The candidate terminal set includes the terminals of the current bus network, as well as all other possible terminals, which are defined as bus stops located within the maximum walking distance of the main service centres within the city boundary (see Figure 6-1 for an example). Based on *WebTAG Public Transport Assignment* (Department for Transport, 2014a) advice, a value of 1,200 metres was used as the maximum walking distance in this model. Eight categories of main service centres are selected; they are railway stations, ferry stations, airport, hospitals, universities and colleges, employment centres, city/town/district centres, and main open spaces.

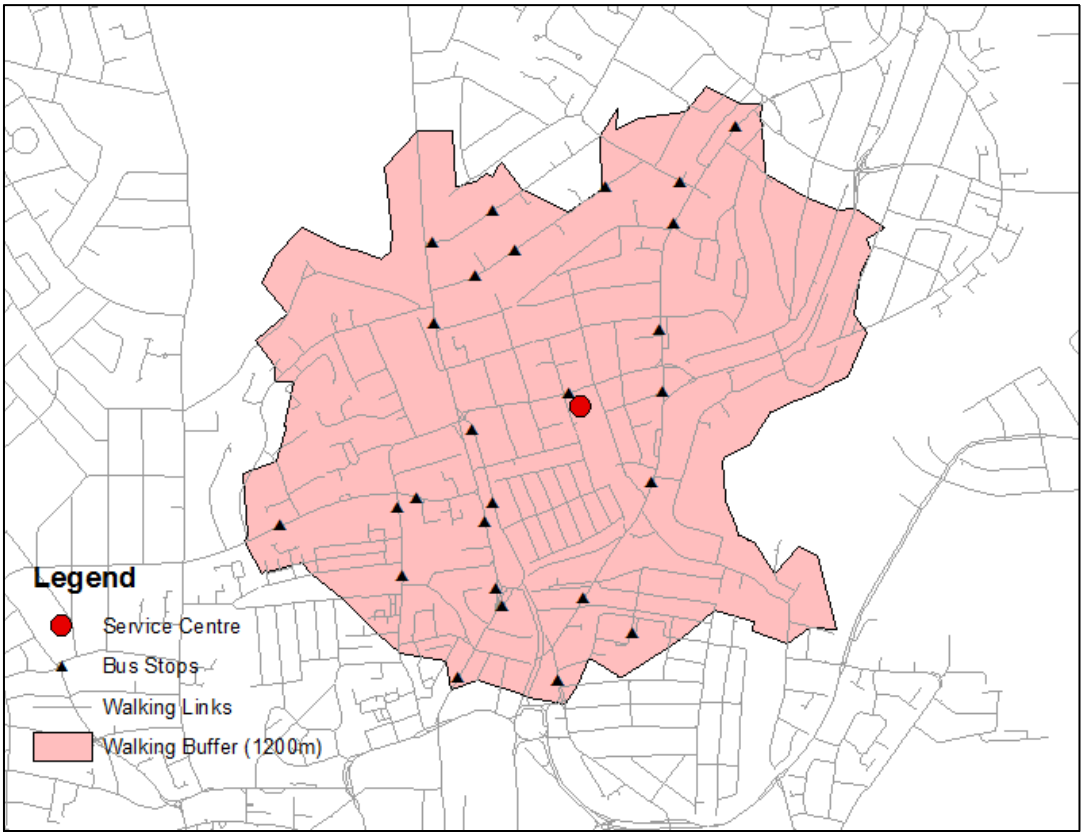

Figure 6-1 Definition of Potential Terminals

6.3 Model Formulation

Before describing the composition of the methodology, it is necessary to set out the decision variables, assumptions, basic concepts and notions, objective function, and constraints which underpin the research in this section.

6.3.1 Decision variables

This research focuses on solving the TNDP problem for city-size bus networks. Two decision variables are therefore involved in this optimisation model:

- Choose an optimal set of bus routes from the candidate route set;
- Set optimal route frequency for each bus route in the network.

6.3.2 Assumptions

For simplicity, the following assumptions were made in this optimisation model:

- The improvements are only applied to the bus network, and the rail service remains fixed during the improvement process.

- The bus network improvement methods only include route planning and frequency setting, while the fare system and quality of services and facilities remain at current levels.
- Bus speed is constant on all routes, and is not subject to congestion effects. The value of the average bus speed can be extracted from the current bus timetable data, available from the TNDS 2016.
- There is no consideration of vehicle overcrowding and capacity constraints, so it is assumed that all passengers can and will board the first bus to arrive.
- The assignment sub-model assumes that all passengers share a perfect and equal perception of the travel cost to their destinations and that all choose the cheapest option in terms of total travel cost (all-or-nothing assignment model).

6.3.3 Basic Concepts and Notations

The bus network is represented as a directed graph G = {N, A}, where N is the set of bus stops and A is the set of bus links representing connections between bus stops. A bus route is a sequence of adjacent links in G. A solution S for the TNDP is a pair (R, F) where R = $\{r_1, r_2, \ldots r_n\}$ is the set of routes and F = $\{f_1, f_2, \ldots f_n\}$ is the set of frequencies. The set of origin-destination (OD) pairs is defined as OD = $\{od_{ij}\}$ where *i* and *j* are the origin and destination point respectively.

The notation used in the mathematical formulation is as follows:

$\gamma_1, \gamma_2, \gamma_3$	Weights of operator cost, user cost and external cost, which must sum to equal 1
C_{vkm}	Unit operation cost, distance related (£ per vehicle-kilometre)
C_{vh}	Unit operation cost, time related (£ per vehicle-hour)
L_{r_k}	Length of route k (km)
f_{r_k}	Frequency of route k (number of buses per hour)
h_{r_k}	Headway of route k (hour)
T_{r_k}	Round trip time of route k (minutes)
f_{min}	Minimum frequency permitted for any route (number of buses per hour)
f_{max}	Maximum frequency permitted for any route (number of buses per hour)
FS_{r_k}	Number of buses required to operate route k
$f_{crossboundary}$	Total bus frequencies linking city centre with nearby towns and cities based on the current bus network (number of buses per hour)
v	Average bus speed (km/h)
W_{wkt}	Perception of a given unit of walking time compared to the same unit of in vehicle time (e.g. if W_{wkt} = 2 then walking time is given double the weight of in vehicle time when calculating

	travel cost)
W_{TUC}	Value of dividing the number of passenger journeys (per morning peak hour) within the research area by the number of possible OD pairs
W_{wtt}	Perception of a given unit waiting time compared to the same unit of in vehicle time
$T_{penalty}$	Transfer penalty (in minutes)
W_j	Weight of destination type, where the sum of weights across all destination types must equal 1
T_n	Number of transfers within OD journey n
C_{ivt}	Value of passenger time (£ per in-vehicle hour)
C_{air}	Unit air pollution cost (£ per vehicle-kilometre)
C_{noise}	Unit noise pollution cost (£ per vehicle- kilometre)
$C_{climate}$	Unit climate change cost (£ per vehicle-kilometre)
$C_{accident}$	Unit external accident cost (£ per vehicle-kilometre)
FS_{max}	Maximum bus fleet size available for operations across the network

6.3.4 Objective function and constraints

The objective function for this optimisation model is to minimise total social cost (TSC), which is defined as the weighted sum of total operator cost (TOC), total user cost (TUC) and total external cost (TEC). This bus service planning problem therefore becomes a complex multi-objective problem. The three weights $\gamma_1, \gamma_2, \gamma_3$ are introduced to reflect the trade-offs between the relative importance attached to TOC, TUC and TEC. Clearly, different values of these weights may result in different optimal designs of the transit network. Based on the case study applied in Chapter 7, the sensitivity of the optimisation model has been checked by assigning different weight sets to the objective function in section 7.4.2.2.

Based on the linear operator cost function by Small (1992), the TOC is calculated as a combination of total operated bus distance and total bus running time. The TUC, according to the *WebTAG Public Transport Assignment* (Department for Transport, 2014a), is a weighted sum of in-vehicle travel time (IVT), walk time (WKT), waiting time (WTT) and transfer penalties ($T_{penalty}$) for all possible OD pairs which can be prepared following the steps provided in section 5.2.3. However, the OD pairs demand data only lists the potential origins and destinations between which passengers may make journeys, and excludes the number of passengers for each OD pair, thus the actual demand of passengers cannot be guaranteed to be represented. For example, there are at total 1,172,325 possible OD pairs which have to be evaluated for the TUC calculation in the Southampton case study according to the definition of OD pairs demand data developed for the optimisation model. In reality, the number of bus journeys in Southampton in 2015 is 18.6 million (Department for Transport, 2015c) and only 12% of them are during morning peak hour (Department for Transport, 2016b), resulting in approximately 6,000 bus trips in Southampton per morning peak hour. It therefore indicates that the number of passengers for majority of possible OD trips is zero during morning peak hour. In order to improving the accuracy of final results, the value of TUC was weighted by W_{TUC}, which is defined as the value of dividing the number of passenger journeys per morning peak hour within the research area by the number of possible OD pairs. TEC involves all costs related to air pollution, noise pollution, climate change and accident costs across the network, based on *WebTAG unit A3 environment impact appraisal* (Department for Transport, 2015b). Accordingly, the mathematical formulation of the model can be expressed as follows:

$$Minimise\ TSC = \gamma_1 TOC + \gamma_2 TUC + \gamma_3 TEC \quad (6.1)$$

Where

$$TOC = \sum_{k=1}^{n} f_{r_k} L_{r_k} \left(C_{vkm} + \frac{C_{vh}}{v} \right) \quad (6.2)$$

$$TUC = W_{TUC} \sum_{od_{ij \in OD}} W_j C_{ivt} \left(IVT + W_{wkt} WKT + W_{wtt} WTT + T_{penalty} T_n \right) \quad (6.3)$$

$$TEC = \sum_{k=1}^{n} f_{r_k} L_{r_k} (C_{air} + C_{noise} + C_{climate} + C_{accident}) \quad (6.4)$$

Subject to

$$f_{min} \le f_{r_k} \le f_{max} \text{ (Frequency Feasibility)} \quad (6.5)$$

$$INT \left(\sum_{k=1}^{n} \frac{T_{r_k}}{h_{r_k}} \right) \le FS_{max} \text{ (Fleet Size)} \quad (6.6)$$

$INT()$ = Integer function: rounds a number down to the nearest integer.

$$\left(\sum_{k \in S_{crossboundary}} f_k \right) = f_{crossboundary} \text{ (Cross-boundary Constraint)} \quad (6.7)$$

There are three main constraints involved in this model. The first constraint (6.5) concerns frequency feasibility, setting the minimum and maximum frequencies permitted for each candidate bus route. The second is the fleet size constraint (6.6), which guarantees that the optimal network never uses more vehicles than are available to operate the base network. Obviously, this could be adjusted to allow a larger (or smaller) fleet size than the base case depending on particular local circumstances and funding considerations. The last constraint (6.7) is to retain the service levels to nearby towns and cities at current levels, thus avoiding the cross-boundary problem where optimising a network in one area might have a detrimental impact on the network provided in an adjacent area.

According to the definition of objective function, the values of the TOC and TEC are directly decided by the vehicle size across the network. This is because the round trip time of the route k (T_{r_k}) can be calculated by following formula:

$$T_{r_k} = \frac{2L_{r_k}}{v} \tag{6.8}$$

Thus, the mathematical function of calculating fleet size is given by equation 6.9:

$$\text{fleet size} = INT\left(\sum_{k=1}^{n} \frac{2L_{r_k} f_{r_k}}{v}\right) \tag{6.9}$$

And TOC and TEC can be written as functions of fleet size:

$$TOC = \frac{1}{2}(vC_{vkm} + C_{vh})\text{fleet size} \tag{6.10}$$

$$TEC = \frac{v}{2}(C_{air} + C_{noise} + C_{climate} + C_{accident})\ \text{fleet size} \tag{6.11}$$

6.4 Methodology

6.4.1 Overview of Methodology

The methodology of bus network improvement, including both route design and frequency setting, consists of three main components: the candidate route set generation procedure, the solution evaluation procedure and the optimal solution search procedure (see Figure 6-2). In the candidate route set generation procedure, all candidate routes are created with a set of possible frequencies associated with each one. Next, the optimal solution search procedure selects a possible optimum set of routes (potential solution) from the candidate route set. Each potential solution is then evaluated by the objective function (TSC) in the solution evaluation procedure, with iteration then occurring between this and the solution search procedure until a pre-specified time period or number of solutions has elapsed. The final output of this optimisation model is then an optimal bus network as measured by TSC, consisting of a set of bus routes with associated frequencies. The stages of the methodology are described in more detail in the following sections. Based on the methodology described here, the optimisation model has been developed under the environment of ArcObjects for Java, and detailed building steps are available in Appendix E.

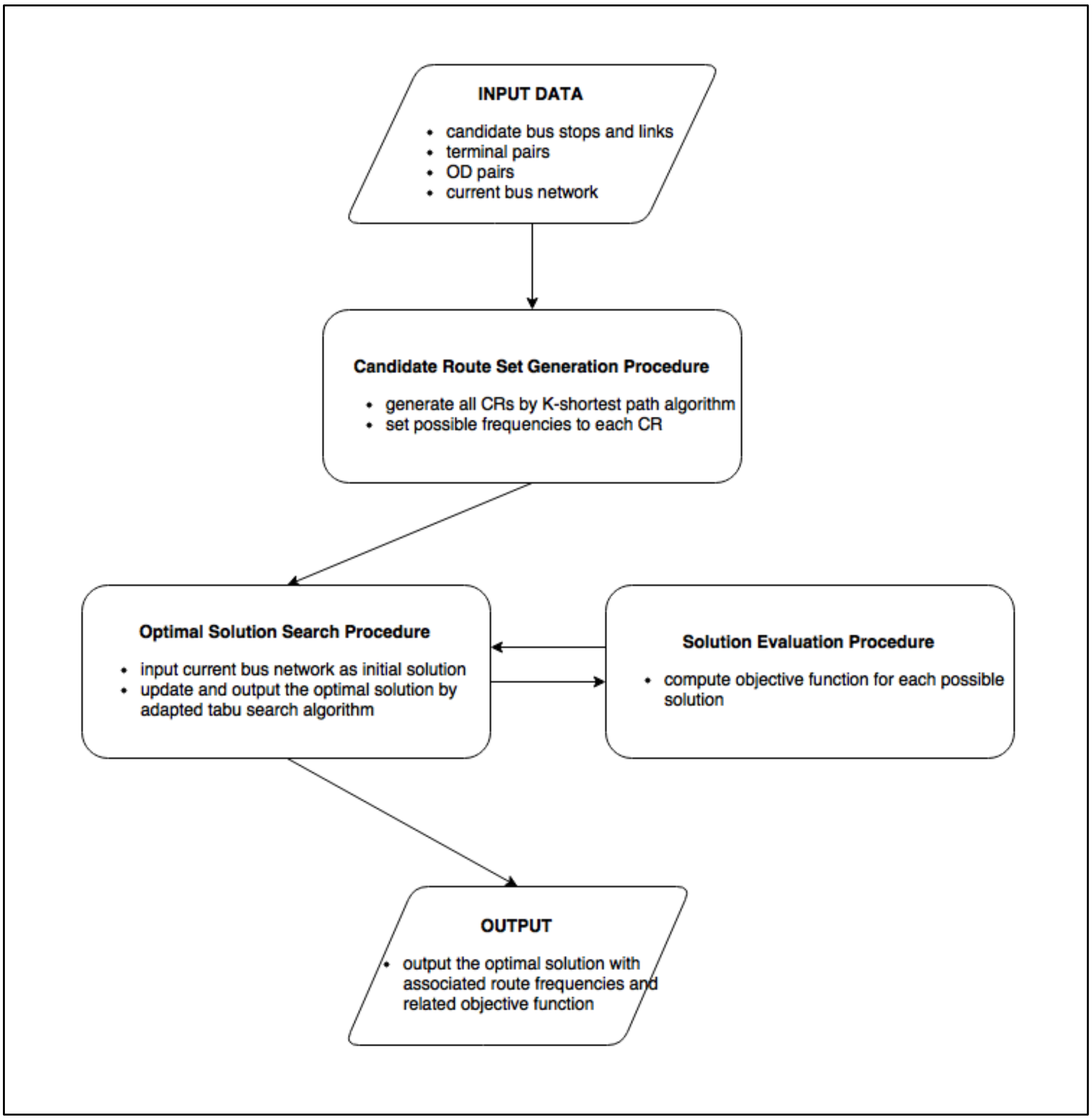

Figure 6-2 Methodology of the Optimisation Model

6.4.2 Candidate Route Set Generation Procedure

In the candidate route set generation procedure, candidate routes are generated by the k-shortest path algorithm for each terminal pair in the possible terminal set. Because the Network Analyst extension of ArcGIS includes algorithms for finding shortest paths, this procedure was processed using this functionality. By calling the 'new route' tool in the extension, ArcGIS will automatically calculate and select shortest paths based on the input ITN road layers and terminal pairs.

When the candidate route set is created, each possible frequency available in the frequency set is assigned for each candidate route, where the possible frequency set is expressed as the number of buses per hour in each direction and constrained by the minimum and maximum permitted frequencies. Thus, there are multiple possible frequencies allocated to each candidate route.

6.4.3 Solution Evaluation Procedure

In this procedure each proposed solution network is evaluated by the objective function (TSC). As set out above, TSC consists of three components: TOC, TEC and TUC. Once the proposed solution network is generated by the optimal solution search procedure, the associated candidate bus routes and related frequencies are determined, allowing the TOC and TEC to be calculated based on vehicle mileage. The TUC for the solution network are calculated by summing the travel cost of each OD pair, weighted based on the destination types served by each route. Based on data on the frequency of different trip purposes from *Transport Statistics Great Britain 2014* (Department for Transport, 2014b), the used weights are as follows:

- Educational establishments - 0.21
- Health services – 0.10
- Open spaces - 0.10
- Employment centres - 0.19
- City/town/district centres - 0.40.

Travel costs were calculated based on the UK Department for Transport's *WebTAG Public Transport Assignment* (Department for Transport, 2014a), which states that the travel cost (C_{ij}) from origin point i to destination point j comprises a weighted sum of the walking time (WKT), waiting time (WTT), in-vehicle time (IVT), and transfer penalty ($T_{penalty}$), which were defined in the model as follows:

- Walking time (WKT): Walking is considered to be the only available access and egress mode for bus services. The maximum permitted walking time is 15 minutes and the average walk speed is 4.8 kilometres per hour.
- Waiting time (WTT): For the first bus service used in a trip, the origin waiting time is defined as a function of the headway, being set as half the headway for headways up to 15 minutes, after which the waiting time is capped at 7.5 minutes. For subsequent services, passengers arrive at transfer bus stops randomly (due to the constraints of the timetable), and for simplicity the value of the transfer waiting time is therefore set to be equal to half the headway of the service boarded at the transfer stop.
- In-vehicle time (IVT): This is calculated by dividing the bus route length by the average bus speed.
- Transfer penalty: based on *WebTAG Public Transport Assignment* (Department for Transport, 2014a) advice, a transfer penalty of 7.5 minutes of IVT per interchange was applied.

In this solution evaluation procedure, the most crucial and most time-consuming component is to calculate travel costs for TUC. By adopting the travel costs calculation model already built for the accessibility model (see section 5.4), this procedure has been built under the environment of ArcObjects for Java.

6.4.4 Optimal Solution Search Procedure

Because of its advantages in both theory and practice (as discussed in section 4.5.2.3), the tabu search algorithm was chosen as the meta-heuristic technique in searching the optimal solutions. In order to further improve the performance of the search procedure, an adapted tabu search algorithm was applied in the methodology developed here. Firstly, the current bus network was selected as the initial solution, instead of a randomly selected initial solution, as it was assumed that the current network was more likely to be a moderately 'good' initial solution in terms of accessibility. Secondly, rather than using small standard moves (the swap moves), large moves, where half of the bus routes in the solution are replaced by new routes in each iteration, were used in this tabu search methodology (adding a key feature of the very large-scale neighbourhood search algorithm (Ahuja et al. 2002) into the tabu search algorithm). Hence, a larger neighbourhood space will be searched within a given time period, and more global optima should be output.

Figure 6-3 presents the flowchart of the adaptive tabu search methodology used in the optimal solution search procedure. The steps in the process can be described as follows:

- Step 1: input the current bus network as the initial solution, and evaluate the initial solution using the objective function.
- Step 2: tabu search neighbour search process for the initial solution
    - Step 2.0: preparation process
        - Set the set of tabu neighbours to be empty.
        - Save the initial solution as the current best solution.
    - Step 2.1: generate the set of feasible neighbours using the neighbourhood function and evaluate each solution in the set.
        - Each neighbourhood solution should meet cross-boundary and fleet size constraints
        - Evaluate each neighbourhood solution using the objective function
    - Step 2.2: define the set of non-tabu neighbours as the difference between the set of feasible neighbours and the set of tabu neighbours.

  - Step 2.3: find the best neighbour (evaluated by objective function) from the set of feasible neighbours and set of non-tabu neighbours (they may coincide).
  - Step 2.4: If the best neighbour from the set of non-tabu neighbours is better than the current best solution, update it as the current best solution and add it to the set of tabu neighbours.
  - Step 2.5: If the best neighbour from the set of non-tabu neighbours is worse than the current best solution, compare the best neighbour from the set of feasible neighbours and the current best solution.
    - If the best neighbour from the set of feasible neighbours is better than the current best solution, update it as the current best solution and add it to the set of tabu neighbours (tabu search aspiration process).
    - If the best neighbour in the set of feasible neighbours is worse than the current best solution, update the best solution from the non-tabu neighbours as the current best solution and add all neighbours in the set of feasible neighbours to the set of tabu neighbours.
  - Step 2.6: apply the diversification and intensification procedure to the current best solution.
- Step 3: repeat step 2 until the maximum number of generations allowed in the study has been reached. The final output of this procedure is an optimal solution (set of routes and related frequencies) and its value of objective function.

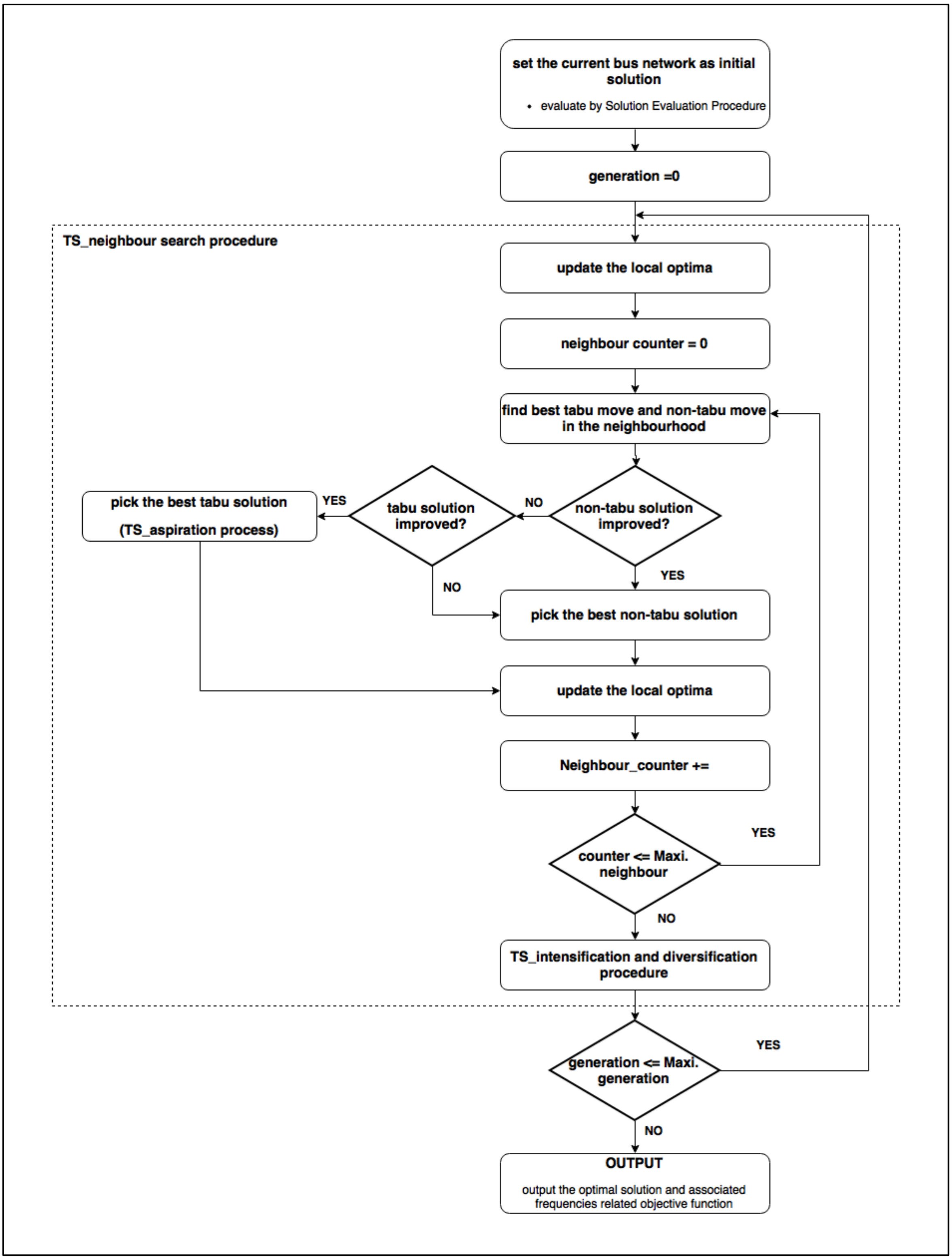

Figure 6-3 Workflow of the Optimal Solution Search Procedure

6.5 Conclusion

This chapter developed a practical methodology to explore the potential improvements, including both route planning and frequency setting, for real-word size multimodal public transport networks under the centralised planning environment. Based on an adapted tabu search algorithm, the methodology consists of three main components: the candidate route set generation procedure, the solution evaluation procedure and the optimal solution search procedure. The optimisation model described has been built under the environment of ArcObjects for Java (see Appendix E), and will be implemented based on a city-size public transport network, the current Southampton bus network, in Chapter 7.

Chapter 7: Case Study Application

7.1 Introduction

In this chapter, both the accessibility model and optimisation model developed above have been implemented based on a real-world size bus network, the current Southampton bus network. The remainder of this chapter therefore is divided into following four sections. Detailed information on the current Southampton bus network, including service supply, demand, and recent local government initiatives to improve local bus services and increase bus patronage, are displayed in section 7.2. The following two sections are the key components of this chapter, and discuss in detail the output results from the accessibility model (in section 7.3) and the optimisation model (in section 7.4). The final section summarises and discusses the whole chapter.

7.2 Current Southampton Bus Network

7.2.1 Local Bus Supply

Based on the Python conversion process (described in section 5.2.2), detailed information on the current bus network in Southampton, including bus stops, bus routes, and timetable, were extracted from the TNDS 2016. This showed that there are 7 operators providing a total of 38 services in today's bus network in Southampton during the Monday morning peak hour (08:00-09:00) (see Table 7-1). In terms of vehicle kilometres (VKM), First Southampton, Bluestar and Unilink dominate the local bus market in Southampton, with over 90% of the local bus market shared between them. Details of each service are displayed in Appendix B, such as service number, operator's name, OD terminals, route length, run time, frequency, and direction (in/outbound).

Figure 7-1 displays the current bus network in Southampton. In addition to services entirely within the city boundaries, Southampton City Centre is linked with nearby towns and districts along six corridors, known as the Western approach, Shirley, Avenue, Bevois Valley, Northam, and Itchen Bridge. Figure 7-2 illustrates that operators compete with each other along these key corridors, and corresponding services are listed in Table 7-2 for each corridor.

Table 7-1 Bus operators and services in current bus network in Southampton (During the Monday morning peak hour 08:00-09:00)

Operators	Services	No. of services	VKM	VKM (%)
FIRST IN HAMPSHIRE	72, 80	2	39.84	3.20%
FIRST SOUTHAMPTON	1, 10A, 11A, 11C, 12A, 12C, 16, 16A, 17, 17A, 1A, 21A, 5, 7, 7A, 8A, 9	17	714.34	57.37%
HAMPSHIRE BUS CO LTD	46, 46B	2	16.15	1.30%
BLUESTAR	001, 10, 11, 12, 18, 2, 3, 4, 8, LINK	10	260.35	20.91%
UNILINK	U1, U2, U6	3	183.02	14.70%
TRAVELGUEST	X5	1	5.51	0.44%
WILTS&DORSET	56, 56A, X7	3	25.82	2.07%
	TOTAL	**38**	**1245.04**	**100.00%**

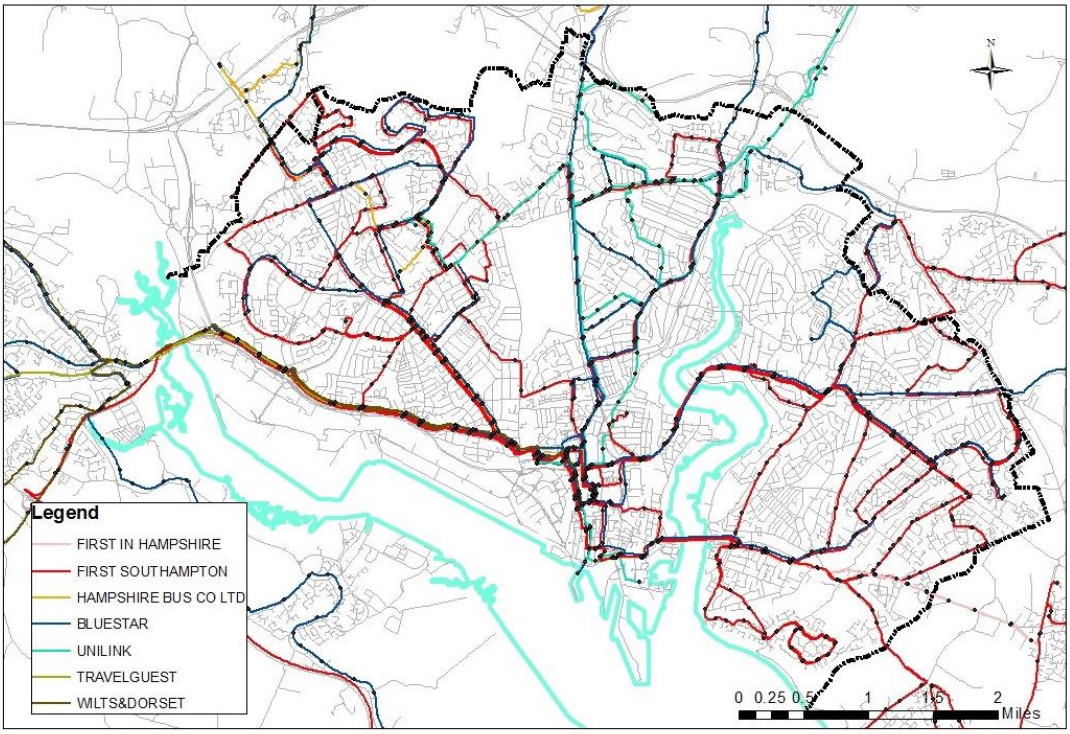

Figure 7-1 Bus Operators and Services in Current Bus Network in Southampton (During Monday Moring Peak hour 08:00-09:00)

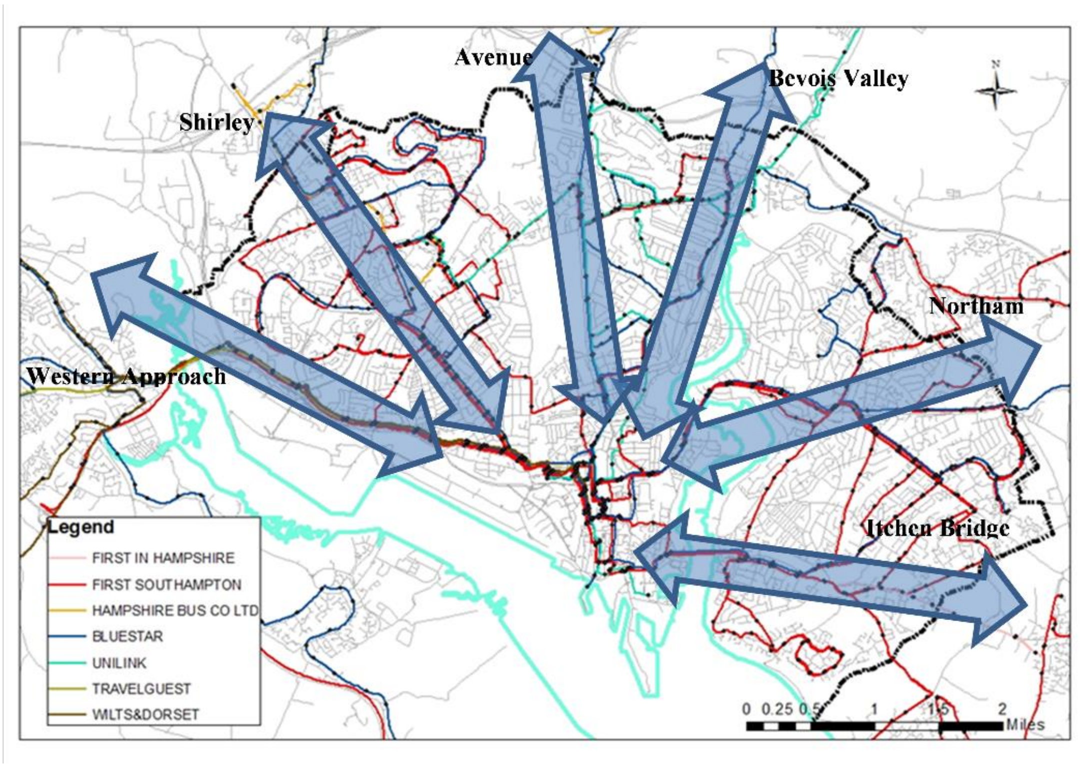

Figure 7-2 Six Corridors of Bus Routes Linking City Centre to Nearby Towns and Districts

Table 7-2 Services Along Key Corridors

Six corridors	Services
Western Approach	FIRST SOUTHAMPTON: 9. BLUESTAR: 8, 11, 12. WILTS&DORSET: 56, 56A, X7.
Shirley	HAMPSHIRE BUS CO LTD: 46, 46B. FIRST SOUTHAMPTON: 1, 12. BLUESTAR: 4, 18.
Avenue	BLUESTAR: 001. UNILINK: U2.
Bevois Valley	FIRST SOUTHAMPTON: 7. BLUESTAR: 2. UNILINK: U6.
Northam	FIRST SOUTHAMPTON: 8A, 10. BLUESTAR: 3.
Itchen Bridge	FIRST IN HAMPSHIRE: 72, 80. FIRST SOUTHAMPTON: 5, 11, 16, 16A.

7.2.2 Local Bus Demand

To local citizens, bus services are the first choice option among other public transport modes, such as rail services, for intra-city journeys. According to *Local Transport Plan (LTP3)* (Southampton City Council, 2015), around a quarter of peak period trips and a fifth of off-peak trips are made using public transport in Southampton; and approximately 85% of them are made on the bus network.

However, the trends of the local demand (measured by passenger journeys) are not very positive. Figure 7-3 suggests there are three turning points of the bus patronage trend in Southampton from 2004/05 to 2014/15: bus patronage started rising from 2005/06, kept falling from 2008/09, and started increasing from 2012/13. The rising period of bus patronage between 2005/06 and 2008/09 is likely to be due to the extension of the concessionary fare scheme in that period (Song et al., 2014). Since 2006, a free fare policy for bus use has existed in England for the over 60s and eligible disabled people. This statutory concession operates between 09:30 am and 11:00 pm Monday to Friday and all day on Saturdays and Sundays and originally covered travel within a Travel Concessions Authority. In April 2008, a national scheme was introduced which extended free travel for concessionaires to any journey on a local bus in England (Baker and White, 2010). However, the bus market in Southampton lost customers in the period from 2008/09. Although the large gap between 2008/2009 and 2009/10 is partly due to the change of data collection methodology, there is still an obvious declining trend of the annual number of bus passenger journeys made in Southampton from 2009/10. Since 2012/13, there is a modest growth of bus usage, and the annual increase number is around 4%. The current financial supports, such as Local Sustainable Travel Fund (LSTF) and The Better Bus Area Fund (BBAF), improve the service quality across the city and to some extent contribute to the current growth of the bus network in Southampton (although the study by Song et al. (2014) has suggested that the impact of LSTF and BBAF is only marginal compared to the control areas). Although the recent growth in bus patronage compensates for the sharp loss since 2008/2009, the current bus network in Southampton still attracts less passengers compared with its peak in 2008. The future trend of bus patronage in Southampton is likely to be a concern for both the bus operators and Southampton City Council.

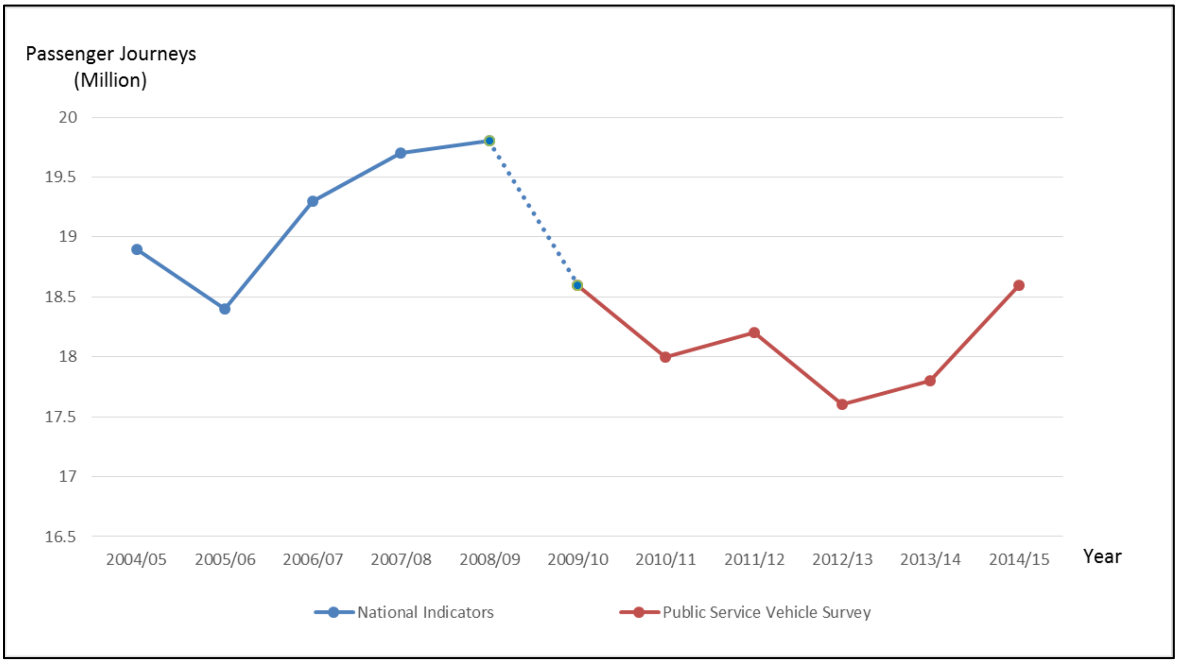

Figure 7-3 Annual Bus Patronage in Southampton

7.2.3 Applied Improvement methods

At the moment, the bus network in Southampton is still operated under a highly-deregulated environment, without any formal Bus Quality Partnerships (BQPs). As a result, three operators, First Southampton, Bluestar and Unilink, dominate the local bus market, and compete with each other on the roads, especially along the six corridors. In order to reverse the declining bus market since 2008, there have been a number of local government initiatives to improve local bus services and increase bus patronage in Southampton over recent years, including Local Sustainable Travel fund (LSTF) and The Better Bus Area Fund (BBAF) (Southampton City Council, 2012; Song et al., 2014; Newcombe, 2014).

Southampton City Council, Hampshire County Council and Portsmouth City Council work under a partnership, Solent Transport (previously Transport for South Hampshire and the Isle of Wight (TfSH)), with the aim of improving transport in South Hampshire. Solent Transport has been successful in gaining funding of £17.8 million from the Local Sustainable Travel fund (LSTF) over the period 2012 to 2015 for a number of transport initiatives, including improvements to existing bus and rail interchanges, real time passenger information, the introduction of a smart card ticketing system and improved bus priority and junctions on some corridors (Department for Transport, 2013b). An additional £630,000 has been awarded for Southampton to upgrade 37 buses with pollution reducing technology as part of the Clean Bus Technology Fund (CBTF) (Southampton City Council, 2012; Song et al., 2014; Newcombe, 2014). The Better Bus Area Fund (BBAF) supplied Solent Transport with £4.5 million (TfSH, 2012) to invest in a number of specific improvements to bus services between 2012 and 2014. The improvements included the installation of Wi-Fi, LED lighting, and next stop displays/ announcements to buses, in addition to the refurbishment of a number of buses (Song et al., 2014).

The majority of the measures being implemented as part of the CBTF and the BBAF can be described as ‘soft measures’, meaning that these measures provide improvements to the quality of the service or a more desirable travel experience, but their effectiveness is difficult to accurately quantify (Preston et al., 2005; Davison and Knowles, 2006; Currie and Wallis, 2008; Department of Transport, 2009; Song et al., 2014). According to the *WebTAG Public Transport Assignment* (Department for Transport, 2014a), introduction of a quality measure (or soft measure) does not represent a time saving in one journey, but will increases attractiveness and can therefore be modelled as a reduction in travel time. Therefore, based on the elasticity of demand with respect to travel time, Balcombe et al. (2004), Curie & Wallis (2008), and Newcombe (2014) have suggested that soft measures do not lead to large rises in bus patronage. The study by Song et al. (2014) also has suggested that the impact of LSTF and BBAF is only marginal compared to the control areas, and fails to totally compensate for the sharp decline in demand since 2008.

Southampton City Council has signed a formal agreement with the South Hampshire Bus Operators Association to increase bus patronage by an annual 5% growth, resulting in a total of 50% growth over the next two decades (Transport for South Hampshire, 2013; Southampton City Council, 2015). The current CBTF and BBAF are apparently not enough to achieve such challenging goals, and more efficient improvement approaches should be considered. The BQPs and Quality Contracts have been considered by the Southampton Council as possible solutions of reversing the current shrinking bus market in their *Local Transport Plan (LTP3)* (Southampton City Council, 2015). By adopting the idea of regulation, both BQPs and Quality Contracts will help to cut down the costs wasted in competition on the roads, and deliver integrated bus networks with more equal network distribution and less unnecessary duplication in service provision (Southampton City Council, 2015). Combined with the simple ticketing system and enforceable standards for performances and quality promoted by the CBTF and the BBAF, BQPs and Quality Contracts can therefore improve local bus services and increase bus patronage, and are potential solutions to be considered for achieving the challenging bus patronage goals in Southampton.

7.3 Current Accessibility Map

7.3.1 Data Preparation

7.3.1.1 Road Network

ITN data was downloaded from the Digimap website, and used to represent the road network of Southampton (see Figure 7-4). Alongside the city boundary, the motorway, M27, links the city to other South Hampshire areas. Within the city boundary, Southampton has a comprehensive local road network, and the majority of them are single carriageways. The main roads (labelled as A roads in ITN layers) in the city are primarily radial routes, linking the City Centre to the suburbs.

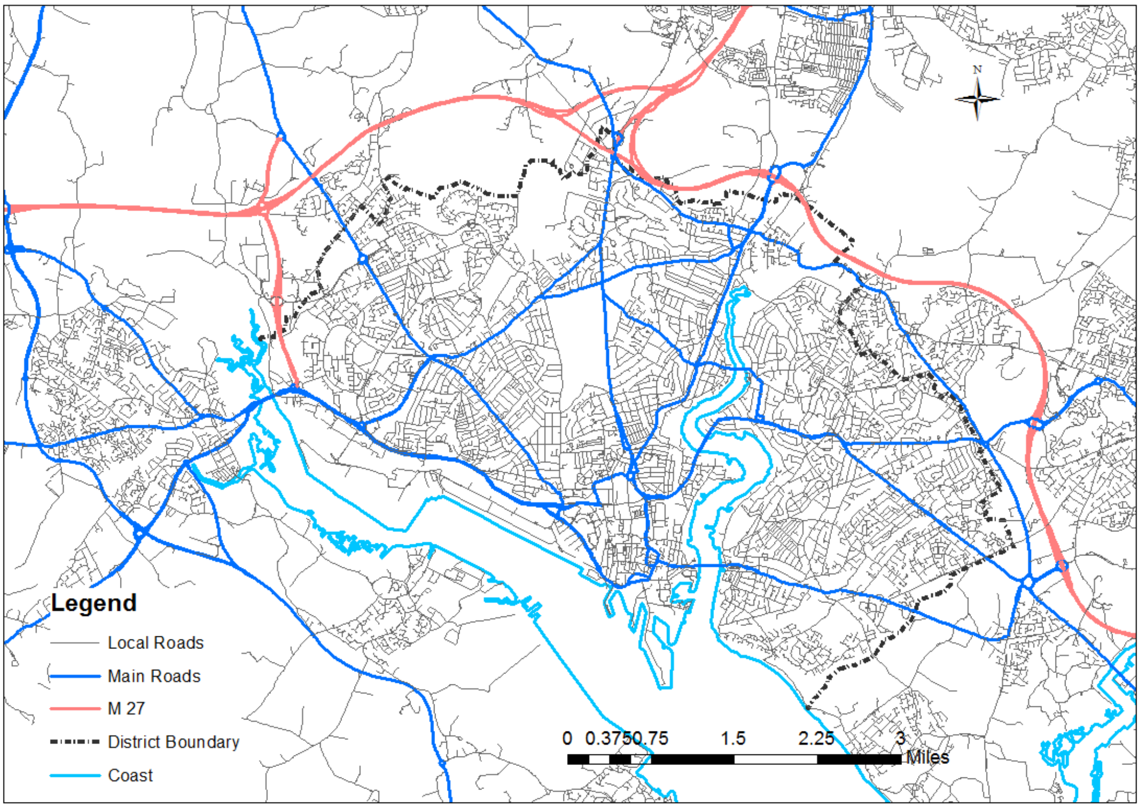

Figure 7-4 Road Network in Southampton

7.3.1.2 Public Transport Networks

Two public transport modes, bus and rail services, are involved in this accessibility model. To local citizens, bus services are the first choice option among other public transport modes for intra-city journeys, while the rail services are generally chosen for regional and inter-regional journeys. Based on the Python conversion process (details in section 5.2.2), the route and timetable information of the bus and rail services have been extracted from the TNDS 2016. Using the geocoding functions in ArcGIS, the layouts of the current public transport network in Southampton are displayed in Figure 7-5.

In today's Southampton bus network, there are a total of 1,839 local bus stops and 38 services provided by 7 operators during the Monday morning peak hour (08:00-09:00). The current bus services not only provide convenient services to key locations within the city boundary, but also link the City Centre with nearby towns and districts along six corridors, known as the Western approach, Shirley, Avenue, Bevois Valley, Northam, and Itchen Bridge. Details of current bus network have been displayed in section 7.2.1 and Appendix B.

The rail network in Southampton is linked by eight rail stations located within the city boundary; they are Southampton Central station, Woolston station, Sholing station, Millbrook station, Bitterne station, Redbridge station, Swaythling station, and St Denys station. Among them, Southampton Central station is a major regional transport hub, and is the 6th busiest station in the southeast region of England (Southampton City Council, 2015).

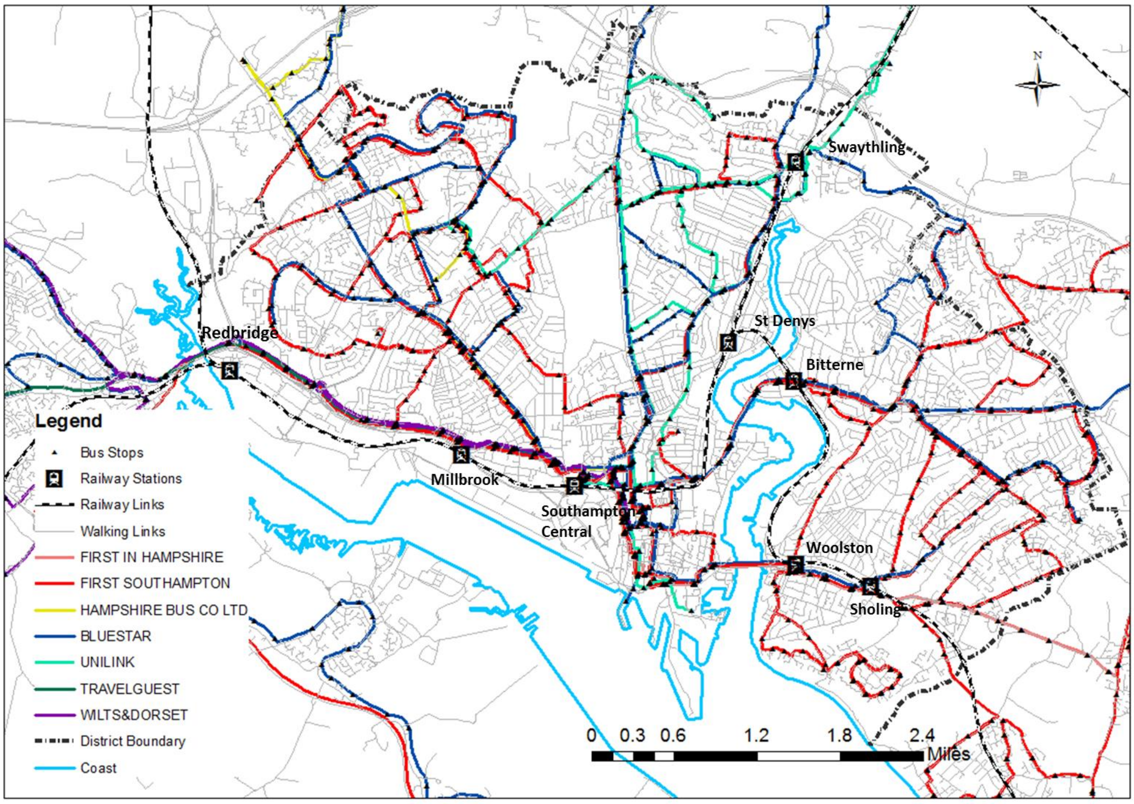

Figure 7-5 Public Transport Network in Southampton: Bus and Rail

7.3.1.3 OD Pairs

According to statistical data of the UK 2011 census, the population of Southampton is 236,855. In order to give more details of population distribution in reality, the population centroids of six/seven digit postcode units (which typically contain around 10 households) were defined as the set of possible origin points. Hence, there are at total of 5,075 origins for the Southampton area (see Figure 7-6).

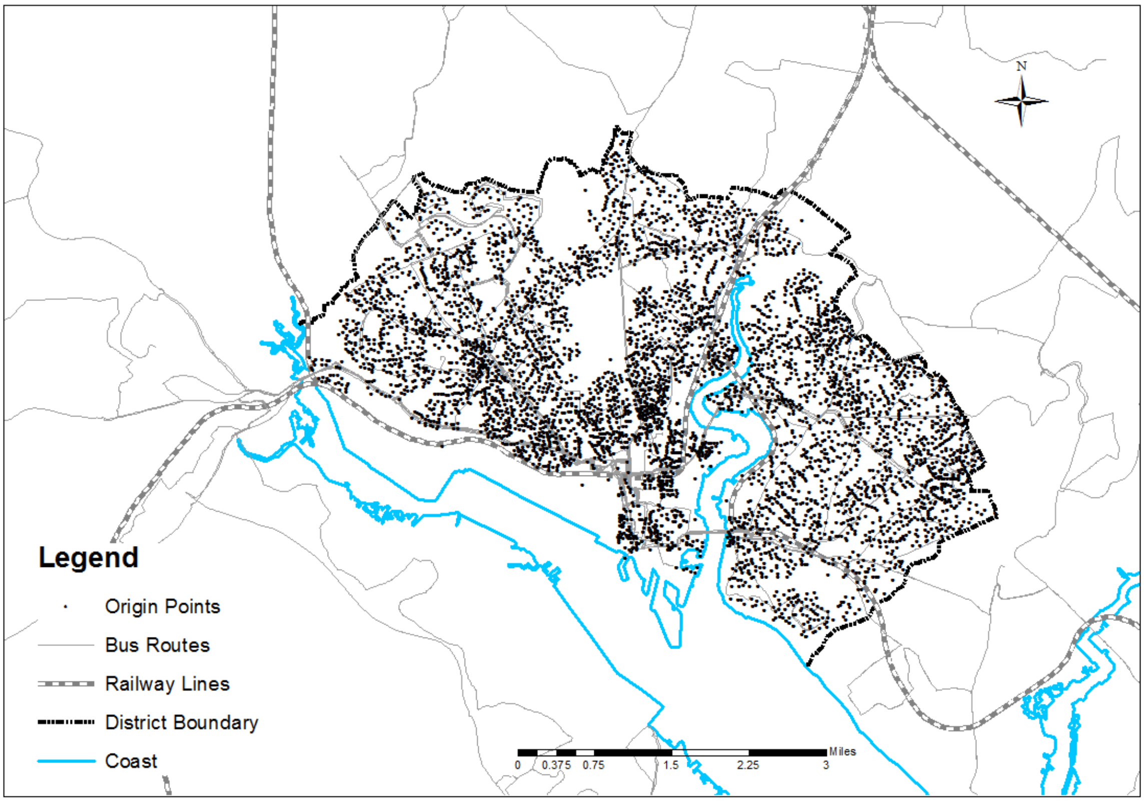

Figure 7-6 Origin Points for Southampton

Key services, including educational establishments, health services (GPs), employment centres, city/town/district centres and open spaces, were defined as destination points in the process of calculating the gravity-based accessibility index. The locations of these key destination services are displayed in Figure 7-7.

- Educational establishments: there are 54 educational establishments located within the city boundary, including 34 primary schools, 12 secondary schools, 6 colleges and 2 universities.
- Health services (GPs): there are at total of 36 GPs who provide services for Southampton residents.
- City/town/district centres: besides Southampton City Centre, there is one town centre (Shirley Town Centre) and four district centres (Portswood, Bitterne, Woolston and Lordshill Local Centres).
- Employment centres: there are a total of 18 employment centres (including 6 city/town/district centres) in Southampton.
- Open spaces: There are a total of 56 parks and open spaces in Southampton, including 5 city parks (Central parks, Mayflower Park, Southampton Common, Sports Centre and

Weston Shore), 4 district parks (Riverside Park, Mansel Park, St James Park and Mayfield Park), 40 local parks and 7 green spaces.

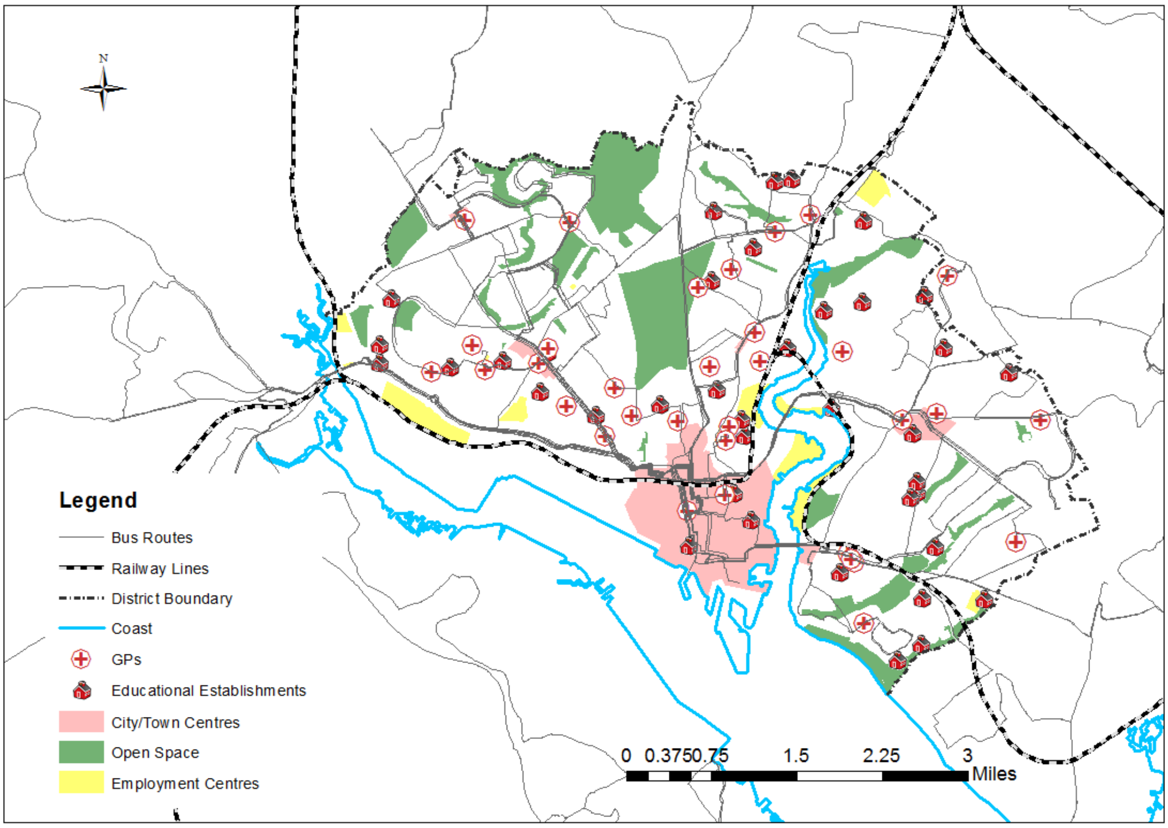

Figure 7-7 Key services in Southampton

The locations of the point destinations, such as educational establishments and GPs, were directly saved as potential destination points. For the remaining polygon destinations, alternative point locations were selected as the locations of them in the calculation based on the methodology provided in section 5.2.3.2. These definitions therefore generated a total of 231 potential destinations points for the Southampton area. In summary, there are a total of 5,075 origins and 231 destinations, resulting in 1,172,325 possible OD pairs which have to be evaluated for the travel costs calculation.

7.3.2 Results and Discussion

Following the methodology described in section 5.3, the composite accessibility index for each origin point has been calculated, and is displayed as a coloured contour map in Figure 7-8. Based on the value of its accessibility index, all origin points were equally grouped into 5 categories, where origin points in level A (red points in Figure 7-8) have the worst level of accessibility and level E (green points in Figure 7-8) the best.

Table 7-3 illustrates that over half (56.24%) of the total population enjoy relatively higher accessibility levels (the value of the accessibility index is D or E) to access key services using the current bus network in Southampton, and the number will increase to 76.82% when extending the criteria to C, D or E. Correspondingly, these residents who grouped in D or E, represented as green points in Figure 7-8, live around the City Common and in the City Centre. In contrast, areas with poor accessibility levels using the bus network (the value of accessibility index is A) are mainly located around the city boundaries, especially the northeast areas of the city, and contain 9.71% of the total residents.

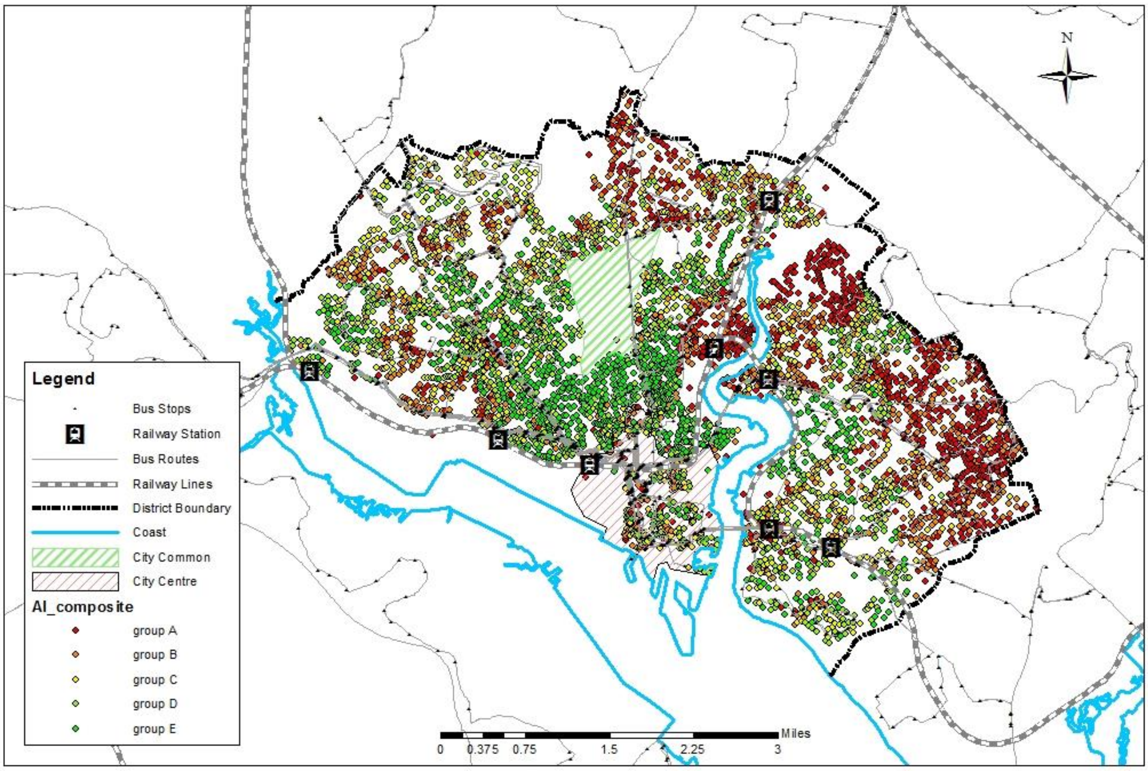

Figure 7-8 Composite Accessibility Levels in Southampton (multi-mode: walk/bus/rail)

Table 7-3 Population Distribution Based on Composite Accessibility Levels

	Population	Population (%)
Group A	22989	9.71%
Group B	31906	13.47%
Group C	48765	20.59%
Group D	61003	25.76%
Group E	72192	30.48%
SUM	236855	100.00%

7.4 Results of Optimisation Model

7.4.1 Data Preparation and Parameters

There are three categories of input data required in the optimisation model: candidate bus stops and links, possible origin-destination (OD) pairs, and the possible terminal set within the Southampton boundary. Candidate bus stops were created based on the current bus stops and their locations, and no additional bus stops were designed for this optimisation model. The potential OD pairs were directly extracted from the accessibility model. As defined in the methodology chapter (Chapter 6), the candidate terminal set includes the terminals of the current bus network, as well as all other possible terminals, which are defined as bus stops located within 1200 metres (the maximum walking distance) of the main service centres within the city boundary. Eight categories of main service centres were selected; they are railway stations, ferry stations, airport, hospitals, universities and colleges, employment centres, city/town/district centres, and main open spaces. The locations of the point destinations, such as railway stations, ferry stations, airport, hospitals, universities and colleges, were directly extracted from the PointX national Points of Interest database (available from the Digimap website: www.edina.ac.uk/digimap), and ArcGIS was used to geocode them. For the remaining polygon destinations, the boundaries of them have been defined in the process of building OD pairs for the accessibility model. Therefore, there are 293 stops selected as the candidate terminals in the Southampton implementation of the optimisation model, and any two of them were grouped as a candidate terminal pair, resulting in 41,243 terminal pairs (routes) in the possible terminal set.

Other parameters used in this optimisation model are listed in Table 7-4.

Table 7-4 Parameters for Optimisation Model

Parameter (unit)	**Value**	**Source**
Unit operation cost, distance related (£ per VKM)	C_{vkm} = £ 0.277 per VKM	Default unit operation cost, based on the works by Li (2015)[11]
Unit operation cost, time related (£ per VH)	C_{vh} = £ 13.250 per VH	Default unit operation cost, based on the works by Li (2015)[11]
Possible frequency set (number of buses per hour)	f = {0.5, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12}	Self-defined $f_{min.}$ and $f_{max.}$

[11] The value of unit operation cost (both distance-related and time-related) is difficult to obtain because of the commercial confidentiality. The default values of the operation cost used in this thesis are taken from Li (2015), and the values are based on price level in 2011 and are suitable for UK urban areas. Compared with other urban areas in UK, the Southampton case study shows no difference, thus the value of unit operation cost in the UK urban context could be applied equally well in Southampton.

Parameter (unit)	Value	Source
Cross-boundary Frequencies (number of buses per hour, for outbound direction)	f_{Avenue} = 11 $f_{Bevois\ Valley}$ = 17 $f_{Itchen\ Bridge}$ = 17 $f_{Northam}$ = 12 $f_{Shirley}$ = 21 $f_{Western\ Approach}$ = 15	Based on the current bus network data from the TNDS 2016
Average bus speed (KM/Hour)	v = 18 km/h	Based on the current bus timetable data from the TNDS 2016
Weight of TUC	W_{TUC} = 1/195	According to the definition of OD pairs demand data in section 5.2.3, there are a total of 1,172,325 possible OD pairs which have to be evaluated for the TUC calculation in the Southampton case study. In reality, the number of bus journeys in Southampton in 2015 is 18.6 million (Department for Transport, 2015c) and only 12% of them are during morning peak hour (Department for Transport, 2016b), resulting in approximately 6,000 bus trips in Southampton per morning peak hour. Therefore, $W_{TUC} = \frac{6000}{1172325} \approx \frac{1}{195}$
Perception of WKT v.s. IVT	W_{wkt} = 1.5 -2.0	*WebTAG Public Transport Assignment* (Department for Transport, 2014a)
Perception of WTT v.s. IVT	W_{wtt} = 1.5 -2.5	*WebTAG Public Transport Assignment* (Department for Transport, 2014a)
Transfer penalty (minutes)	$T_{penalty}$ = 5-10 minutes	*WebTAG Public Transport Assignment* (Department for Transport, 2014a)
Value of passenger time (£ per in-vehicle hour)	C_{ivt} = £6.24 per in-vehicle hour	*WebTAG data book* (Department of Transport, 2015a)
Unit air pollution cost (£ per VKM)	C_{air}= £0.276 per VKM	Default unit external cost, based on the works by Li (2015)[12]
Unit noise pollution cost (£ per VKM)	C_{noise} = £0.118 per VKM	Default unit external cost, based on the works by Li (2015)[12]
Unit climate change cost (£ per VKM)	$C_{climate}$ = £0.024 per VKM	Default unit external cost, based on the works by Li (2015)[12]
Unit external accident cost (£ per VKM)	$C_{accident}$ = £0.017 per VKM	Default unit external cost, based on the works by Li (2015)[12]

7.4.2 Sensitivity Analysis

The results produced by the optimisation model depend to some extent on the values assigned to the user-defined parameters, such as the maximum number of solutions generated by the tabu search algorithm, the weights given to the three components of the objective function, the

[12] The values of unit external cost (including air pollution, noise pollution, climate change and accident cost) are based on the work by Li (2015), and are suitable for UK urban areas. Compared with other urban areas in UK, the Southampton case study shows no appreciable difference, thus the values of unit external cost in the UK urban context could be applied equally well in Southampton.

weights given to the walking time (WKT) and waiting time (WTT) in TUC, and the value set for the transfer penalty. Different values of these parameters will result in different output results. Each parameter is continuous and has many possible values, as for example the number of generations can vary from 1 to infinity. It is therefore impossible to compare the performance of each possible value of each parameter in order to determine the range of associated 'optimal' network solutions which might result. However, it was possible to carry out a sensitivity analysis of these parameters based on the current Southampton bus network, to assess how the performance of the model is affected by varying the generation number, the weights associated with different elements of the TSC, the weights given to WKT and WTT, and the value of the transfer penalty.

7.4.2.1 Effects of Varying the Generation Number

Generation is a user-defined parameter, deciding the number of iterations the tabu search algorithm will run before outputting the final optimal solutions. The larger the chosen number of generations, the larger the neighbourhood space which will be searched and therefore the more global optima which will be output. However, a larger number of generations will also require more calculation time, and therefore an appropriate generation number needs to be chosen to output a reasonable number of potential optimal solutions within a reasonable calculation time. For simplicity, this section examines the effect of increasing the generation number from 10 to 100, with the corresponding calculation times ranging from six hours to three days on a standard desktop PC. In the process of searching optimal solutions, the tabu search algorithm began with the current bus network as initial solution, and recorded the current best solution after each 10 generations, until the maximum generation number 100 had been met. Only the generation number was varied, with the other optimisation settings held constant, as follows: 0.4, 0.4, and 0.2 as the weights of TOC, TUC and TEC, respectively, 1.75 and 2.0 as the weights of WKT and WTT, and 7.5 minutes of IVT per interchange as the transfer penalty. In order to get rid of the uncertainly from the single calculation, the whole process has been repeated for 10 times, and the average values of them are displayed in Figure 7-9 as the final results. The results show that the value of the objective function (TSC) tends to decrease as the number of generations increases. The improvement in TSC shows strong positive correlation with increasing generation number until it reaches 60; after that, the improvement is slight as the generation number keeps increasing.

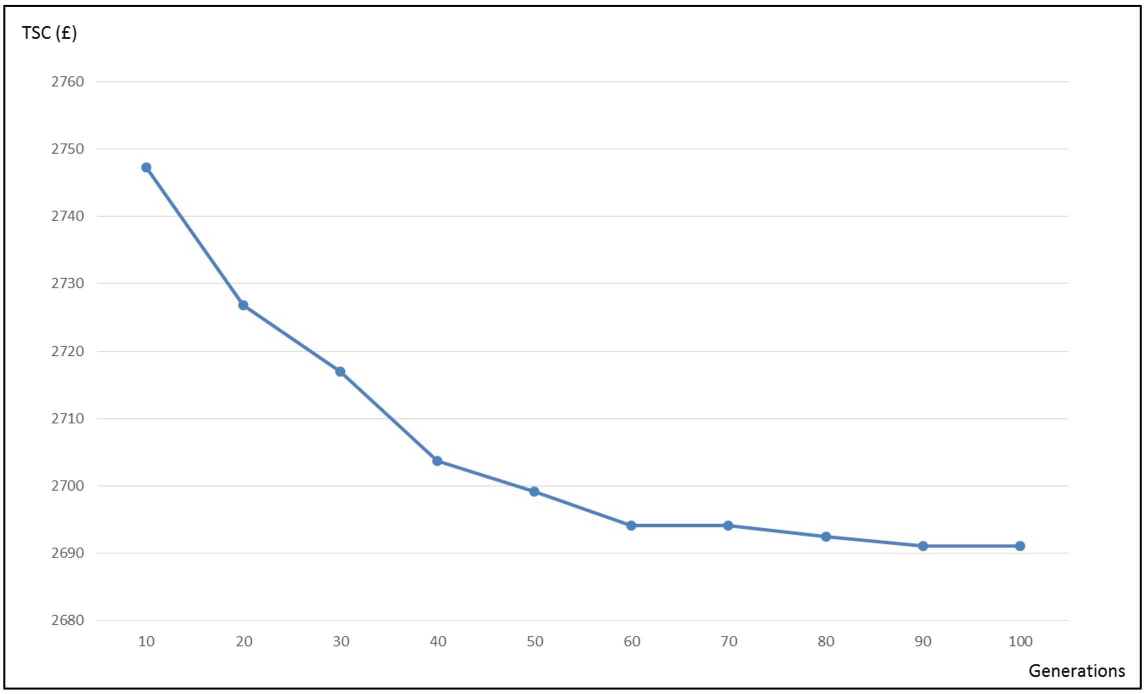

Figure 7-9 Effects of Generations

7.4.2.2 Effects of Weight Set of the Multi-objective Function

The objective function of the optimisation model is to minimise total social cost (TSC), which is a composite multi-objective function defined as the weighted sum of three components: total operator cost (TOC), total external cost (TEC), and total user cost (TUC). The three weights $\gamma_1, \gamma_2, \gamma_3$ are introduced to reflect the relative importance of TOC, TEC and TUC in determining TSC. As noted above, different values of these weights may result in different optimal designs of the transit network. In this section, the sensitivity of the model was checked by assigning different weight sets to the objective function, giving the results shown in Figure 7-10. In order to control for the effects of other parameters, the results were calculated by holding the other optimisation settings constant, as follows: 60 as the maximum generation number, 1.75 and 2.0 as the weights of WKT and WTT, and 7.5 minutes of IVT per interchange as the transfer penalty.

For each graph in Figure 7-10, the weight of TEC (γ_2) is fixed at a value between 0.1 and 0.4. The horizontal axis indicates the weight of TUC (γ_3), and the vertical axis shows the value of TSC. Therefore, a total of 26 weight sets were tested in this section. For each possible weight set, the TSC of both the current bus network (red bar) and the optimal solution output from the model (blue bar) were displayed and compared. The results show that the TSC of both initial and optimal solutions tend to increase as the weight of TUC increases. This is expected because the value of TUC is greater than the TOC, and the increase in TSC resulting from a 0.1 unit increase in the weight of TUC outweighs the decrease in TSC resulting from a 0.1 unit decrease in the weight of TOC. Figure 7-10 also show that the difference between the initial and optimal solutions increases when TUC is given a greater weight. This is because the fluctuations of the objective function mainly result from changes in TUC due to the maximum fleet size constraint which limits variations in TOC and TEC.

Figure 7-10 indicates a strong positive correlation between the weight of TUC and the improvements in TSC, but does not determine whether the fluctuations in the TSC are determined only by differences in the weight of TUC or are also linked to the value of TUC. The relationship between the weight set of the objective function and the TUC of the optimal solution was therefore also checked (see Figure 7-11). For each line in Figure 7-11, the weight of TEC (γ_2) is fixed at a value between 0.1 and 0.4. The horizontal axis indicates the weight of TUC (γ_3), and the vertical axis shows the value of TUC for the corresponding optimal solution. The results show that the TUC of optimal solution varies by the weight set of objective function, this is because of the randomly search principle adopted in the optimisation model. For each possible weight set, the optimisation model began with the current bus network as initial solution, and searched for 60 possible solutions before output the optimal result. Each possible solution was generated by randomly replacing half of the bus routes in the solution generated in previous iteration by new routes. Therefore, the optimisation model output totally different 60 possible solutions when varying the value of weights given to the three components of the objective function, and resulted in different optimal solution and related TUC. Although the TUC of optimal solution varies by the weight set of objective function, there is a positive correlation between TUC and the weight of TUC (i.e. the model outputs better solutions when TUC is given a greater weight).

In summary, the optimisation model shows strong positive correlation between the weight of TUC and the improvements in objective function (TSC) under the maximum fleet size constraint. The increasing improvements in TSC not only come from the adding weight of TUC, but also from the better network (less TUC) output from the model.

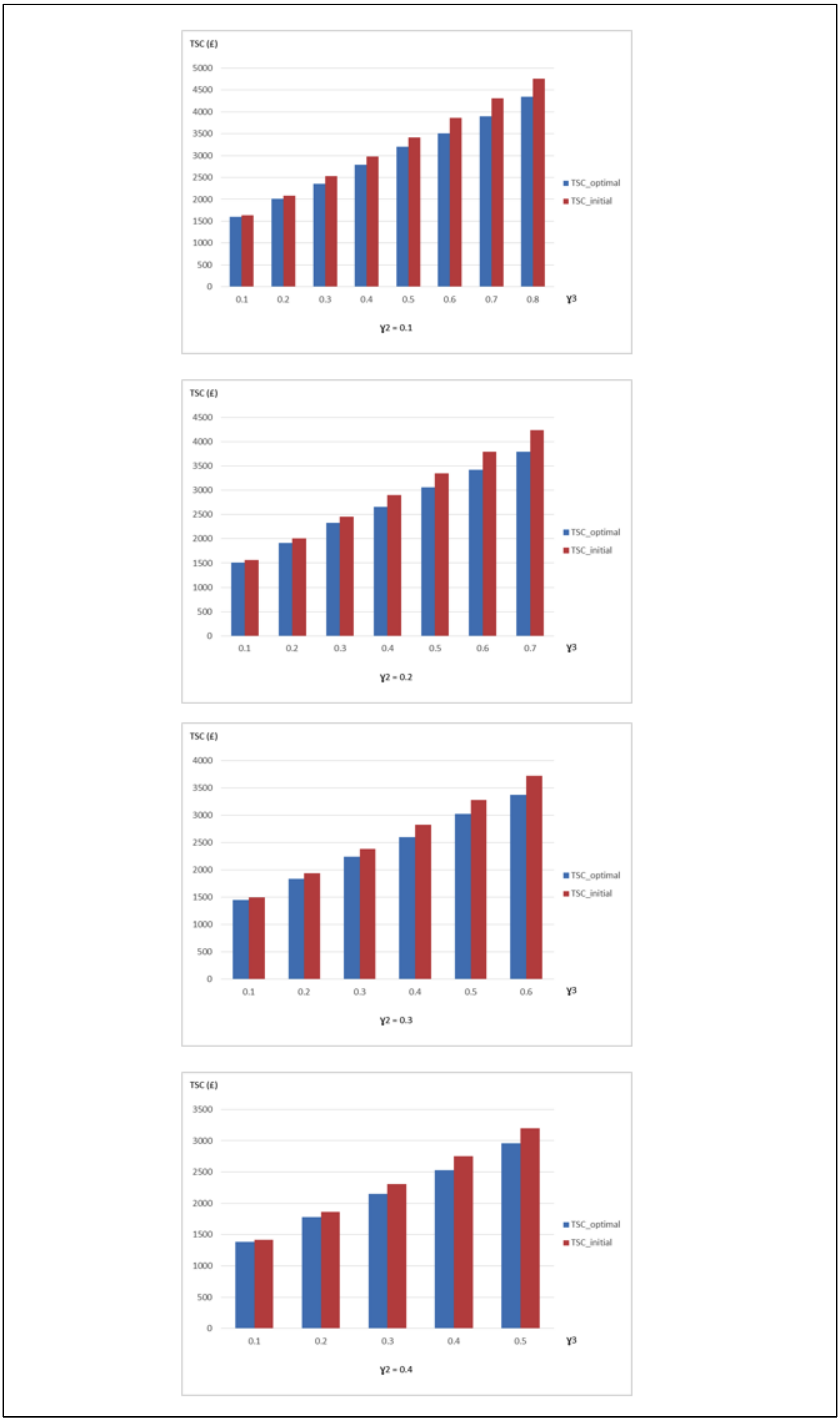

Figure 7-10 Effect of weight set of the multi-objective function (in terms of TSC)

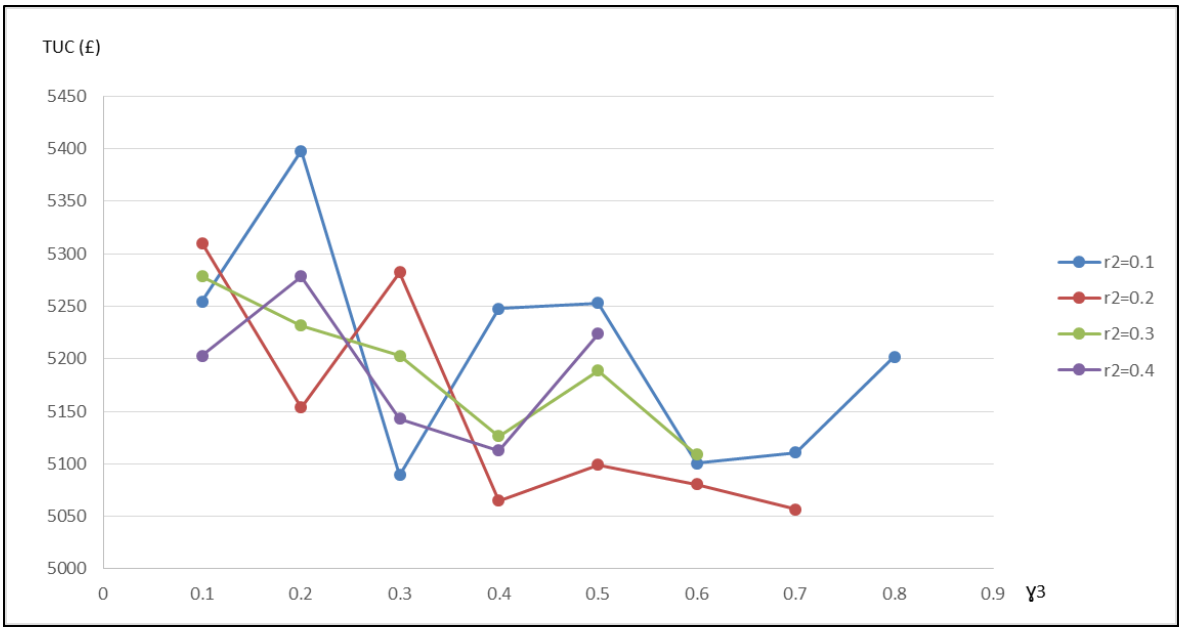

Figure 7-11 Effect of weight set of the multi-objective function (in terms of TUC)

7.4.2.3 Effect of Weight Set of WKT and WTT

Under the fixed fleet size constraint, the major improvements to the optimal solutions come from a reduction in TUC compared with the current bus network. The parameters used for calculating TUC should therefore be tested in a sensitivity analysis before implementing the model. Two categories of parameters, the weight set of WKT and WTT and the value of the transfer penalty, are essential in the process of calculating TUC, and sensitivity analyses of them are displayed in this and next section.

According to *WebTAG Public Transport Assignment* (Department for Transport, 2014a), the value of WKT is equivalent to 1.5-2.0 times the value of the same amount of IVT, while WTT is equivalent to 1.5-2.5 times IVT. Thus, the W_{wkt} set is {1.5, 2.0}, the W_{wtt} set is {1.5, 2.0, 2.5}, and weight set of (W_{wkt}, W_{wtt}) = {(1.5, 1.5), (1.5, 2.0), (1.5, 2.5), (2.0, 1.5), (2.0, 2.0), (2.0, 2.5)}. In this section, the sensitivity of the model was tested by assigning each value in the weight set of (W_{wkt}, W_{wtt}) to TUC, with the other optimisation settings held constant, as follows: 60 as the maximum generation number, 0.4, 0.4, and 0.2 as the weights of TOC, TUC and TEC, respectively, and 7.5 minutes of IVT per interchange as the transfer penalty. Results are shown in Figure 7-12 and Figure 7-13. Figure 7-12 illustrates that the TSC of both the initial (red bar) and the optimal solution (blue bar) increase when W_{wkt} and W_{wtt} are given a greater value. This is because the value of TUC will increase if WKT and WTT are assumed to have a greater cost for users. With the same weight set, the difference between the red and blue bars shows the improvement of the optimal solution compared with the initial solution, and Figure 7-13 shows this in more detail. The magnitude of the improvement in the optimal solution shows no strong relationship with the weight set of WKT and WTT, ranging between 5.65% and 7.91%.

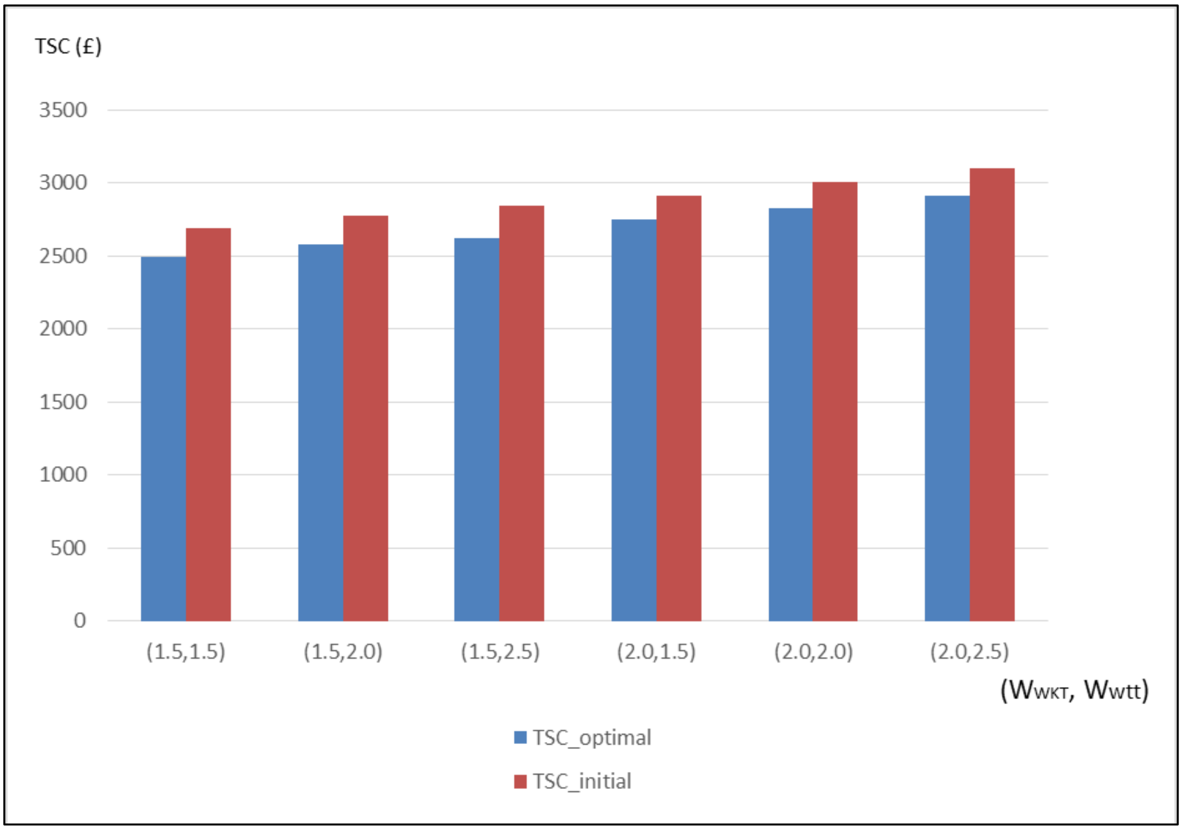

Figure 7-12 Effect of Weight Set of WKT and WTT (in terms of TSC (£))

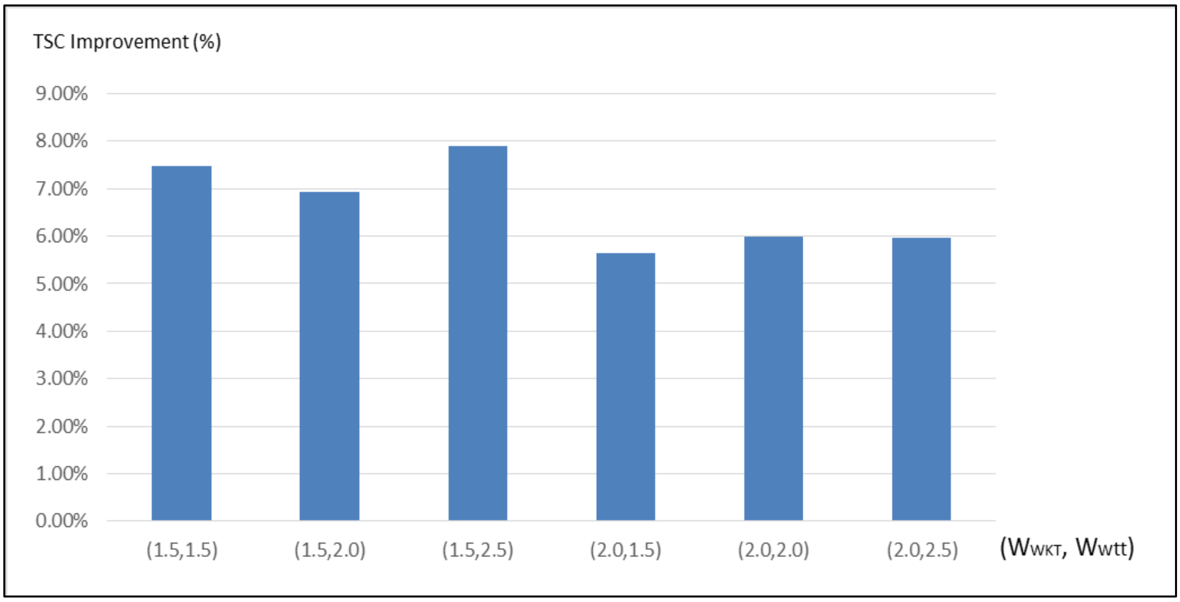

Figure 7-13 Effect of Weight Set of WKT and WTT (in terms of TSC improvement (%))

7.4.2.4 Effect of Varying the Transfer Penalty

According to *WebTAG Public Transport Assignment* (Department for Transport, 2014a), the value of the transfer penalty is equivalent to 5-10 minutes of IVT per interchange, so the possible transfer penalty set is {5, 6, 7, 8, 9, 10}. Only the value of transfer penalty was varied, with the other optimisation settings remaining constant, as follows: 60 as the maximum generation number, 0.4, 0.4, and 0.2 as the weights of TOC, TUC and TEC, respectively, and 1.75 and 2.0 as the weights of WKT and WTT. The results from varying the value of the transfer penalty are shown in Figure 7-14 and Figure 7-15. Figure 7-14 shows that the TSC of both the initial and optimal solutions increase when higher values are used for the transfer penalty. This would be expected because the value of TUC will increase if a larger transfer penalty is used. The relationship between transfer penalty and the level of improvement in TSC is displayed in Figure 7-15. This shows that there is no consistent relationship between the level of transfer penalty and the corresponding improvement in TSC, which fluctuates between 6.67% and 9.19%.

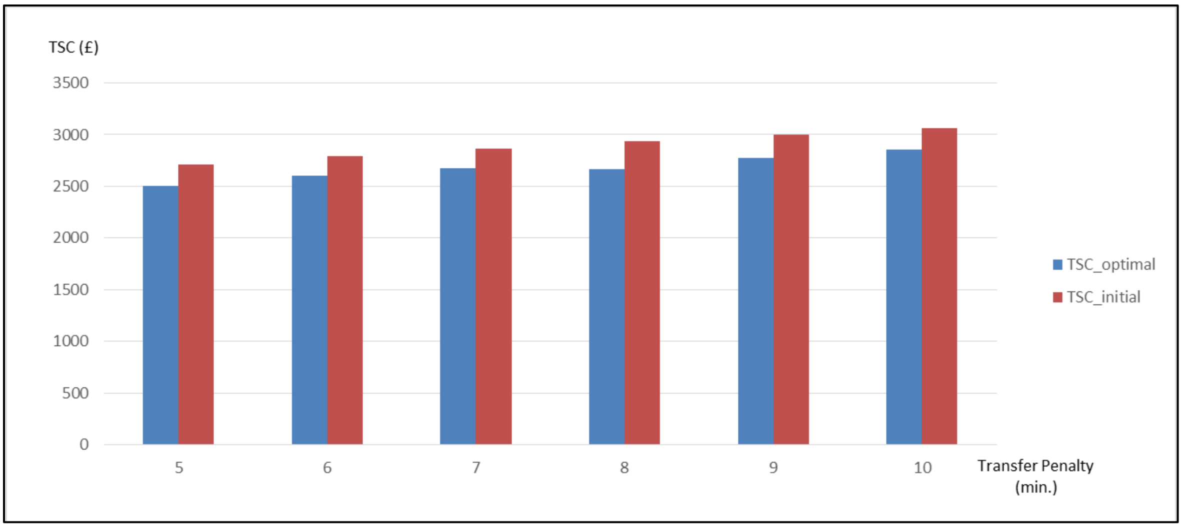

Figure 7-14 Effect of Transfer Penalty (in terms of TSC (£))

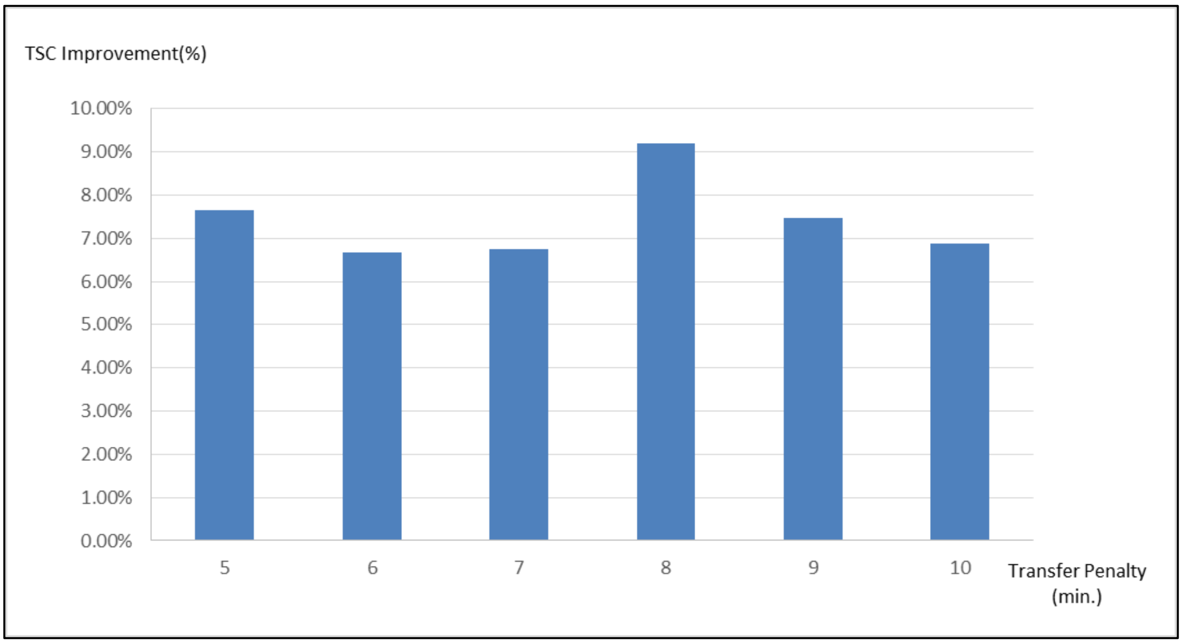

Figure 7-15 Effect of Transfer Penalty (in terms of TSC improvement (%))

7.4.2.5 Summary

The above sections presented the sensitivity analyses for user-defined parameters of the optimisation model, including the maximum number of solutions generated by the TS algorithm, the weights given to the three components of the objective function, the weights given to the WKT and WTT, and the value set for the transfer penalty. The results of these sensitivity analyses suggest:

- The accuracy of the final result has high sensitivity to the maximum generation number chosen for the tabu search algorithm. The larger the chosen number of generations, the more accurate result will be output, but more calculation time will be required. However, the improvements in TSC will get smaller after the generation number reaches a given number (based on the Southampton case study, the improvements in TSC shows strong positive correlation with increasing generation number until it reaches 60; after that, the improvement is slight as the generation number keeping increasing).
- Under the maximum fleet size constraint, the optimisation model shows strong positive correlation between the weight of TUC and the improvements in objective function (TSC). The increasing improvements in TSC not only come from the greater value given to the weight of TUC (this is because the value of TUC is greater than the TOC and TEC, thus the increase in TSC resulting from a 0.1 unit increase in the weight of TUC outweighs the decrease in TSC from a 0.1 unit decrease in the weight of TOC or TEC), but also from the better network (less TUC) output from the model.

- Based on the guidelines given by *WebTAG Public Transport Assignment* (Department for Transport, 2014a), the model shows low sensitivity to parameters contributing to TUC, including both weight set for WKT and WTT, and the values set for transfer penalty.

7.4.3 Results and Discussions

The current bus network in Southampton was improved by following two scenarios:

- Optimal solutions were generated under the maximum fleet size constraint, which means the optimal solution never uses more vehicles than are available to operate the current network (details in section 7.4.3.1).
- Optimal solutions were generated with various fleet size, varying the number of fleet size from -50% less to 100% more of the current network (details in section 7.4.3.2).

In order to control for the effects of self-defined parameters, the results were calculated by holding the optimisation settings constant, as follows: 60 as the maximum generation number, 0.4, 0.4, and 0.2 as the weights of TOC, TUC and TEC, respectively, 1.75 and 2.0 as the weights of WKT and WTT, and 7.5 minutes of IVT per interchange as the transfer penalty.

7.4.3.1 Optimal Solutions Under the Fixed Fleet Size Constraint

Without adding additional vehicles to the network, optimal solutions have been output from the optimisation model, and the best three of them were chosen as the final results. Table 7-5 lists and compares the characteristics of these output optimal solutions, as well as the current bus network. The difference in TSC between the optimal solutions and the initial solution is around 7%, which mainly comes from the improvements in TUC because of the maximum fleet size constraint. Compared with the current bus network, the optimal solutions have a higher number of routes, shorter lengths of individual routes on average, slightly lower mean frequency across the network, and slightly higher value of route overlap factor (defined as the ratio of total route length to total road length available in the network). This is expected because the candidate routes were generated by the k-shortest path algorithm for each terminal pair in the possible terminal set. In reality, bus operators are concerned about the economic benefits as well as service convenience. Hence, despite the existence of terminals (the starting and ending bus stops of the route), bus routes tend to be designed to link more key trip attractors and residential locations between these terminals rather than necessarily following the shortest path. For example, the terminals of the U1 service provided by Unilink are Southampton Airport and National Oceanography Centre (NOC), but the service also links University of Southampton (Highfield Campus), Portswood, and City Centre on the route between these terminals. The optimal solutions therefore have shorter lengths for individual routes on average compared with the current bus network. In order to meet the maximum fleet size constraint, the optimal solutions make a trade-off between the shorter lengths of individual routes and a larger number of routes across the network. In summary, although the output solutions are characterised by shorter lengths of individual routes and larger number of routes, and therefore could require more complicated vehicle and crew scheduling systems for operators and might increase transfer time in passengers' journeys, they do save on average 9% of travel time for each possible trip.

Table 7-5 Comparison Between Current and Optimal Networks

		Top 1	Top 2	Top 3	Mean	Current
Number of Routes		72	59	67	66	38
VKM		1258.16	1242.75	1250.79	1250.57	1245.04
TOC(£)		1274.66	1259.04	1267.19	1266.96	1261.36
TEC(£)		547.30	540.59	544.10	544.00	541.59
TUC(£)		5126.62	5231.83	5227.97	5195.47	5717.62
TSC(£)		2669.97	2704.47	2706.88	2693.77	2899.91
Improvement (%)		7.93%	6.74%	6.66%	7.11%	0%(baseline)
Route Length (km)	Mean	5.40	5.14	5.70	5.41	8.37
	Min.	1.21	1.24	1.25	1.23	1.90
	Max.	11.59	11.83	11.50	11.64	16.81
	Sum	388.92	344.45	336.17	356.52	360.22
Frequency	Mean	3.58	3.80	4.11	3.83	3.96
	Min.	0.5	0.5	0.5	0.5	1
	Max.	12	12	12	12	9
Route overlap		2.82	2.74	2.66	2.74	2.67

$$* route\ overlap\ factor = {total\ route\ length\ (km)}\Big/{total\ road\ length\ available\ in\ the\ nework\ (km)}$$

Figure 7-16 - Figure 7-19 display the network layouts of these optimal solutions, as well as the current network. Although the routes chosen by the best solutions are 99% different in terms of routes, as a whole they represent similar network layouts. According to Table 7-6, any two of the best three solutions share approximately 70% of their total road coverage, while this figure is around 60% when compared with the current network. This is partly because of the cross-boundary constraint applied in the process of selecting potential solutions from the candidate route set. In order to avoid the cross-boundary problem, the constraint retains the service levels to nearby towns and cities at current levels. Hence, six groups of cross-boundary terminals were chosen based on the six corridors linking the Southampton City Centre to nearby towns and districts. In the process of selecting potential solutions, the candidate routes linking these cross-boundary terminals and the possible terminals within the city boundary were selected and set corresponding frequencies. As a result, all potential solutions (along with the current network) share the same cross-boundary terminals and have the same cross-boundary service levels along the six corridors, leading to inevitable similarities in their network layouts. Furthermore, the six key corridors which link the city to nearby districts as well as key locations within the city boundary are based on major roads across the city and are relatively straight. When the candidate routes are generated based on the k-shortest algorithm, the routes along these corridors are therefore highly likely to be chosen by the model. This also helps to explain the high percentage of sharing roads available in the networks of optimal solutions, and makes a contribution to the slightly higher route overlapping factors of optimal solutions compared with the current bus network.

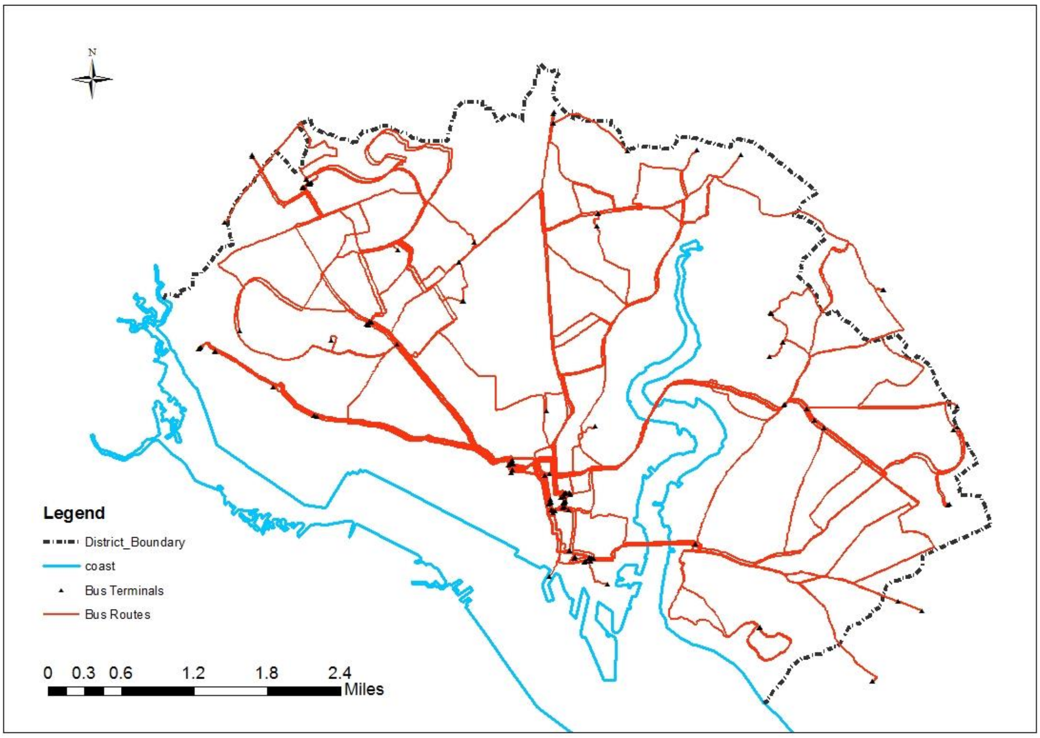

Figure 7-16 Network Layout of Current Bus Network in Southampton

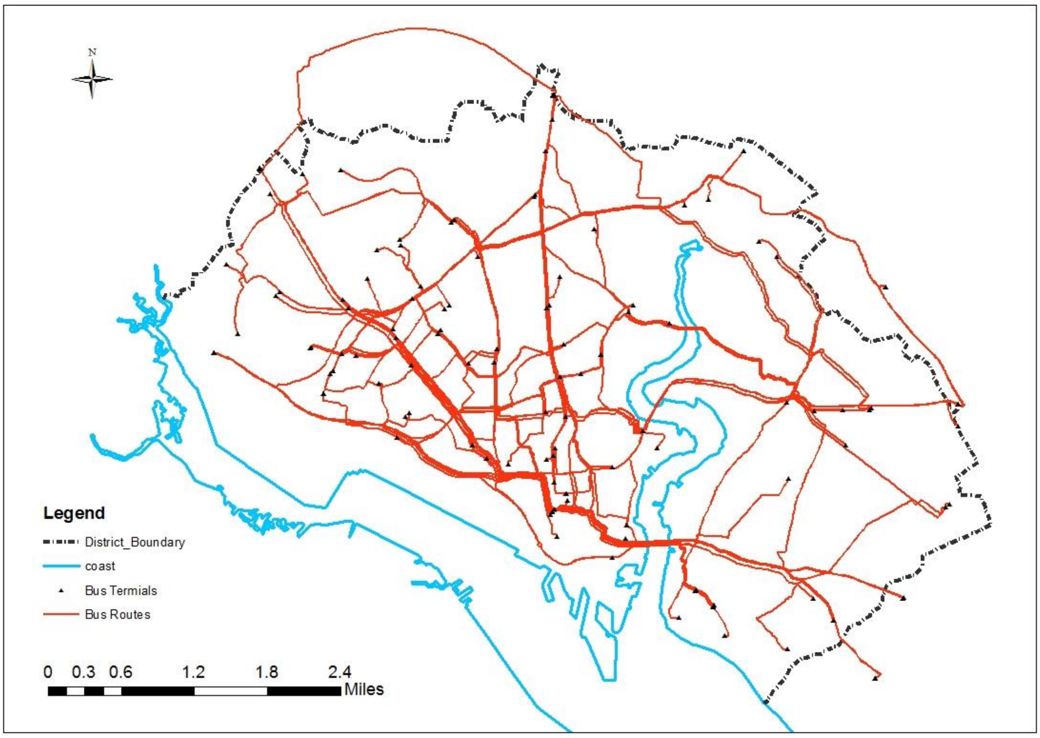

Figure 7-17 Network Layout of Best Solution Output from the Optimisation Model (Top 1)

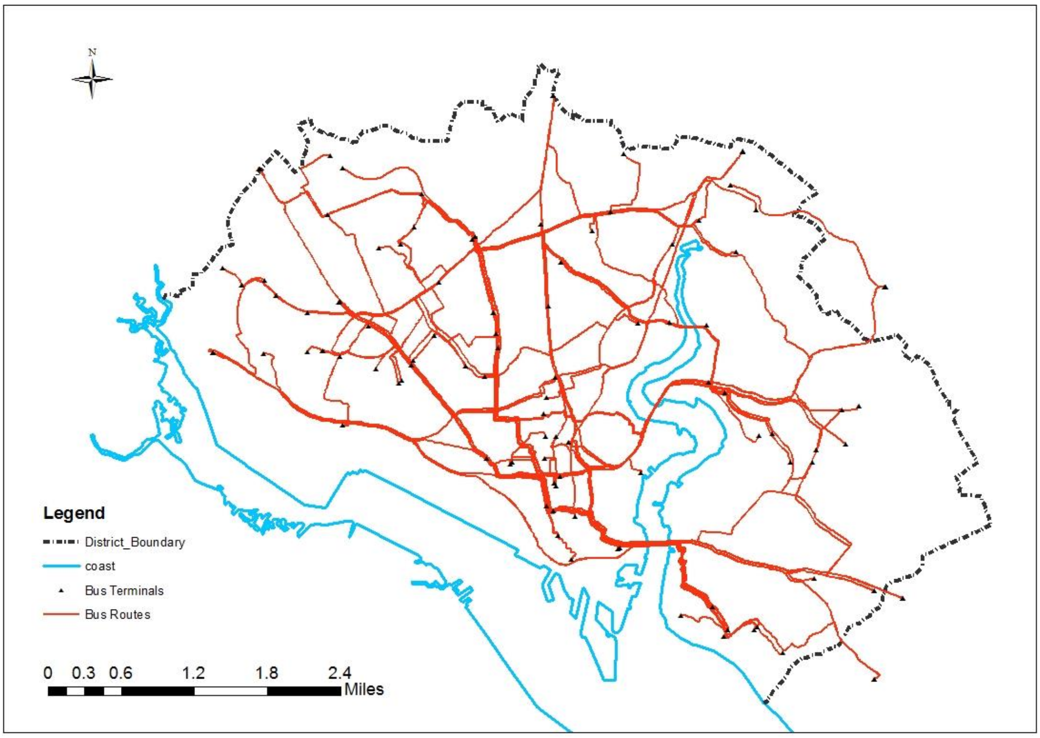

Figure 7-18 Network Layout of Best Solution Output from the Optimisation Model (Top 2)

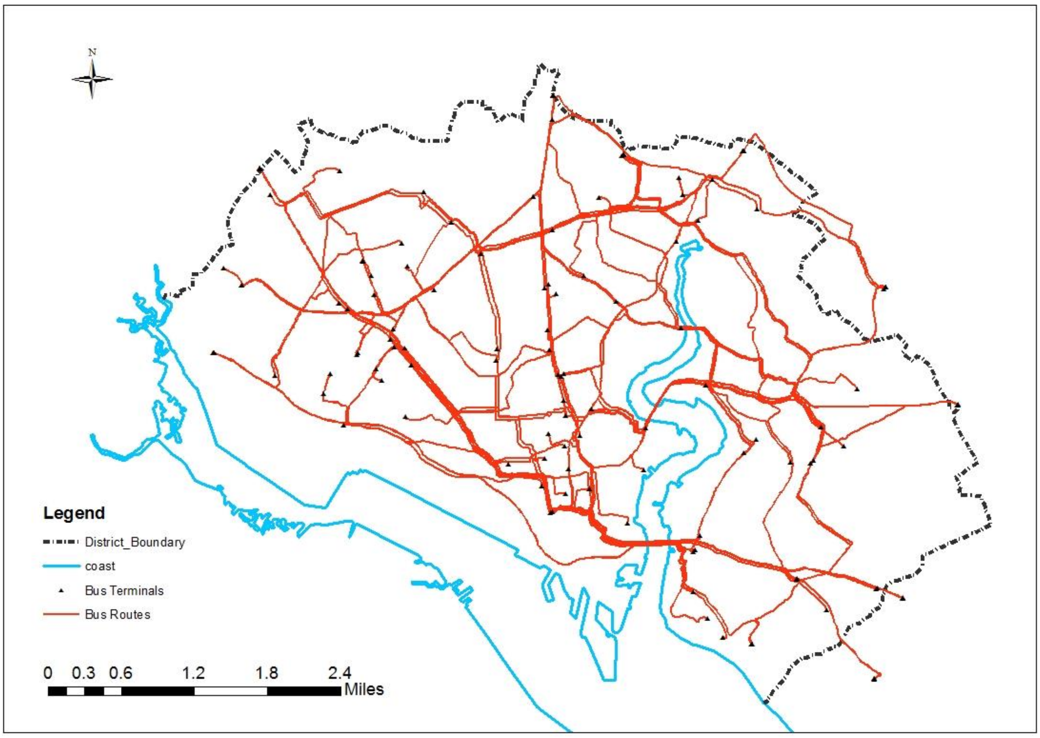

Figure 7-19 Network Layout of Best Solution Output from the Optimisation Model (Top 3)

Table 7-6 Comparison Between Current and Optimal Networks (in terms of network layout)

	Top 1	**Top 2**	**Top 3**	**Current Solution**
Sharing road length with Top 1 (km, %)		95.57 (77.81%)	94.56 (72.89%)	80.02 (59.27%)
Sharing road length with Top 2 (km, %)	95.57 (69.23%)		94.56 (72.90%)	76.98 (57.02%)
Sharing road length with Top 3 (km, %)	94.56 (68.50%)	96.24 (78.35%)		76.69 (56.81%)
Sharing road length with current solution (km, %)	80.02 (57.78%)	76.98 (62.67%)	76.69 (59.11%)	

For the purpose of comparison of network performances, the accessibility levels of the best optimal solution (Top 1) and the current network are compared and discussed in this section as well. The composite accessibility index of the current network were divided into 5 groups, where origin points in group A have the 20% worst level of accessibility to the service and group E the 20% best. This group criterion was applied to accessibility maps of both current and optimal network, and a direct visualization of results using the coloured contour map by ArcGIS is provided in

Figure 7-20. Compared with the two accessibility maps in

Figure 7-20, the majority of areas with poor accessibility levels (red or orange points, meaning the value of accessibility index is A or B) in the accessibility map of current network are replaced by green points (the value of the accessibility index is D or E) in the accessibility map of the improved network, especially the areas located around the city boundaries. According to Table 7-7, the proportion of the population enjoying the best accessibility levels (the value of accessibility group is E) to access key services will double when updating the current network to the improved one. While for the other accessibility groups (A, B, C, and D), the population number reduces. As a result, over 70% of the residents in Southampton will have relatively higher accessibility levels to access key services using the improved network compared with the current bus network in Southampton.

According to the definition of the composite accessibility index, the accessibility levels of each population-weighted centroid (postcode units were chosen in this model) are positively related to the attractiveness of the destination, and negatively related to the travel cost between them. Hence, the difference of accessibility index between the initial and optimal solution come from the difference of travel cost of each possible OD pair. Compared with the current network, the best optimal solution cuts travel time for over 60% of the overall possible trips, saves on average 9% of travel time for each possible trip, and provides more convenient services to over 70% of the total population within the city.

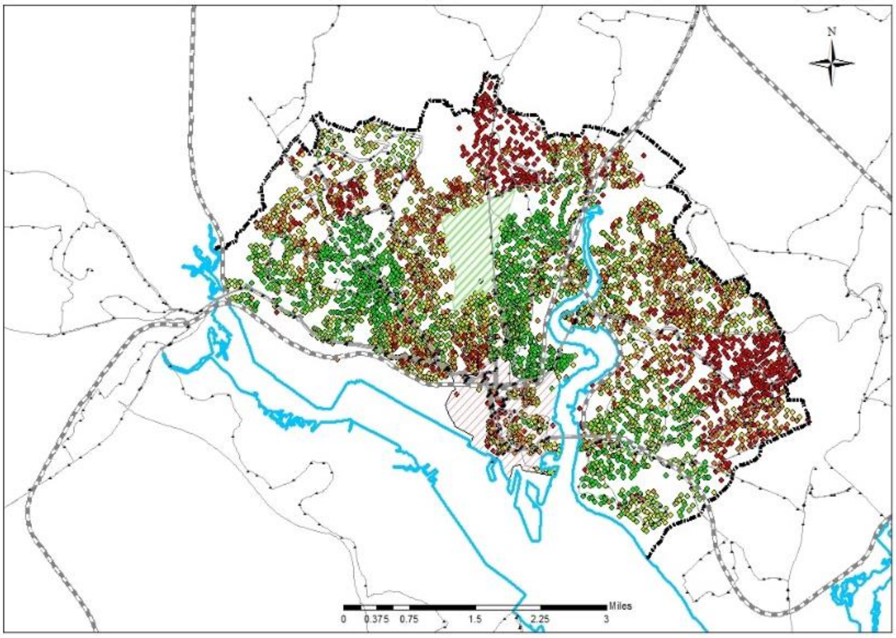

Figure 7-20a. Composite accessibility levels of current network

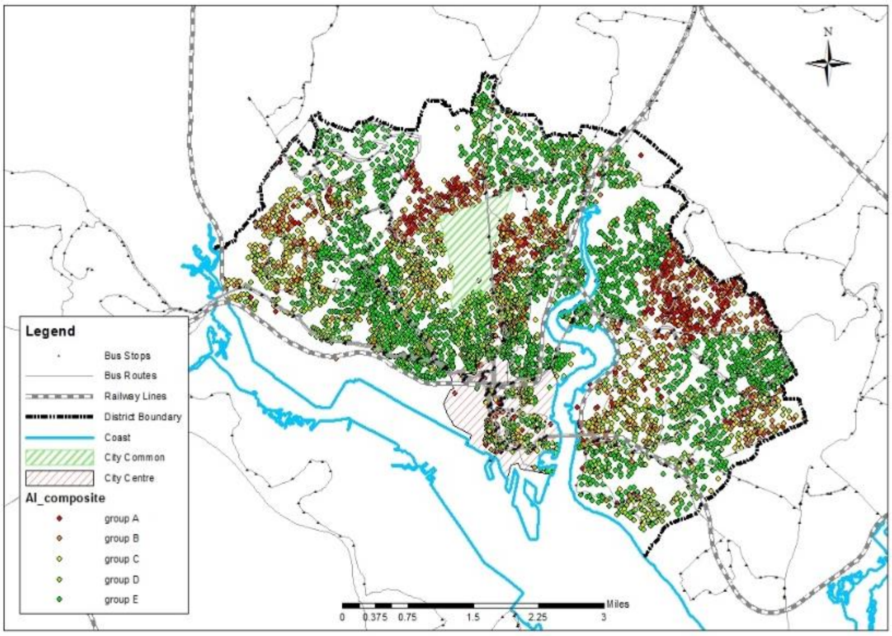

Figure 7-20b. Composite accessibility levels of optimal solution

Figure 7-20 Composite Accessibility Levels by the Current and Best Network

Table 7-7 Comparison of Accessibility levels by the Current and Best Network

	Population		**Population (%)**	
	Current Network	**Optimal Solution**	**Current Network**	**Optimal Solution**
Group A	22989	6036	9.71%	2.55%
Group B	31906	21406	13.47%	9.04%
Group C	48765	27034	20.59%	11.41%
Group D	61003	45107	25.76%	19.04%
Group E	72192	137272	30.48%	57.96%
SUM	236855	236855	100.00%	100.00%

7.4.3.2 Optimal Solutions With Various Fleet Size

In this section, optimal networks were obtained by varying the number of fleet size in the optimisation model. The range of fleet size is from half less than the current fleet size within the network to double of it.

As expected, there is a strong positive correlation between the number of routes and the fleet size across the network (Figure 7-21a). This is because of the random selection principle applied in the process of selecting potential solutions from the candidate route set. The model will randomly select candidate routes to form potential solutions from the candidate route set and set corresponding frequency randomly selected from the possible frequency set, until meet the maximum fleet size constraint. As a result, the average route length (Figure 7-21b) and average frequency (Figure 7-21c) remains stable and did not show sensitivity to the change of fleet size. More candidate routes therefore will be selected by the model with the number of maximum fleet size adding.

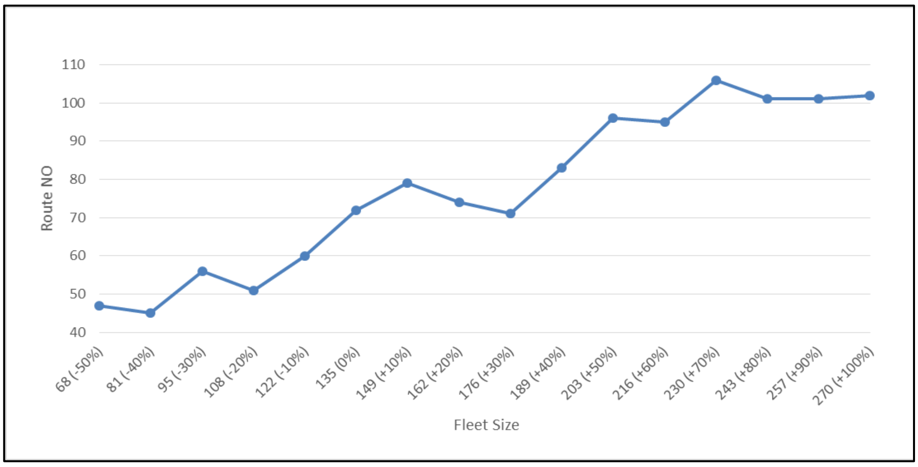

Figure 7-21a

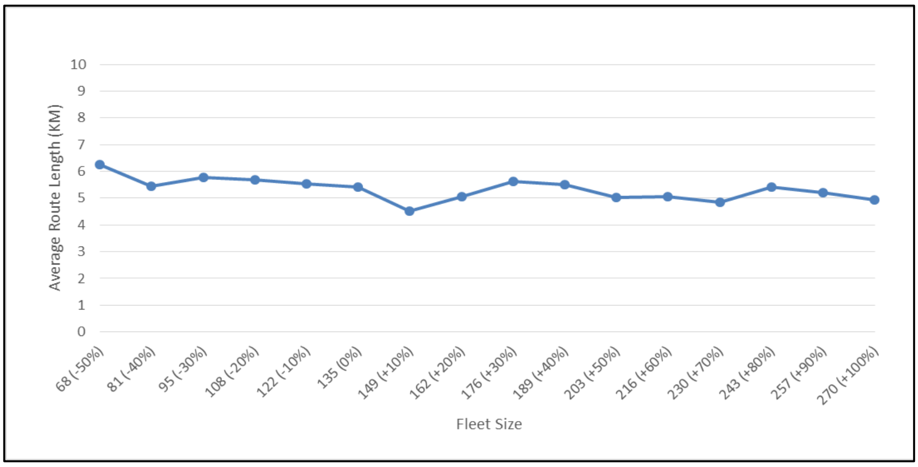

Figure 7-21b

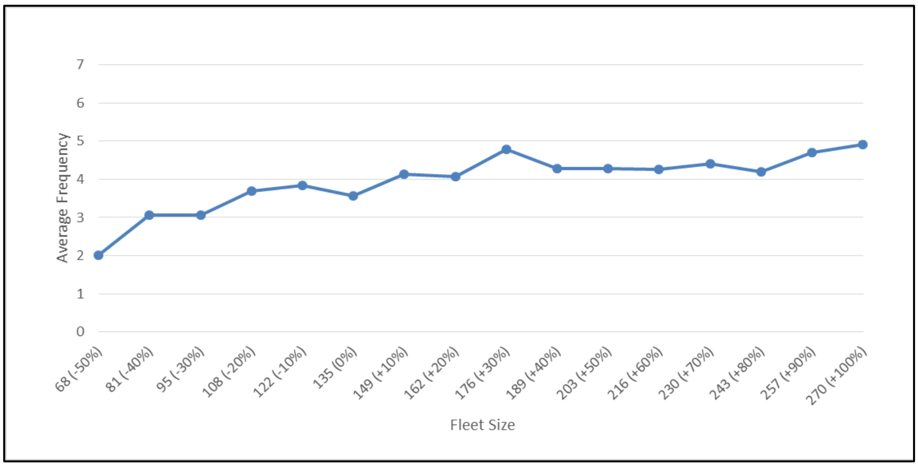

Figure 7-21c

Figure 7-21 Comparison Among Optimal Solutions with Various Fleet Size (in terms of route number, average route length, and average frequency)

The increasing number of the fleet size not only equals to more routes involved in the network, but also contributes to a more complicated network layout. Network layouts of the results were displayed from Figure 7-22 to Figure 7-27, and could be characterized by following:

- Whatever the number of vehicles across the network, the networks have similar skeletons to link nearby towns as well as key locations within the city boundary along six corridors.
- With the increasing fleet size, the network has larger number of routes, longer total route length, longer occupied road length, and more complicated network layout in areas between the corridors (see Figure 7-28a and Figure 7-28b).
- When the number of fleet size increasing, there are more overlapping routes especially through six corridors across the network, resulting in a larger number of route overlap factor (see Figure 7-28c).

There are many reasons contributing to these network layout characteristics. At first, the cross-boundary constraint is the key cause of the similar skeletons of the networks. In order to retain the service levels to nearby towns and cities at current level, the cross-boundary routes are selected from the candidate route set and set related frequencies before the within-boundary routes in the process of generating potential solutions. Hence, whatever the number of vehicles across the network, service levels provided by the cross-boundary routes are fixed, which will contribute to the similar six-corridor skeleton. In other words, the fluctuation in fleet size will directly cause the fluctuation in number of within-boundary routes and their service levels. As a result, more within-boundary routes will be included in the network with the increasing fleet size, representing more complicated network layouts in areas between the corridors. At second, the k-shortest algorithm, which was used for generating candidate routes, is the reason to explain the increasing overlapping routes across the networks when the fleet size adding. The six corridors, linking the city to nearby districts as well as key locations within the city boundary, are based on main motorways across the city and straight-line shaped. When the candidate routes are generated based on the k-shortest algorithm, the routes along these corridors will automatically be chosen by the model. As a result, there are more overlapping routes, especially through six corridors, when the fleet size increases.

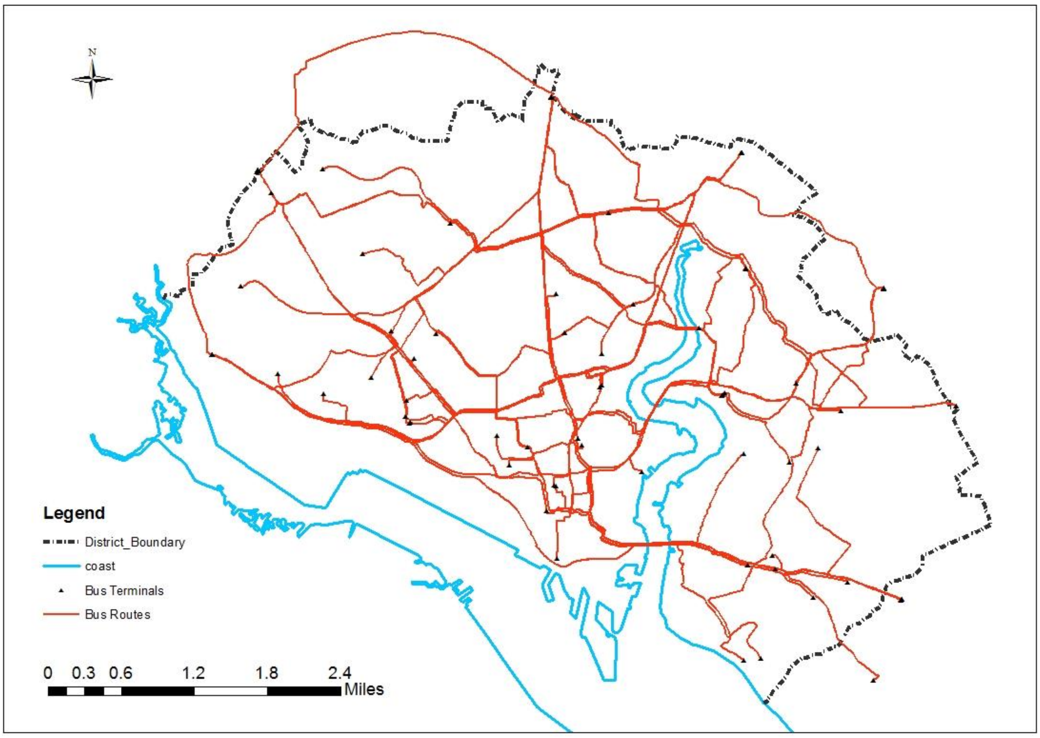

Figure 7-22 Network Layout of Optimal Solution with 50% Less Fleet Size

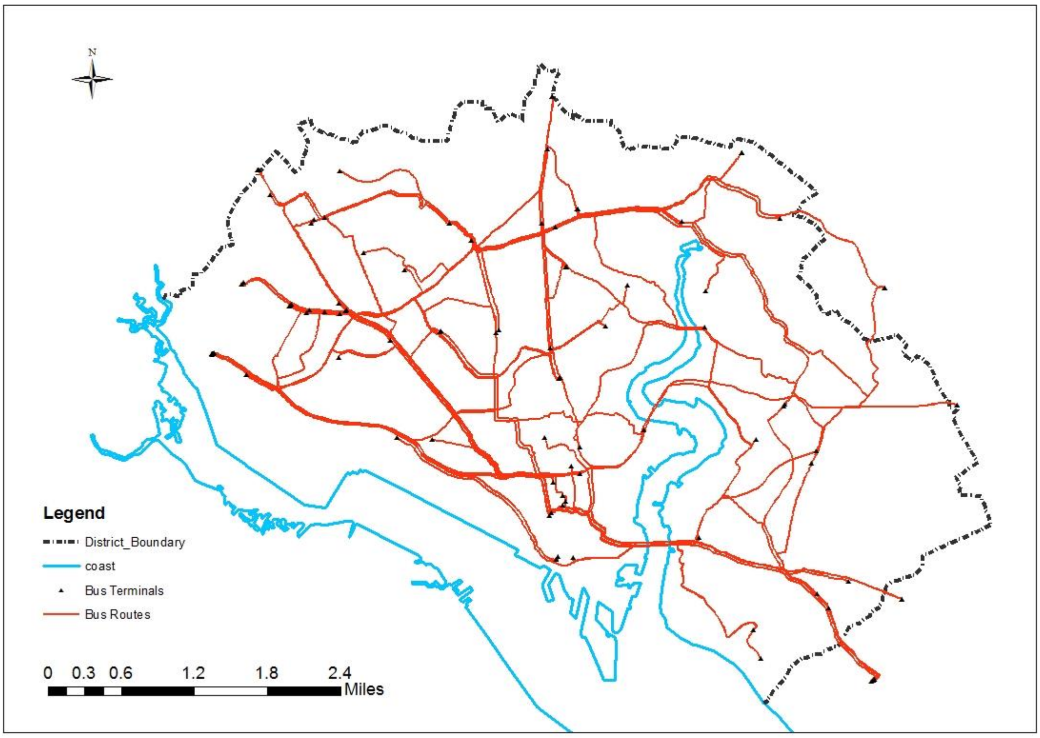

Figure 7-23 Network Layout of Optimal Solution with 30% Less Fleet Size

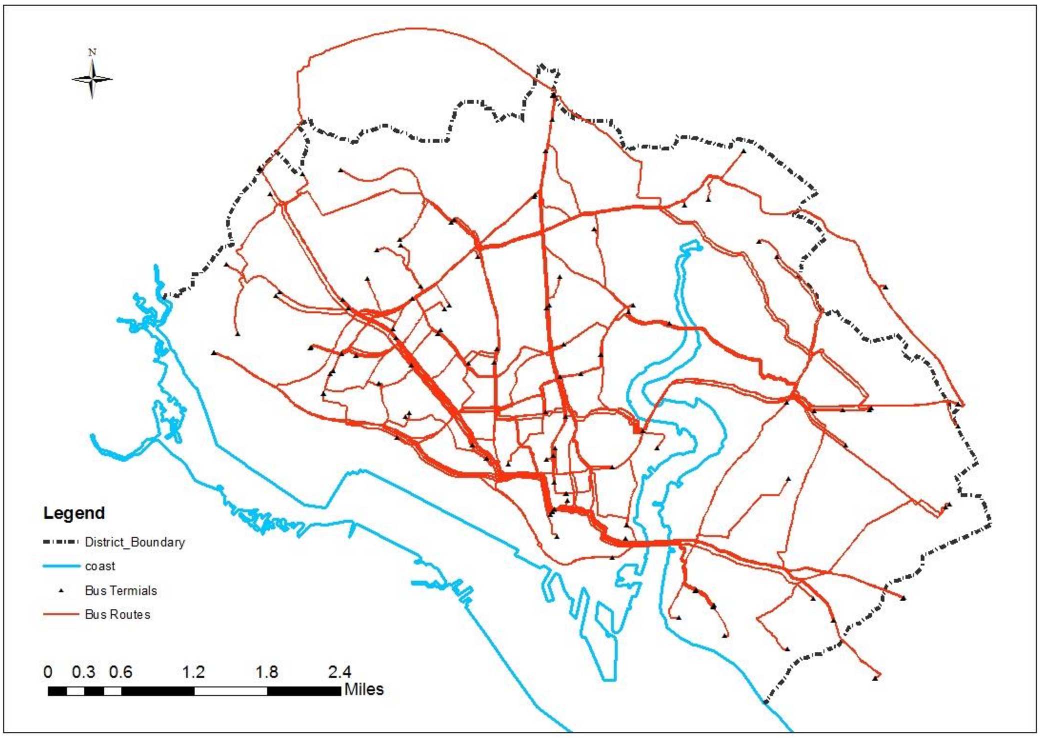

Figure 7-24 Network Layout of Optimal Solution with Same Fleet Size of Current Network

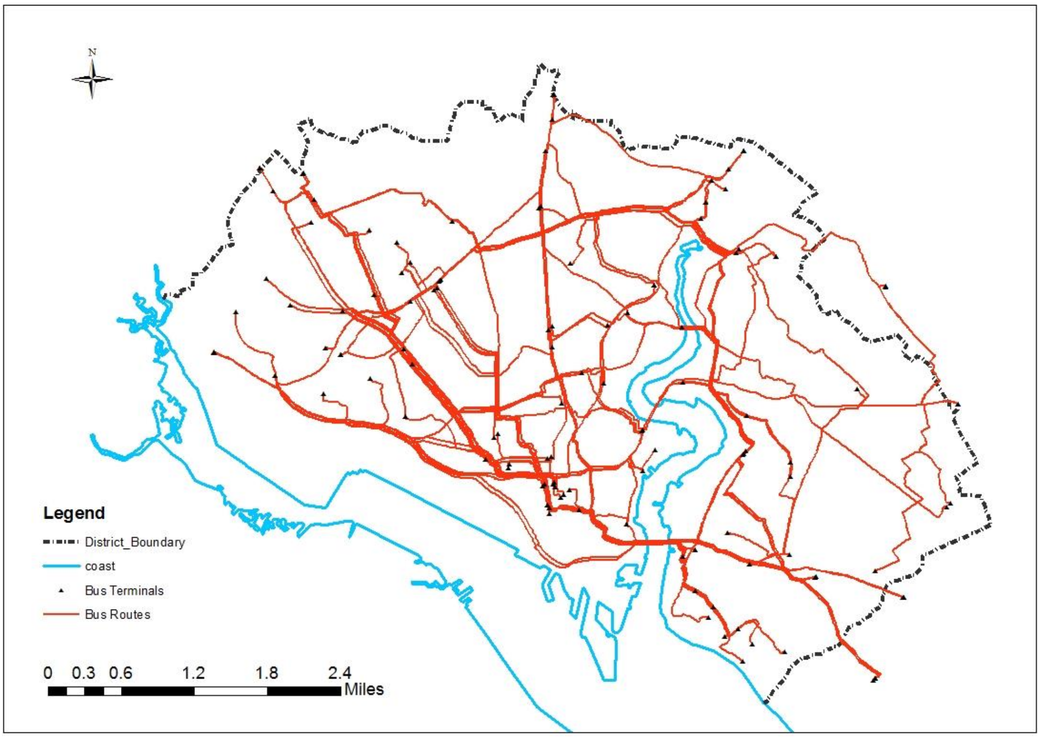

Figure 7-25 Network Layout of Optimal Solution with 30% More Fleet Size

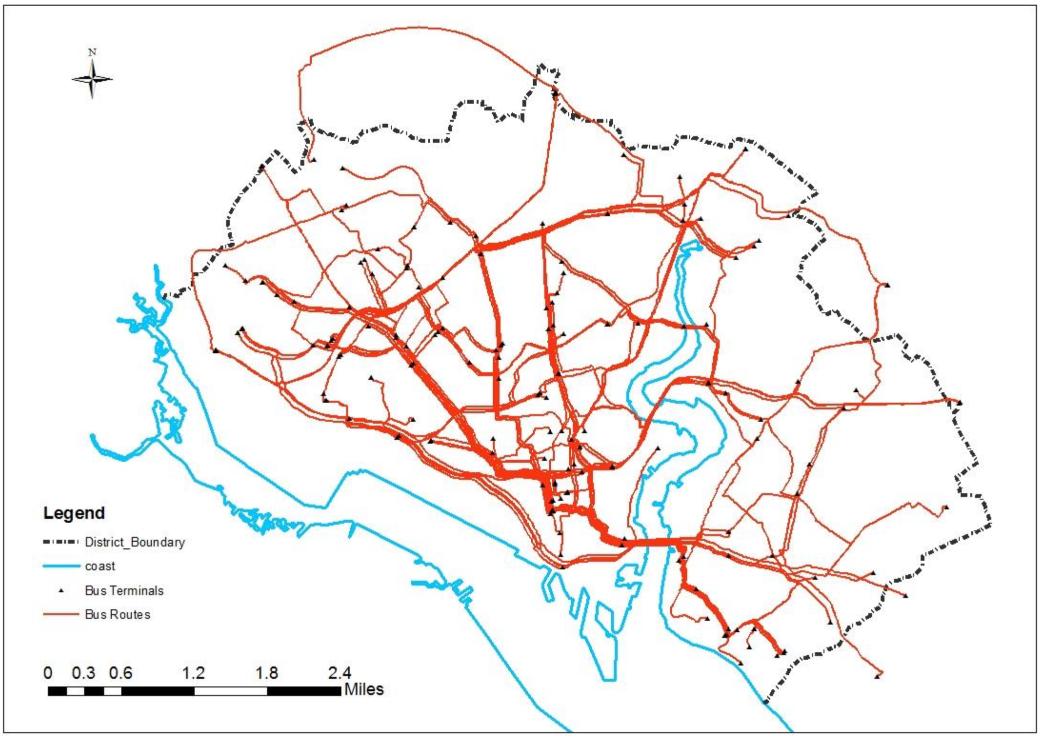

Figure 7-26 Network Layout of Optimal Solution with 60% More Fleet Size

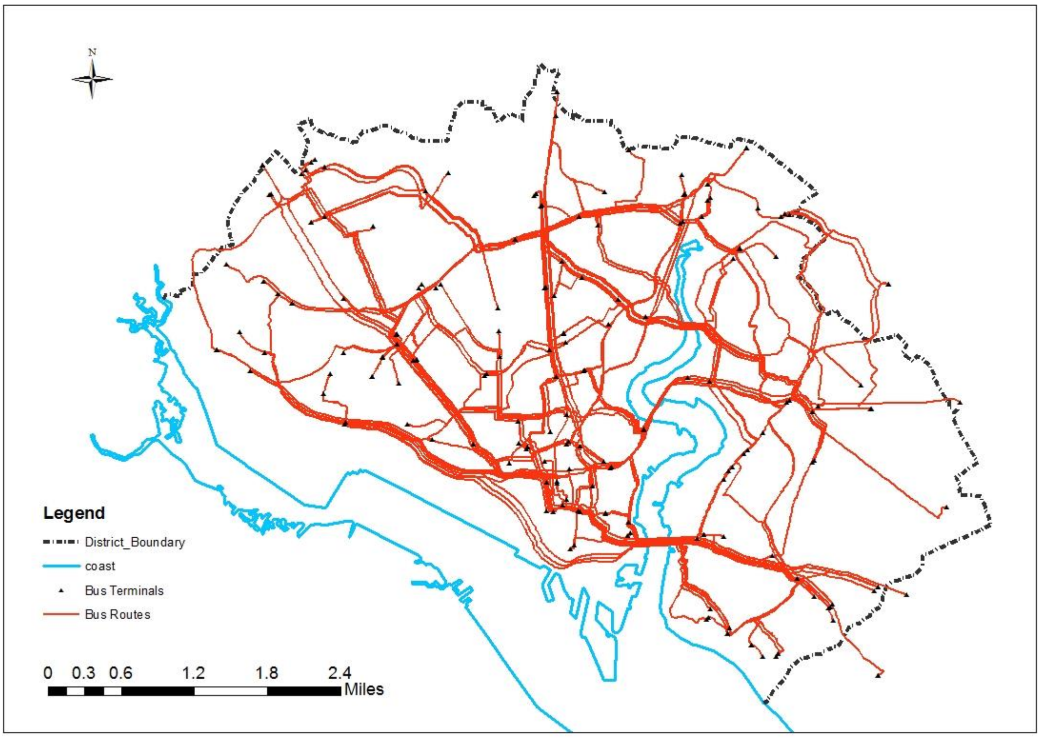

Figure 7-27 Network Layout of Optimal Solution with Double Fleet Size

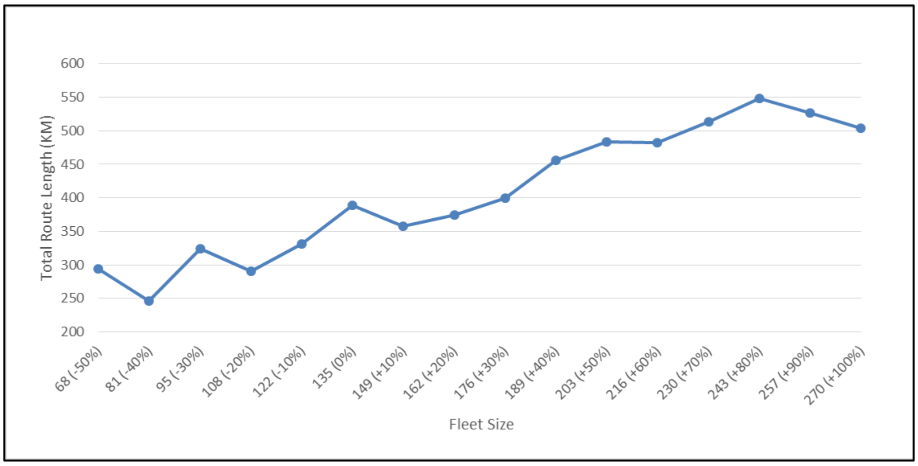

Figure 7-28a

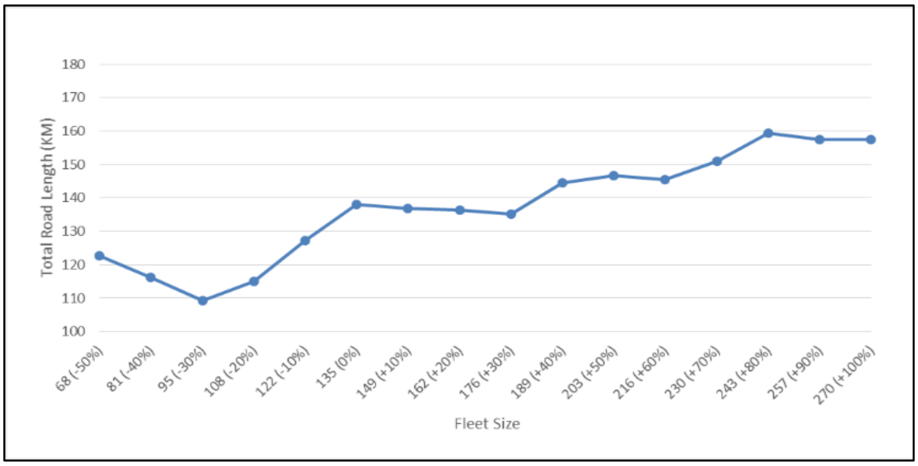

Figure 7-28b

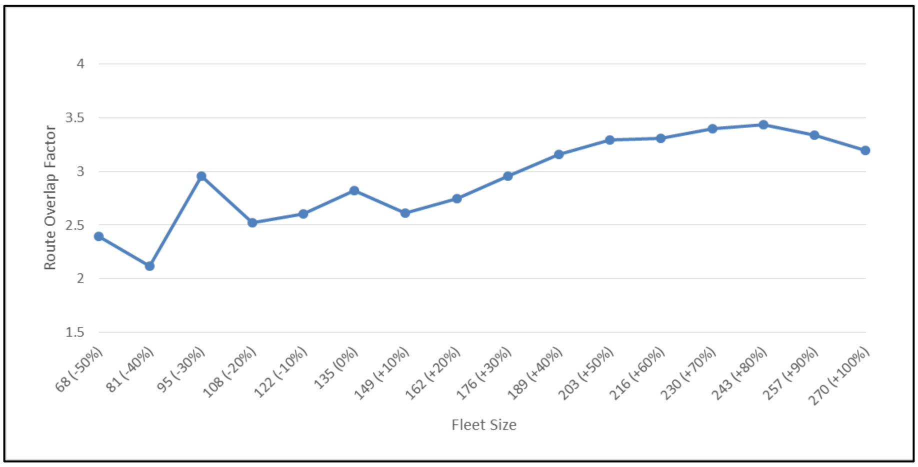

Figure 7-28c

Figure 7-28 Comparison among Optimal Solutions with Various Fleet Size (in terms of total route length, total road length across the network, and route overlap factor)

Figure 7-29 compares and summarizes the results in terms of the three components of the objective function with the varying fleet size, while the optimal network with the same number of vehicles within the current network is chosen as the baseline. According to the definition of objective function, the values of the TOC and TEC are directly decided by the vehicle size across the network. Hence, they fluctuate by same percentage of the changes in fleet size: adding 10% more vehicles across the network will result in 10% more TOC and TEC. As expected, the value of TUC decreases as the number of fleet size increasing. However, the improvements in TUC generated by adding more vehicles in the network are slight compared with the added costs in TOC and TEC. For example, there is only 4.84% improvement in TUC when doubling the number of vehicles in the current network, while the value of TUC only increases 10% when cutting half of the current fleet size. As a result, the value of objective function (TSC) increases as the number of fleet size increasing.

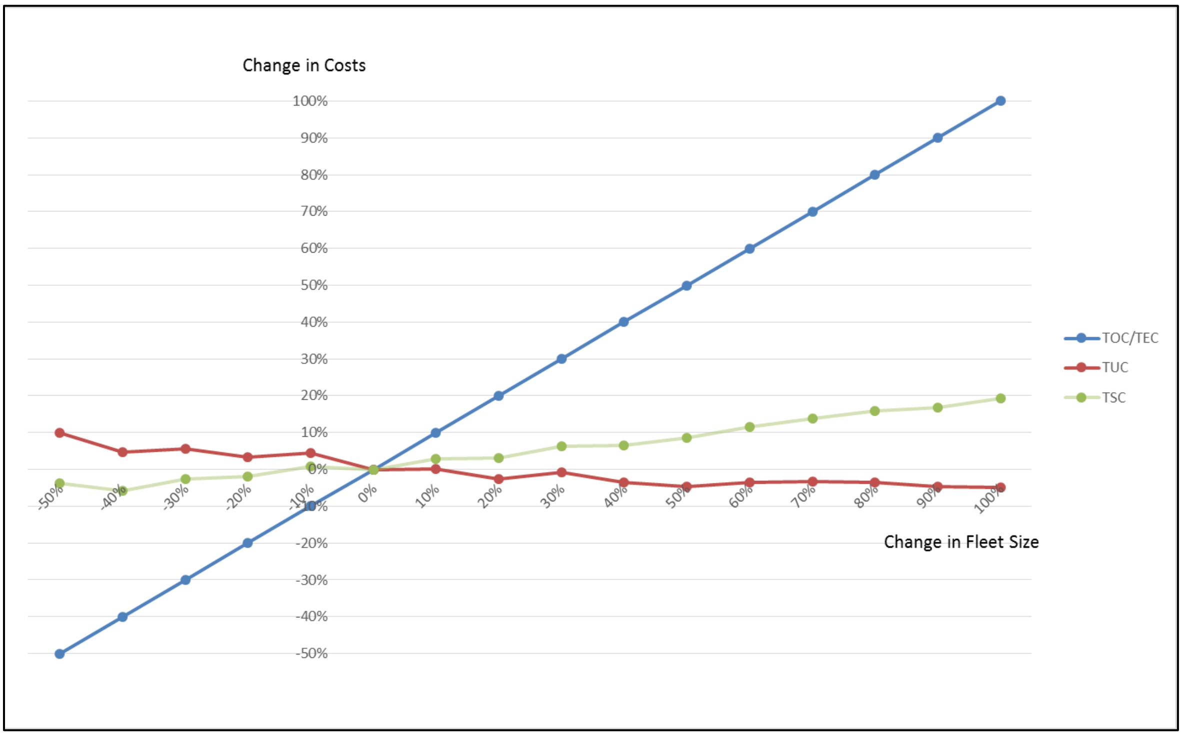

Figure 7-29 Comparison Among Optimal Solutions with Various Fleet Size

There are many reasons that help to explain why the improvements in TUC generated by adding more vehicles across the network are so slight, listed as follows:

Firstly, the cross-boundary constraint applied in the process of generating potential solution plays a crucial role. Under the cross-boundary constraint, each output network, whatever the number of fleet size it has, has similar route skeleton as well as the same service levels along each of the six corridors. The six-corridor skeleton is based on main roads across the city, and links well key locations both within and across the city boundary. Consequently, although the network with 50% less of the current fleet size has much simpler layout map than the network with double of the vehicle number, the performance of it will not be sacrificed too much. If the research area extends from the current Southampton city to Southampton bus area (not only include Southampton city, but also nearby towns and cities, such as Totton, Romsey, Eastleigh), more realistic results will be output.

Secondly, the increasing value of the overlap factor, accompanied with the increasing number of fleet size, is caused by more overlapping routes through the six corridors, and is another reason to weaken the efficiency of the network. Because of the cross-boundary constraint, the service levels through the corridors remain at the same levels of the current bus network, and could already meet the demands of local passengers. The new-added routes therefore will cause unnecessary duplication in service provision, and cannot help to reduce user cost to a large extent.

Thirdly, the results are constrained by some of the assumptions made for the optimisation model. For example, there is no consideration of vehicle overcrowding and capacity constraints when modelling the assignment sub-model of the optimisation model, so it is assumed that all passengers can and will board the first bus to arrive. This assumption is reasonable if improvement methods are implemented with fleet size remained at current level or extended into a larger one. However, the problem of overcrowding should be considered when cutting vehicles from the network. When cutting half of the vehicles across the network, passengers may not be able to board the first bus which arrives, they will need to wait for the second, or even third coming services, which will result in longer waiting time and will significantly increase the user cost.

Fourthly, OD pairs are input as demand data for the optimisation model, and can be categorized as a kind of ‘fixed’ demand. In reality, the demand should vary with changing quantity of services provided by the public transport network, rather than being fixed. According to the Mohring effect (1972), the average user cost of public transport is reduced by the increase of the user demand of the public transport services. Furthermore, the mode shift between the public transport and private cars cannot be ignored in the demand modelling as well. To passengers, less buses running on roads equals to unequal network distribution, less choice of services, longer waiting time at stops, and longer journey time, thus accelerates mode shift from public transport services to private cars, resulting in congestion problems on roads which will increase user costs. On the contrary, the public transport network, characterized by well-designed network distribution and easy-access services will attract more passengers, will help to solve the problem of congestion together with environmental and economic benefits. Ignoring the mode shift between the public transport and private cars, the current output results only measure changes in social cost of the public transport network with ‘fixed’ demand. More realistic results will be output if adopting the ideas of demand elasticity and mode shift to demand modelling in the current optimisation model (details in section 8.4).

Fifthly, the range of fleet size selected in this research is from half less the current fleet size within the network to double of it. More global results will be obtained when extending the range of possible fleet size, as for example from 1 to infinity. Better bus services will be provided to passengers (with less TUC) when more vehicles are involved within the network, although the improvements in TUC resulting from the fleet size increase will slow down (the marginal benefit of adding one vehicle into the network declines). When adding the TOC and TEC into consideration (the values of them are directly decided by the vehicle size), the trend line of the objective function (TSC) should contain three stages when increase the fleet size from 1 to infinity: it begins with some sharp decreases because of the large improvements from TUC; then the improvements in TSC will slow down due to the increasing values of TOC and TEC but little improvements in TUC (the range of the fleet size selected in this research is located at this stage); at last, a upturn will follow when the improvements in TUC are offset by the increasing values of TOC and TEC.

7.4.3.3 Summary

According to the results discussed in above two sections, the optimisation model has been shown to work well for a real-word size multimodal transport network, the current Southampton public transport network (bus/rail/walk), based on a complex road network topology. The optimisation process therefore is characterized as NP-hard with large-size database: each potential solution is selected from a candidate route made up of 41,243 potential routes, then evaluated based on adding travel costs of 1,172,325 possible OD pairs. On standard desktop PCs with 3.40GHz CPU and 4GB RAM, the calculation time for one potential solution (including both solution search procedure and evaluation procedure) is around 40 minutes.

Without adding additional vehicles, the model delivered a better bus network based on the criteria used here, with around 7% improvement in TSC compared with the current bus network in Southampton. The improvements in TSC mainly come from the improvements in TUC, because of the maximum fleet size constraint. Compared with the current network, the best optimal solution cuts travel time for over 60% of the overall possible trips, saves on average 9% of travel time for each possible trip, and provides more convenient services to over 70% of the total population within the city.

In terms of objective function (TSC), the model did not output better bus networks when changing the fleet size from half less than the current fleet size within the network to double of it. This is because the improvements in TUC generated by adding more vehicles in the network are slight compared with the added costs in TOC and TEC. The slight improvements in TUC generated by running more vehicles across the network can be partly explained by the characteristics of the network layouts on the output results, such as similar six-corridor network layouts and increasing value of overlap factors. The limitations of the current optimisation model also contribute to the limited improvements in TUC. For example, the elasticity of demand with respond to the quantity of provided services should not be ignored under the various fleet size scenario. Furthermore, the changes in demand will also link to the problems of vehicle overcrowding, mode shift between public transport and private cars, and the congestion on roads. These limitations have been considered as the guidelines of further improvements of the current optimisation model, and details can be found in section 8.4.

7.5 Conclusion

This chapter has implemented both the accessibility model and optimisation model to a real-world size bus network, the current Southampton bus network. The results have shown that it is possible to design a better public transport network which provides better balance between the interests of operators, passengers, and local authorities, under the alternative centralised service planning environment. Without gaining more operating costs to bus operators, the output optimal network cuts on average 9% of travel time for each possible trip, provides more convenient services to over 70% of the total population within the city, and saves around 9% of the total user cost. If this was combined with the introduction of a simple ticketing system, fare capping (equivalent to the price of a daily ticket) and enforceable standards for performance and quality, it would contribute to the provision of a high-quality bus network which better meets the needs of local residents and local economy. The limitations of the current methodology (such as lack of realistic constraints for the current optimisation model under the various fleet size scenario) are discussed and summarised in section 8.3, as well as the further studies listed in section 8.4.

Chapter 8: Conclusions

8.1 Introduction

This final chapter summarises the main achievements made during this research project, and highlights some priorities for further research. The remainder of this chapter therefore is divided into three sections. A summary of major achievements is displayed in section 8.2, as well as a list of unique contributions. Limitations of the current methodology are given in section 8.3, followed by recommendations for future research in section 8.4.

8.2 Current Achievements

8.2.1 Research Tasks

In this section, the main achievements made during the PhD study are listed as follows. In order to check whether all research objectives raised in Chapter 1 are met or not, these completed research tasks are grouped by their achieved research objectives.

Research Objective 1: develop an evaluation methodology to assess the performance of current bus networks.

An accessibility model was developed to measure the performance of current bus networks by calculating gravity-based accessibility levels from population-weighted centroids of postcodes to key services, including education, health, city/town/district centres, employment centres, and open spaces. There are four steps are involved in the calculation process: calculation of travel costs, calculation of service-specific accessibility index using gravity-based measures, calculation of composite accessibility index, and visualization of final results.

Among them, the first step, calculation of travel costs, is the single most important step, and the accuracy of its output results will directly affect the final performance of the model. An integrated ArcGIS model was therefore developed using ArcObjects for Java for it. Based on the 3D capability of ArcGIS, the travel costs calculation model developed here is designed for multimodal public transport networks. Three travel modes, bus, rail and walk, are considered in this research. Attributes which contribute to the travel cost include walk time (include access time, egress time, and transfer walking time between public transport stops), waiting time (both origin and transfer waiting time), in-vehicle time, and transfer penalties. In order to improve the accuracy of the final results, the calculation of travel costs is based on the real bus timetable.

The outputs of the accessibility model, the composite accessibility index for each origin point, were equally categorized into 5 groups, and were displayed using the coloured contour map by ArcGIS. Therefore, the distribution of origin points within the same accessibility category can be clearly illustrated from the map, the areas with high or poor accessibility levels can be identified, and thus the performances of the public transport network can be assessed.

Research Objective 2: generate a practical methodology to explore improvement methods for the current bus networks under an alternative regulated environment.

A practical optimisation model was developed to explore the potential improvements, including both route planning and frequency setting in this research, which could be achieved with centralised planning of bus networks using an adapted tabu search algorithm. The methodology of the improvement approach is to minimise total social cost, which is defined as the weighted sum of operator cost, user cost, and external cost, subject to a variety of constraints which reflect system performances and/or resource limitations. This practical optimisation model is designed to work for real-world size bus networks based on complex road network topology, and consists of three components in the process of exploring optimal solutions: candidate route set generation procedure, the solution evaluation procedure, and optimal solution search procedure. The final output of this optimisation model is then an optimal bus network as measured by the objective function, consisting of a set of bus routes with associated frequencies.

Research Objective 3: build an automated model, which is made up of both evaluation model and optimisation model, based on the developed methodologies and available input data.

In this research, the methodologies developed for both the accessibility model and the optimisation model were built under the environment of ArcObjects for Java. As the developer interface of ArcGIS, ArcObjects for Java contains all tools available in the normal customer interface, as well as provides more flexibility in custom setting and could easily develop specific tools or models to fit any research objectives. Based on the available network-based analysis tools embedded in ArcGIS Network Analyst extension, both the accessibility model and optimisation model therefore were built smoothly under the environment of ArcObjects in Java, and has been proved to work efficiently in case study application.

8.2.2 Summary of Unique Contribution

By demonstrating the evaluation of the potential of centralised service planning to improve the accessibility levels of public transport in UK urban areas outside London, the following contributions have been made:

First, a travel costs calculation model was built using ArcObjects for Java. The calculation process of travel costs for potential OD pairs is an essential step for both the accessibility model and the optimisation model, and the accuracy of its output results will directly affect the final performance of the models. Although some commercial software packages, such as Visography TRACC, are available for calculating travel costs, they lack flexibility in their custom settings and could not be easily adapted to fit the objectives of this research. An integrated ArcGIS model was therefore developed using ArcObjects for Java, which provides the flexibility to generate customised models of the kind required here, as well as being easily adjusted to fit any other research objectives. Different from the available models, the travel costs calculation model developed in this thesis has the following characteristics:

- By applying the 3D capability of ArcGIS, this travel costs calculation model is designed for multimodal public transport networks. Three modes, bus, walk, and rail services, are considered in this research. Followed by the methodology described in section 5.4, the number and categories of modes could be easily adjusted to meet any research objectives.
- In this research, attributes which contribute to the travel cost include walk time (including access time, egress time, and transfer walking time between public transport stops), waiting time (both origin and transfer waiting time), in-vehicle time, and transfer penalties. Any other attributes, such as fares, could be easily added into the model when the input data is available.
- In order to improve the accuracy of the final results, the calculation of travel costs is based on the real bus timetable by using the developed script evaluators. The value of in-vehicle time is the difference between the time the bus/train arrives at the destination stop and the time the bus/train departs from the origin stop (rather than by converting travel distance to a measure of time using an assumed average vehicle speed in available models); and waiting time is modelled as the difference between the next available departure time and the time the passenger arrives at this stop (rather than being calculated as half the headway for headways up to 15 minutes, and with the waiting time capped at 7.5 minutes for longer headways in published models).

Second, a practical optimisation model was developed for real-world size public transport networks. Optimisation models described in published literature focus on using complicated methodologies to improve small-scale networks, therefore these approaches could not be directly applied to the city-scale bus networks being considered in this research. Based on a complex road network topology, real-world bus networks are together with large-size datasets: large number of available bus stops, complicated layout of bus network, verbose timetable data, and large size of demand data. The optimisation problem therefore is characterized as NP-hard with large-size database, and that will result in long calculation time and increase difficulties in modelling. An efficient search algorithm, an adapted tabu search algorithm, was therefore chosen and applied in this optimisation model. Compared with other search algorithms widely-used in previous research, such as Genetic Algorithm, the tabu search algorithm performs better in both theory and practice. Furthermore, ArcObjects for Java was chosen as the main developer tool for the optimisation model. Compared with the customer interface of ArcGIS, the ArcObjects for Java works much more efficiently for large-size datasets, and helps to cut down the calculation time. The developed optimisation model has been proved to work efficiently for the implemented Southampton case study, which consists of 1,839 local bus stops, and 38 services provided by 7 operators during the normal Monday morning peak hour (08:00-09:00). The average calculation time for a possible solution (including both selecting it from the search space by adapted tabu search algorithm and evaluating it by calculating objective function with 1,172,325 possible OD pairs) is approximately 40 minutes on a standard desktop PC. After three days of calculation (or after output 100 possible solutions), the optimisation model output optimal network, which cuts on average 9% of travel time for each possible trip, provides more convenient services to over 70% of the total population within the city, and saves around 7% of the objective function compared with the current network.

Third, because the model makes use of widely available input data, the developed methodologies of both accessibility model and optimisation model could be well applied to any public transport network in Great Britain, or even in other contexts around the world. There are a total of three categories of input data required in this research: road network, routes and timetable data of the current public transport networks, and demand data. In terms of road networks and information on current public transport networks, public datasets for Great Britain are available online and can be directly downloaded. Because of the difficulties in obtaining OD matrices (usual way of representing demand data) for British urban areas, OD pairs are considered as an alternative way: population centroids of postcode are defined as potential origins, while key services, defined as schools, GPs, employment centres, city/town/district centres, and open spaces, are possible destinations. Therefore, all the input data could be directly extracted from public online data sources, and only need simple clear procedure before transferring them into the models for calculation. While the data collection and preparation process described in this thesis (details available in section 5.2 and 6.2) focuses on the British context, the general data requirements for the developed accessibility model and optimisation model that are suitable for any case studies around the world are listed as follows:

- Road network: any well-connected polyline feature class representing the existing road network of the research area is acceptable.
- Public transport network: the modes of the public transport (such as bus, rail, ferry, coach, etc.) can be selected according to research objectives, and for each of the chosen modes, three categories of input data are essential to characterize it, including stops, routes and timetable data.
  - Stops (point feature class): for each public transport stop, the location of the stop and its name are necessary information.
  - Routes (polyline feature class): each pubic transport service is identified as service number, its operator name, in/outbound direction and a unique sequence of stops.
  - Timetable (CSV file): a sequence of arrival and departure times is associated with each service.
- Possible OD pairs: generated by matching each possible origin point and each possible destination point. While the definitions of the potential origins and destinations are decided by researchers to meet various research objectives.
  - Origin points (point feature class): defined as population centroids of census tracts, postcodes, or any self-defined geographic zones. For each possible origin point, its location and associated population number are essential input data to characterize it.
  - Destination points (point feature class): defined as key services within the boundary of research area. For each possible destination point, its location and the number of opportunities provided by it (the definitions of the opportunities provided by destinations vary by the categories of them) are essential input data to characterize it.

Fourth, the developed methodology helps to provide advice to local authorities in their decision-making process. In order to reverse the current shrinking bus markets in areas outside London, local authorities consider adopting the London model (centralised planning for bus services) to their areas by using potential solutions, such as Bus Quality Partnerships (BQPs) and Quality Contracts (both permitted by the *Transport Act 2000* and *Local Transport Act 2008*). Although BQPs have been shown to be successful in several British cities, such as Brighton and Oxford, the impact of BQPs should vary by the characteristics of the city, such as the performance of current public transport network, population distribution, locations of key services, and so on. In terms of Quality Contract, many local authorities are currently actively perusing it, but there are no formal legislative Quality Contract schemes available right now. Thus, there are still disagreements on whether the Quality Contracts will deliver all the predicted benefits or not. Methodologies to evaluate the performance of centralised service planning therefore appear to be in demand, but are in short supply. The methodology developed in this thesis therefore fills this gap. Because it is undemanding of input data, this developed methodology could be well applied to any city, and predict the performance of a centralised planning scheme before actually implementing them, thus help to provide advice and suggestions to local authorities when deciding whether adopting the centralised planning schemes to their areas or not.

8.3 Limitations of Current Methodology

Limitations of current methodology are listed in this section as follows:

- The methodology ignores the impact of boundary effects on the accessibility model: according to the results output from the Southampton case study, areas with poor accessibility levels using the current public transport network are mainly located around the city boundaries. This result is partly due to the boundary limitation of the accessibility model, that is key services located within the city boundary were selected as the possible destinations in the model, ignoring any destinations outside the city boundary. If there was a major town centre or employment centre just outside the city boundary, this might mean that the actual accessibility levels in some of the boundary areas within Southampton are much better than the result suggests. For the Southampton case study, the treatment of contiguous markets in Totton, Rownhams, Chandler's Ford, Eastleigh, West End, Hedge End and Netley should be considered to output a more accurate accessibility map using the current public transport network.
- Lack of realistic assumptions and constraints for the optimisation model, especially under the various fleet size scenario: the results output from the Southampton case study have shown that the current optimisation model delivered a better bus network under the maximum fleet size constraint, but some unexpected results were outputted under the various fleet size scenarios. This is to some extent because of some ideal assumptions and constraints set for the current optimisation model, listed as follows:
    - Bus speed was assumed to be constant across the network, and was not subject to congestion effects. This assumption is only suitable when the optimal networks output from the optimisation model never use more vehicles than are available to operate the current network (under the fixed fleet size scenario). The problem of road congestion should be considered when extending the fleet size into a larger one.

- There was no consideration of vehicle overcrowding and capacity constraint, so it was assumed that all passengers can and will board the first bus to arrive. This assumption is reasonable if improvement methods are implemented with the fleet size remaining at its current level or being increased. The problem of overcrowding should be considered when cutting vehicles from the network. When cutting half of the vehicles across the network, passengers may not board the first bus to arrive, they may need to wait for the second, or even third coming services, which will result in longer waiting time, will significantly increase the user cost, and will change the potentially modal choice.
- OD pairs were input as 'fixed' demand data for the optimisation model, ignoring its elasticity with respect to the changing quantity of services provided by the public transport network. In order to output more realistic results, 'variable' demand data should be considered under the various fleet size scenario.

- The current developed methodology exclude fares and subsidy: although fare is one of the essential attributes contributing to the travel cost according to *WebTAG Public Transport Assignment* (Department for Transport, 2014a), it was excluded in the process of calculating travel costs for both the accessibility model and the optimisation model. This is because the bus network improvement methods considered in this research only include route planning and frequency setting, while the fare system remains at current levels. However, the centralised planning for bus services not only helps to deliver an integrated bus network with more equal network distribution and less unnecessary duplication in service provision, but also helps to introduce a simple ticketing system among multi-operators and fare capping (equivalent to the price of a daily ticket). Therefore, the update in fare system should be included as one of the improvement methods in the methodology, as well as the route planning and frequency setting.

8.4 Future Work

Based on the limitations of the current methodology listed in the above section, some potential future works are discussed in this section, listed as follows:

8.4.1 Implement the Developed Methodology to Other Case Studies

Only one case study, the current Southampton bus network, has been implemented in this thesis. The developed methodology has been shown to work well when implementing the Southampton case study. The results have shown that the optimisation model delivered better bus network under the maximum fleet size constraint with a 7% improvements in terms of the objective function compared with the current network. In order to test the performance of developed methodology, more real world case studies need to be considered as the next step. This might include a British city which has been relatively successful in implementing a quality partnership based approach to bus service provision (such as Brighton or Oxford) to investigate whether such bus networks are closer to the 'optimum' produced by the model.

8.4.2 Update Current Methodology with OD Matrix Input Demand Data

Because of the difficulties in obtaining OD matrices for British urban areas, possible OD pairs weighted based on their destination types are selected as an alternative way of modelling demand data in the current optimisation model. Compared with an OD matrix, the OD pairs is a much easier way of modelling demand, and can be prepared for any case studies following the simple data preparation process provided in section 5.2.3. However, the OD pairs only list the potential origins and destinations between which passengers may make journeys, and exclude the number of passengers for each OD pair, thus the actual demand of passengers cannot be guaranteed to be represented. Furthermore, the input demand data formatted as OD pairs will limit the further improvements of the optimisation model. For example, an OD matrix is an essential input data when modelling vehicle overcrowding and capacity constraint and adopting the idea of demand elasticity to the optimisation model. In further study, the current methodology should be adjusted to accept multi-formatted demand data: the first choice option of the demand data is OD matrix, while the OD pairs are also acceptable when an OD matrix is not available.

8.4.3 Add More Realistic Assumptions and Constraints for Optimisation Model

According to the results output from the Southampton case study, the current optimisation model delivered a better bus network under the maximum fleet size constraint, but output some unexpected results under the various fleet size scenarios. When adopting the OD matrix demand data into the methodology, more realistic assumptions and constraints therefore should be considered as the next step to improve the performance of the optimisation model under the various fleet size scenarios, such as adding vehicle overcrowding and capacity constraint, considering the impact of congestion on roads, and transferring the current 'fixed' demand data into 'variable' (mode shift between public transport and private cars).

8.4.4 Add Revenue into Objective Function for Optimisation Model

The objective function for the optimisation model developed in this thesis is to minimise total social cost, which is defined as weighted sum of total operator cost, total user cost and total external cost. Besides, the number of routes and the level of services are determined by operating revenue as well. An optimal public transport network should provide a balance between the operating cost and revenue it get. According to the *Bus Statistics* (Department for Transport, 2016b), operating revenue includes Bus Service Operators Grant, Concessionary Fare Rebates, Public Transport Support, and passenger fare receipts. When the input data are available, the operating revenue should be considered in the further research.

8.4.5 Consider Improvement Methods in Timetabling, Fare and Service Quality

Alongside the routes planning and frequency setting which have been modelled in the current optimisation model, improvements in the timetabling, fare system and service quality should be considered in the future. In practice, timetable provides more detailed information to passengers than frequency and is an essential component of public transport network planning, thus the timetable development should to be considered in the future research. The centralised planning for public transport services not only helps to deliver an integrated bus network with more equal network distribution and less unnecessary duplication in service provision (which has been approved by the output results from the Southampton case study), it also helps to introduce a simple ticketing system among multi-operators and to provide high-quality of bus services. Better results will be output if the current quantity improvement methods are combined with the introduction of a simple ticketing system, fare capping (equivalent to the price of a daily ticket) and enforceable standards for service performance and quality.

Appendices

Appendix A Python Parse Process

Public transport network data, both NPTDR and TNDS, are supplied in TransXChange (TXC) format, which is a general purpose interchange format for timetable information and can be applied to any mode of public transport. Although the TXC files are open-source and provide a highly adaptable transfer format for timetable information, they are verbose and unsuitable for direct analysis by further analysis software, such as ArcGIS. This problem was solved by using the Python ElementTree module (xml.etree.ElementTree) to parse the TXC files into CSV files, which are directly readable by ArcGIS.

Based on the research objective, stops, routes and timetable data of public transport networks are essential input data for both accessibility and optimisation model. Three CSV files were therefore outputted from the Python conversion process, and the Python codes used were attached in this section.

- Stops file: details of all stops included in the schedules are listed, including stop name and NaPTAN ATCO code.
- Routes file: services are identified as service code (service number), its operator name, OD terminal stops, direction (in/outbound) and a unique sequence of stops.
- Timetable file: a sequence of arrival and departure times in associated with each journey.

```
##################################CodesStart######################################

from xml.etree.ElementTree import ElementTree

from xml.etree.ElementTree import Element

from xml.etree.ElementTree import SubElement as SE


doc=ElementTree(file="INPUT TXC FILE")

root=doc.getroot()


services=doc.find("{http://www.transxchange.org.uk/}Services")

service=services.findall("{http://www.transxchange.org.uk/}Service")

journeypatternsecions=doc.find("{http://www.transxchange.org.uk/}JourneyPattern
Sections")
```

```
journeypatternsection=journeypatternsecions.findall("{http://www.transxchange.org.uk/}JourneyPatternSection")

stops=doc.find("{http://www.transxchange.org.uk/}StopPoints")

stop=stops.findall("{http://www.transxchange.org.uk/}AnnotatedStopPointRef")

jous=doc.find("{http://www.transxchange.org.uk/}VehicleJourneys")

jou=jous.findall("{http://www.transxchange.org.uk/}VehicleJourney")


#STEP1: OUTPUT BUS STOPS.CSV#

#for each bus stop, 2 fields: stop name / NaPTAN ATCO code #

build a dictionary of all stops involved in the bus network#

stopdic={}

for AnnotatedStopPointRef in stop:

    stopid=AnnotatedStopPointRef.find("{http://www.transxchange.org.uk/}StopPointRef").text

    stopname=AnnotatedStopPointRef.find("{http://www.transxchange.org.uk/}CommonName").text

    stopdic[stopid]=stopname


#build a dictionary of all journery pattern involved in the bus network#

journeypatterndic={}

for JourneyPatternSection in journeypatternsection:

    journeypatternsectionid=JourneyPatternSection.get("id")

    key = journeypatternsectionid

    journeypatternlink=JourneyPatternSection.findall("{http://www.transxchange.org.uk/}JourneyPatternTimingLink")

    for JourneyPatternTimingLink in journeypatternlink:

        fromstop=JourneyPatternTimingLink.find("{http://www.transxchange.org.uk/}From")
```

```
        fromstopref=fromstop.find("{http://www.transxchange.org.uk/}StopPoint
        Ref").text

        tostop=JourneyPatternTimingLink.find("{http://www.transxchange.org.uk
        /}To")

        tostopref=tostop.find("{http://www.transxchange.org.uk/}StopPointRef"
        ).text

        runtime=JourneyPatternTimingLink.find("{http://www.transxchange.org.u
        k/}RunTime").text


        journeypatterndic.setdefault(key, [])

        journeypatterndic[key].append((fromstopref,stopdic.get(fromstopref),t
        ostopref,stopdic.get(tostopref),runtime))


#STEP2: OUTPUT BUS ROUTES.CSV

#for each service, 5 fields: its operator, service code, OD, direction, and
sequence of stops #

for Service in service:

    servicecode=Service.find("{http://www.transxchange.org.uk/}ServiceCode").t
    ext

    operator=Service.find("{http://www.transxchange.org.uk/}RegisteredOperator
    Ref").text

    standservice=Service.find("{http://www.transxchange.org.uk/}StandardServic
    e")

    origin=standservice.find("{http://www.transxchange.org.uk/}Origin").text

    destination=standservice.find("{http://www.transxchange.org.uk/}Destinatio
    n").text

    print operator,servicecode,origin,"--",destination


    journeypattern=standservice.findall("{http://www.transxchange.org.uk/}Jour
    neyPattern")
```

```
    for JourneyPattern in journeypattern:

    destinationdisplay=JourneyPattern.find("{http://www.transxchange.org.uk/}D
    estinationDisplay").text

    direction=JourneyPattern.find("{http://www.transxchange.org.uk/}Direction"
    ).text

    for JourneyPatternSectionReFirst Southampton in JourneyPattern.findall
    ("{http://www.transxchange.org.uk/}JourneyPatternSectionRefs"):

        print direction, JourneyPatternSectionRefs.text

        print journeypatterndic.get(JourneyPatternSectionRefs.text)


# STEP3: OUTPUT TIMETABLE.CSV

frequencydic={}

for VehicleJourney in jou:

    number = VehicleJourney.get("SequenceNumber")

    operator=VehicleJourney.find("{http://www.transxchange.org.uk/}OperatorRef
    ").text

    service=VehicleJourney.find("{http://www.transxchange.org.uk/}ServiceRef")
    .text

    departuretime=VehicleJourney.find("{http://www.transxchange.org.uk/}Depart
    ureTime").text



    profile=VehicleJourney.find("{http://www.transxchange.org.uk/}OperatingPro
    file")

    regularday=profile.find("{http://www.transxchange.org.uk/}RegularDayType")

    daysofweek=regularday.find("{http://www.transxchange.org.uk/}DaysOfWeek").
    getchildren()[0].tag

    list=daysofweek.split("}")

    days=list[1]
```

```
        key=service
        frequencydic.setdefault(key, [])
        frequencydic[key].append(days)


for key in frequencydic:
    num=0
    for item in frequencydic[key]:
        if item=="Monday" :
            num +=1
        if item=="MondayToFriday":
            num+=1
    print key,num
```

##################################CodesEnd######################################

Appendix B Current Bus Network in Southampton

- Based on Monday morning peak hour 0800-0900

Service NO	Operator	OD Terminals	Route length (within city boundary, KM)	Run Time (hour)	Frequency (In each direction)	Direction
72	FIRST IN HAMPSHIRE	Central Station—Gosport Bus Station	6.64	0.37	2	In/outbound
80	FIRST IN HAMPSHIRE	Central Station—Fareham Bus Station	6.64	0.37	4	In/outbound
1	FIRST SOUTHAMPTON	Kipling Court—Kingsclere Avenue	6.96	0.39	8	In/outbound
10A	FIRST SOUTHAMPTON	Lord's Hill Terminus—Fair fax Court	16.65	0.93	5	In/outbound
11A	FIRST SOUTHAMPTON	Vincent's Walk--Vincent's Walk	13.13	0.73	2	In/outbound
11C	FIRST SOUTHAMPTON	Pound Tree Road--Vincent's Walk	13.48	0.75	2	Outbound only
12A	FIRST SOUTHAMPTON	Vincent's Walk--Vincent's Walk	14.06	0.78	2	In/outbound
12C	FIRST SOUTHAMPTON	Pound Tree Road--Vincent's Walk	14.28	0.79	2	Outbound only
16	FIRST SOUTHAMPTON	Hamble Bluestaruare—Pound Tree Road	6.76	0.38	5	In/outbound
16A	FIRST SOUTHAMPTON	Hedge End Superstores--Vincent's Walk	6.73	0.37	1	In/outbound

Appendix B: Current Bus Network in Southampton

Service NO	Operator	OD Terminals	Route length (within city boundary, KM)	Run Time (hour)	Frequency (In each direction)	Direction
17	FIRST SOUTHAMPTON	Lord's Hill Terminus--Vincent's Walk	9.22	0.51	6	In/outbound
17A	FIRST SOUTHAMPTON	Lord's Hill Terminus--Vincent's Walk	12.10	0.67	6	In/outbound
1A	FIRST SOUTHAMPTON	Kipling Court--Vincent's Walk	7.43	0.41	4	In/outbound
21A	FIRST SOUTHAMPTON	Mauretania Road—Royal South Hant's Hospital	16.81	0.93	3	In/outbound
5	FIRST SOUTHAMPTON	Lord's Hill Terminus—Pound Tree Road	11.91	0.66	3	In/outbound
7	FIRST SOUTHAMPTON	Forest Gardens—Bargate Street	6.67	0.37	6	In/outbound
7A	FIRST SOUTHAMPTON	Tesco—Pound Tree Road	14.95	0.83	1	In/outbound
8A	FIRST SOUTHAMPTON	Lord's Hill Terminus—Hedge End Station	13.78	0.77	6	In/outbound
9	FIRST SOUTHAMPTON	Calshot Beach—West Quay Shopping Centre	7.25	0.40	6	In/outbound
46	HAMPSHIRE BUS CO LTD	Vincent's Walk—Winchester Bus Station	7.78	0.43	1	In/outbound
46B	HAMPSHIRE BUS CO LTD	Vincent's Walk--Winchester Bus Station	8.37	0.46	1	In/outbound
001	BLUESTAR	Winchester Bus Station—Hanover Buildings	6.22	0.35	5	In/outbound
10	BLUESTAR	Lord's Hill Terminus—Fairfax Court	16.10	0.89	2	In/outbound

Service NO	Operator	OD Terminals	Route length (within city boundary, KM)	Run Time (hour)	Frequency (In each direction)	Direction
11	BLUESTAR	Romsey Road—West Quay Shopping Centre	6.42	0.36	1	In/outbound
12	BLUESTAR	Sarum Compton House—West Quay Shopping Centre	6.42	0.36	2	In/outbound
18	BLUESTAR	Burgoyne Road—Kendal Avenue Shops	14.01	0.78	6	In/outbound
2	BLUESTAR	Fair Oak—Hanover Buildings	6.99	0.39	6	In/outbound
3	BLUESTAR	Kings Corner—St Annes Convent School	9.45	0.53	1	In/outbound
4	BLUESTAR	Romsey Bus Station—Hanover Buildings	7.30	0.41	3	In/outbound
8	BLUESTAR	Hythe Ferry Yard—West Quay Shopping Centre	6.42	0.36	2	In/outbound
LINK	BLUESTAR	Western Esplanade—Passenger Terminal	1.90	0.11	4	In/outbound
U1	UNILINK	Eastleigh Hampshire Bus Co Ltd Bus Station—Oceanography Centre	11.65	0.65	9	In/outbound
U2	UNILINK	Crematorium—Civic Centre	8.57	0.48	6	In/outbound
U6	UNILINK	Southampton General Hospital—West Quay Shopping Centre	12.21	0.68	5	In/outbound
X5	TRAVELGUEST	West Quay Shopping Centre—Meeting House Lane	5.51	0.31	1	In/outbound
56	TRAVELGUEST	Lymington Bus Station—West Quay Shopping Centre	6.39	0.36	1	In/outbound

Appendix B: Current Bus Network in Southampton

Service NO	**Operator**	**OD Terminals**	**Route length (within city boundary, KM)**	**Run Time (hour)**	**Frequency (In each direction)**	**Direction**
56A	TRAVELGUEST	Lymington Bus Station—West Quay Shopping Centre	6.39	0.36	2	In/outbound
X7	TRAVELGUEST	Castle Way—Bus Station	6.65	0.37	1	In/outbound

Appendix C Script Evaluators for IVT and WTT Calculation Based on Timetable

The custom evaluators for IVT and WTT calculation were developed based on a code sample called 'Network Analyst- Departure Time Transit Evaluator' available at ArcGIS Help website (http://www.arcgis.com/home/item.html?id=72ef24542857413c8981f2e196f1bb13). The methodology of building the both evaluators is similar: link timetable data stored in a CSV file by 'CacheSchedules' method, and calculate IVT/WTT by 'QueryValueAtTime' method. Detailed calculation processes for both IVT and WTT calculation evaluators will be explained in this section, and corresponding codes will be attached as well.

C.1 IVT Calculation based on Timetable

Script evaluator for IVT calculation is assigned to bus/rail link feature class. Before using this evaluator, all timetable data need to be saved in a CSV file, formatted as 'OID, DepartureTime, ArriveTime'. OIDs are the numeric identifiers (Object ID) of the source features (bus/ rail link features), and are used as keys by the evaluator linking timetable data to the network analysis functions in ArcGIS. Departure time is the time a bus departures from the origin stop of this specific link, while arrive time is the time arrives at the destination stop. When a bus/rail link is traversed, the IVT evaluator's 'QueryValueAtTime' method is called: the evaluator will search for the timetable data identified by matching OIDs, and return IVT as the difference between its arrive time and departure time. The codes of two key methods, 'CacheSchedules' and 'QueryValueAtTime' method, involving in builing this IVT calculation evaluator are represented below.

###################################CodesStart#####################################

```
//Codes for CacheSchedules Method in Evaluator for IVT Calculation:
//link timetable data to the network analysis functions in ArcGIS

private void CacheSchedules()
{
      // If the properties haven't been set, use the defaults.
      if (m_Data == null)
      {
            m_Data = new PropertySet();
            m_Data.SetProperty(PROPNAME_TURNSCHEDULE_FILE_PATH,
            DEFAULT_TURNSCHEDULE_FILE_PATH);
            m_Data.SetProperty(PROPNAME_SOURCEID_FIELDNAME,
            DEFAULT_SOURCEID_FIELDNAME);
            m_Data.SetProperty(PROPNAME_OID_FIELDNAME, DEFAULT_OID_FIELDNAME);
            m_Data.SetProperty(PROPNAME_DEPARTURETIMES_FIELDNAME,
            DEFAULT_DEPARTURETIMES_FIELDNAME);
      }
```

```
// Retrieve all of the properties for this evaluator.
string scheduleFilePath =
m_Data.GetProperty(PROPNAME_TURNSCHEDULE_FILE_PATH).ToString();
string sourceIDField =
m_Data.GetProperty(PROPNAME_SOURCEID_FIELDNAME).ToString();
string oidField = m_Data.GetProperty(PROPNAME_OID_FIELDNAME).ToString();
string departureTimeField =
m_Data.GetProperty(PROPNAME_DEPARTURETIMES_FIELDNAME).ToString();

if (!File.Exists(scheduleFilePath))
{
      MessageBox.Show("Restriction file could not be found: " +
      scheduleFilePath);
      return;
}

// If the file is still fresh, then no need to load speeds.
DateTime lastUpdate = File.GetLastWriteTime(scheduleFilePath);
if (lastUpdate > m_lastFileUpdate)
      m_lastFileUpdate = lastUpdate;
else
return;

// Initialize the hash of Source OIDs along with departure times.
if (m_Schedules == null)
      m_Schedules = new Dictionary<int, List<TimeSpan>>();
else
      m_Schedules.Clear();

// Open the schedules external file, allowing for read/write sharing.
using (System.IO.FileStream stream = new System.IO.FileStream(scheduleFilePath,
FileMode.Open, FileAccess.Read, FileShare.ReadWrite))
{
      using (TextReader tr = new StreamReader(stream))
      {
            // First, validate the field names.
            if (!ValidateScheduleFileHeader(tr.ReadLine(), sourceIDField,
            oidField, departureTimeField))
            {
                  tr.Close();
                  stream.Close();
                  return;
            }
            // Read in and store the schedules.
            string line = "";

            while ((line = tr.ReadLine()) != null)
            {
                  string[] values = line.Split(',');
                  try
                  {
                  // SourceOID is the object idea for this element's associated
                  source feature.
                        int oid = Convert.ToInt32(values[1]);
                        DateTime departureDateTime;
                        TimeSpan departureTimeOfDay;
                        if (DateTime.TryParse(values[2], out departureDateTime))
                              departureTimeOfDay = departureDateTime.TimeOfDay;
                        else
                              continue;
                        if (m_Schedules.ContainsKey(oid))
                        {
                              var scheduleList = m_Schedules[oid];
                              int index =
                              scheduleList.BinarySearch(departureTimeOfDay);
```

```
                    if (index < 0)
                    {
                        scheduleList.Insert(~index,
                        departureTimeOfDay);
                    }
                }
                else
                    m_Schedules.Add(oid, new List<TimeSpan>()
                    { departureTimeOfDay });
            }
            catch
            {
                // Skip any invalid entries.
                continue;
            }
        }
    }
}

}
```

```
//Codes for ITimeAwareEvaluator Method in Evaluator for IVT Calculation:
//calculate IVT based on timetable data

#region ITimeAwareEvaluator

public object QueryValueAtTime(INetworkElement element, DateTime queryTime,
esriNetworkTimeUsage timeUsage)
{
    int oid = element.OID;
    if (m_Schedules.ContainsKey(oid))
    {
        // IVT = arrive time – departure time
        double IVT = schedule[2].TotalMinutes - schedule[1].TotalMinutes;
    }
    // If there are no schedule entries for this element, then the added cost is
    zero.
    return 0;
}
```

#################################CodesEnd####################################

C.2 WTT Calculation based on Timetable

Script evaluator for WTT calculation is assigned to from-to direction bus/rail connector feature class. Before using this evaluator, all timetable data need to be saved in a CSV file, formatted as 'OID, DepartureTime'. OIDs are the numeric identifier (Object ID) of the source features (bus/rail connector features), and departure time is the time a bus departures from the bus stop linked by this specific connector. When a from-to direction bus/rail connector is traversed, the WTT evaluator's 'QueryValueAtTime' method is called: the evaluator will search for the timetable data identified by matching OIDs, and return the next available departure time based on the current time (the time the passenger arrives at the departure stop of this connector). As a result, the value of WTT is the difference between the next available departure time and the time the passenger arrives at this stop. Because the 'CacheSchedules' method used in this WTT calculation evaluator is similar with the method used in IVT calculation evaluator, only the codes of 'ITimeAwareEvaluator' method used for IVT calculation are represented in this section.

####################################CodesEnd######################################

```
//Codes for ITimeAwareEvaluator Method in Evaluator for WTT Calculation:
//calculate WTT based on timetable data

#region ITimeAwareEvaluator
public object QueryValueAtTime(INetworkElement element, DateTime queryTime,
esriNetworkTimeUsage timeUsage)
{
      int oid = element.OID;
      if (m_Schedules.ContainsKey(oid))
      {
            // Find the nearest time in the schedule to the query time.
            TimeSpan queryTimeOfDay = queryTime.TimeOfDay;
            List<TimeSpan> schedule = m_Schedules[oid];
            // Find the index of any scheduled times that match the query time.
            int scheduleIndex = schedule.BinarySearch(queryTimeOfDay);
            // If no exact matches are found, the bitwise complement (~) of the value
            returned
            // by the binary search is equal to the index of the next largest value.
            if (scheduleIndex < 0)
            scheduleIndex = ~scheduleIndex;

            // See if there is a scheduled time after the query time.
            if (scheduleIndex < schedule.Count)
            {
                  // The added cost is the difference between the next scheduled time
                  and the query time.
                  TimeSpan nextScheduledTime = schedule[scheduleIndex];
                  if (queryTimeOfDay == nextScheduledTime)
                        return 0; // an exact match
                  else
                        return
                        schedule[scheduleIndex].Subtract(queryTimeOfDay).TotalMinutes;
            }
            else
            {
                  // If no entry came after the start time for that day, then
                  //  use the earliest start time the next day.
                  double totalMinutesInADay = 24 * 60;
                  double timeFromQueryTimeToMidnight = totalMinutesInADay -
                  queryTimeOfDay.TotalMinutes;
                  return schedule[1].TotalMinutes + timeFromQueryTimeToMidnight;
            }
      }
      // If there are no schedule entries for this element, then the added cost is
      zero.
      return 0;
}
```

####################################CodesEnd######################################

Appendix D Automating Travel Cost Calculation Model

According to the detailed methodology represented in section 5.4, there are three steps in building a model for travel costs calculation:

1. Data preparation;
2. Build multi-modal network dataset;
3. Calculate travel costs for each OD pairs.

In order to automate the repetitive data preparation process and to improve the calculation speed for large-size datasets, the travel cost calculation model was developed under the environment of ArcObjects for Java. Followed by detailed guidelines available at the ArcGIS Resource Centre website (http://help.arcgis.com/en/sdk/10.0/java_ao_adf/ao_home.html), the model was developed using codes displayed below.

##################################CodesStart######################################

Step 1: data preparation

```
private static void DataClear(IFeatureClass inputBusStopFC, Dictionary<Double,
Double> dic)
{
      Try
      {
            GeoProcessor gp = new GeoProcessor();
            gp.setOverwriteOutput(true);

            /*
             *  step 1: tranfer the input bus stop FC TO layer
             */
            MakeFeatureLayer makeFeatureLayer = new MakeFeatureLayer();
            makeFeatureLayer.setInFeatures(inputBusStopFC);
            makeFeatureLayer.setOutLayer("inputLayer");
            gp.execute(makeFeatureLayer, null);

           /*
            * step 2: open bus routes.gdb & bus links.gdb & bus stops.gdb
            *
            */
            // Open the feature dataset and cast to the IGeoDataset interface.
            IWorkspaceFactory workspaceFactory = new FileGDBWorkspaceFactory();
            // open bus routes.gdb
            IWorkspace busRouteWorkspace = workspaceFactory.openFromFile
            ("C:\\GIS practice\\Data Preparation for Network Dataset\\Bus
            Routes.gdb", 0);
            IFeatureWorkspace busRouteFeatureWorkspace = new
            IFeatureWorkspaceProxy(busRouteWorkspace);
            //open selected bus stops.gdb
            IWorkspace selectedStopWorkspace =
            workspaceFactory.openFromFile("C:\\GIS practice\\Data Preparation for
            Network Dataset\\busStops.gdb", 0);
            IFeatureWorkspace selectedStopFeatureWorkspace = new
            IFeatureWorkspaceProxy(selectedStopWorkspace);
            // open bus links.gdb
            IWorkspace busLinkWorkspace = workspaceFactory.openFromFile("C:\\GIS
            practice\\Data Preparation for Network Dataset\\BusLinks.gdb", 0);
```

```
IFeatureWorkspace busLinkFeatureWorkspace = new
IFeatureWorkspaceProxy(busLinkWorkspace);
// open the connector.gdb
IWorkspace connectorWorkspace = workspaceFactory.openFromFile("C:\\GIS
practice\\Data Preparation for Network Dataset\\Connectors.gdb", 0);
IFeatureWorkspace connectorFeatureWorkspace = new
IFeatureWorkspaceProxy(connectorWorkspace);
/*
 * step 3: for each fc in the bus routes.gdb
 */
// Set the workspace to a folder containing personal geodatabases.
gp.setEnvironmentValue("workspace", "C:\\GIS practice\\Data
Preparation for Network Dataset\\Bus Routes.gdb");
IGpEnumList fcs = gp.listFeatureClasses("", "", "");
String fc= fcs.next(); // string fc = the name of FC
while (!"".equals(fc))
{
      // open fc
      IFeatureClass inputBusRoute =
      busRouteFeatureWorkspace.openFeatureClass(fc);
      /*
       * STEP3. 1: add/ calculate RouteNO field to each bus route FC
       */
      // add field RouteNO (double) to every bus route FC
      AddField addField = new AddField();
      addField.setInTable(inputBusRoute);
      addField.setFieldName("RouteNO");
      addField.setFieldType("DOUBLE");
      gp.execute(addField, null);
      // calculate field
      CalculateField calculateField = new CalculateField();
      calculateField.setInTable(inputBusRoute);
      calculateField.setField("RouteNO");
      calculateField.setExpressionType("PYTHON");
      calculateField.setExpression("!Name!.split()[0]");
      gp.execute(calculateField, null);
      // get the value of RouteNO
      IFeatureCursor featureCursor = inputBusRoute.search(null, true);
      IFeature pFeature = featureCursor.nextFeature();
      int routeNOindex = inputBusRoute.findField("RouteNO");
      double routeNumber = 0;
      while (pFeature != null)
      {

            routeNumber = (double) pFeature.getValue(routeNOindex);
            //System.out.println("route number = "+ routeNumber);
            pFeature= featureCursor.nextFeature();
      } // end of while
      /*
      *  STEP 3.2: export real bus stops
      *  1.  add field RouteNO (double)
      */
      // gp tool: selection by location
      SelectLayerByLocation selectByLocation = new
      SelectLayerByLocation();
      selectByLocation.setSelectFeatures(inputBusRoute);
      selectByLocation.setInLayer("inputLayer");
      selectByLocation.setSelectionType("NEW_SELECTION");
      selectByLocation.setOverlapType("WITHIN");
      gp.execute(selectByLocation, null);
      // save the bus stops of each routes
      CopyFeatures copyFeatures = new CopyFeatures();
      copyFeatures.setInFeatures("inputLayer");
      copyFeatures.setOutFeatureClass("C:\\GIS practice\\Data
      Preparation for Network Dataset\\busStops.gdb\\BS"+ fc);
      gp.execute(copyFeatures, null);
      // open the bus stops FC
      IFeatureClass selectStops =
      selectedStopFeatureWorkspace.openFeatureClass("BS"+fc);
      //add field RouteNO (double) and calculate it
      selectStops = addAndCalculateField(selectStops, routeNumber);
```

```
/*
 *  Step 3.3: export bus links
 *          1. move x and y
 *          2. add field IVT (double)
 */
SplitLineAtPoint split = new SplitLineAtPoint();
split.setInFeatures(inputBusRoute);
split.setPointFeatures(selectStops);
split.setSearchRadius(10);
split.setOutFeatureClass("C:\\GIS practice\\Data Preparation for
Network Dataset\\BusLinks.gdb\\BL"+fc);
gp.execute(split, null);
//open bus links FC
IFeatureClass BusLinks =
busLinkFeatureWorkspace.openFeatureClass("BL"+fc);
// move bus links
BusLinks = moveFeatures (BusLinks);

// add field IVT
AddField IVT = new AddField();
IVT.setInTable(BusLinks);
IVT.setFieldName("IVT");
IVT.setFieldType("DOUBLE");
gp.execute(IVT, null);
// calculate field IVT
CalculateField calculateIVT = new CalculateField();
calculateIVT.setInTable(BusLinks);
calculateIVT.setField("IVT");
calculateIVT.setExpressionType("VB");
calculateIVT.setExpression("[Shape_Length] /309.7745");
gp.execute(calculateIVT, null);
/*
 * step 3.4: export projected bus stops
 *             1. move x and y
// copy the real bus stops
CopyFeatures copyStops = new CopyFeatures();
copyStops.setInFeatures(selectStops);
copyStops.setOutFeatureClass("C:\\GIS practice\\Data Preparation
for Network Dataset\\busStops.gdb\\PBS"+ fc);
gp.execute(copyStops, null);
// Open the projected bus stop
IFeatureClass projectedBusStop =
selectedStopFeatureWorkspace.openFeatureClass("PBS"+fc);
// move X/Y by route NO value
projectedBusStop = moveFeatures(projectedBusStop);

 /*
  * step 3.5: export bus connectors
  *         1. add routeNO field
  *         2. add WTT field
  *
  */

// merge real and projected bus stops
Merge merge = new Merge();
merge.setInputs
 ("C:\\GIS practice\\Data Preparation for Network
Dataset\\busStops.gdb\\BS"+ fc + ";" +
"C:\\GIS practice\\Data Preparation for Network
Dataset\\busStops.gdb\\PBS"+fc);
merge.setOutput
 ("C:\\GIS practice\\Data Preparation for Network
Dataset\\busStops.gdb\\merge"+ fc);
 gp.execute(merge, null);
 // open merge fc
IFeatureClass mergeFC =
selectedStopFeatureWorkspace.openFeatureClass("merge"+ fc);
// export connector FC
MakeFeatureLayer makeFeatureLayer1 = new MakeFeatureLayer();
makeFeatureLayer1.setInFeatures(mergeFC);
makeFeatureLayer1.setOutLayer("inputMergeLayer");
```

```
                gp.execute(makeFeatureLayer1, null);
                PointsToLine connector = new PointsToLine();
                connector.setInputFeatures("inputMergeLayer");
                connector.setOutputFeatureClass("C:\\GIS practice\\Data
                Preparation for Network Dataset\\Connectors.gdb\\connector"+fc);
                connector.setLineField("ATCOCode");
                gp.execute(connector, null);
                // open connector FC
                IFeatureClass connectorFC =
                connectorFeatureWorkspace.openFeatureClass("connector"+ fc);
                // add and calculate RouteNO field
                connectorFC = addAndCalculateField (connectorFC, routeNumber);
                // add and calcualte WTT field
                // add field WTT
               AddField WTT = new AddField();
               WTT.setInTable(connectorFC);
               WTT.setFieldName("WTT");
               WTT.setFieldType("DOUBLE");
               gp.execute(WTT, null);
               // calcualte Field
               IFeatureCursor connectorFeatureCursor = connectorFC.search(null,
               true);
               IFeature connectorFeature = connectorFeatureCursor.nextFeature();
               int WTTIndex = connectorFC.findField("WTT");
               int routeindex = connectorFC.findField("RouteNO");
               while (connectorFeature != null)
               {
                      double frequency
                      (double)dic.get(connectorFeature.getValue(routeindex));
                      if (60/frequency > 15)
                      {
                           connectorFeature.setValue(WTTIndex, 7.5);
                           connectorFeature.store();

                      }// end of if
                      Else
                      {
                           connectorFeature.setValue(WTTIndex, 30/frequency);
                           connectorFeature.store();
                      } // end of else
                      connectorFeature= connectorFeatureCursor.nextFeature();

                 } // end of while
                fc = fcs.next();
         }// end of loop through all FCs in the .gdb

    } // end of try

    catch (Exception e)
    {
         e.printStackTrace();
    } //  end of catch
     System.out.println("finished data preparation process for each route");

}// end of method
```

Step 2: build multimodal network dataset

```
private static void buildNetworkDataset ()
{
     try {
          /*
           * Step 1: PREPARATION AND NAME THE NETWORK DATASET
           *
           */
          // Create an empty data element for a buildable network dataset.
          IDENetworkDataset2 deNetworkDataset = new DENetworkDataset();
          deNetworkDataset.setBuildable(true);
          // Open the feature dataset and cast to the IGeoDataset interface.
          IWorkspaceFactory workspaceFactory = new FileGDBWorkspaceFactory();
```

```
//TODO: edit the .gdb file path
IWorkspace workspace = workspaceFactory.openFromFile
("C:\\GIS practice\\Data Preparation for Network Dataset\\Network
Dataset.gdb", 0);
IFeatureWorkspace featureWorkspace = (IFeatureWorkspace)workspace;
//TODO: edit the name of featureDataset
IFeatureDataset featureDataset =
featureWorkspace.openFeatureDataset("Walk_Bus");
IGeoDataset geoDataset = new IGeoDatasetProxy(featureDataset);
// Copy the feature dataset's extent and spatial reference to the
network dataset data element.
IDEGeoDataset deGeoDataset = (IDEGeoDataset)deNetworkDataset;
deGeoDataset.setExtentByRef(geoDataset.getExtent());
deGeoDataset.setSpatialReferenceByRef(geoDataset.getSpatialReference()
);
// Specify the name of the network dataset.
IDataElement dataElement = (IDataElement)deNetworkDataset;
//TODO: edit the name of network dataset
dataElement.setName("Walk_Bus_ND");
// check the performance
/*
 * Step 2: SELECT SOURCE, CONNECTIVITY AND SET ELEVATION
 *
 */
// 2.1 Walk links (edge feature)
// Specify the network dataset's elevation model.
INetworkSource walkNetworkSource = new EdgeFeatureSource();
//TODO: edit the name of input FC
walkNetworkSource.setName("WalkLinks_3D_1");
walkNetworkSource.setElementType(esriNetworkElementType.esriNETEdge);
// Set the edge feature source's connectivity settings.
IEdgeFeatureSource edgeFeatureSource =
(IEdgeFeatureSource)walkNetworkSource;
edgeFeatureSource.setUsesSubtypes(false);
edgeFeatureSource.setClassConnectivityGroup(3);
edgeFeatureSource.setClassConnectivityPolicy(esriNetworkEdgeConnectivi
tyPolicy.esriNECPEndVertex);
edgeFeatureSource.setFromElevationFieldName("FromGradeSeparation");
edgeFeatureSource.setToElevationFieldName("ToGradeSeparation");

// 2.2 bus links (edge feature)
// Create an EdgeFeatureSource object and point it to the Streets
feature class.
INetworkSource busNetworkSource = new EdgeFeatureSource();
//TODO: edit the name of input FC
busNetworkSource.setName("BusLinks");
busNetworkSource.setElementType(esriNetworkElementType.esriNETEdge);
// Set the edge feature source's connectivity settings.
edgeFeatureSource = (IEdgeFeatureSource)busNetworkSource;
edgeFeatureSource.setUsesSubtypes(false);
edgeFeatureSource.setClassConnectivityGroup(1);
edgeFeatureSource.setClassConnectivityPolicy(esriNetworkEdgeConnectivi
tyPolicy.esriNECPEndVertex);
edgeFeatureSource.setFromElevationFieldName("F_ELEV");
edgeFeatureSource.setToElevationFieldName("T_ELEV");


// 2.3 walk bus connectors (edge feature)
// Create an EdgeFeatureSource object and point it to the Streets
feature class.
INetworkSource wbNetworkSource = new EdgeFeatureSource();
//TODO: edit the name of input FC
wbNetworkSource.setName("BusConnectors");
wbNetworkSource.setElementType(esriNetworkElementType.esriNETEdge);
// Set the edge feature source's connectivity settings.
edgeFeatureSource = (IEdgeFeatureSource)wbNetworkSource;
edgeFeatureSource.setUsesSubtypes(false);
edgeFeatureSource.setClassConnectivityGroup(2);edgeFeatureSource.setCl
assConnectivityPolicy(esriNetworkEdgeConnectivityPolicy.esriNECPEndVer
tex);
edgeFeatureSource.setFromElevationFieldName("F_ELEV");
```

```
edgeFeatureSource.setToElevationFieldName("T_ELEV");
//Create a JunctionFeatureSource object and point it to the
Metro_Stations feature class.
INetworkSource projectedStopNetSource = new JunctionFeatureSource();
projectedStopNetSource.setName("ProjectedBusStops");
projectedStopNetSource.setElementType(esriNetworkElementType.esriNETJu
nction);
//Set the junction feature source's connectivity settings.
IJunctionFeatureSource junctionFS =
(IJunctionFeatureSource)projectedStopNetSource;
junctionFS.setUsesSubtypes(false);
junctionFS.removeAllClassConnectivityGroups();
junctionFS.addClassConnectivityGroup(1);
junctionFS.addClassConnectivityGroup(2);
junctionFS.setClassConnectivityPolicy(esriNetworkJunctionConnectivityP
olicy.esriNJCPOverride);
junctionFS.setElevationFieldName("elevation");
// 2.5 real bus stops (junction feature)
//Create a JunctionFeatureSource object and point it to the
Metro_Stations feature class.
INetworkSource realStopNetSource = new JunctionFeatureSource();
realStopNetSource.setName("RealBusStops");
realStopNetSource.setElementType(esriNetworkElementType.esriNETJunctio
n);
//Set the junction feature source's connectivity settings.
junctionFS = (IJunctionFeatureSource)realStopNetSource;
junctionFS.setUsesSubtypes(false);
junctionFS.removeAllClassConnectivityGroups();
junctionFS.addClassConnectivityGroup(3);
junctionFS.addClassConnectivityGroup(2);
junctionFS.setClassConnectivityPolicy(esriNetworkJunctionConnectivityP
olicy.esriNJCPOverride);
junctionFS.setElevationFieldName("elevation");
/*
 * step 3:  add all source object to the array table
 *
 */
// add the source data to array
IArray sourceArray = new Array();
sourceArray.add(walkNetworkSource);
sourceArray.add(busNetworkSource);
sourceArray.add(wbNetworkSource);
sourceArray.add(projectedStopNetSource);
sourceArray.add(realStopNetSource);
deNetworkDataset.setSourcesByRef(sourceArray);
/*
 * step 4: global turns
 */
//DIRECTION SETTING
deNetworkDataset.setSupportsTurns(true);
/*
 * step 5: attributes
 */
// ATTRIBUTE SETTING
// create Array for the network attributes
IArray attributeArray = new Array();
// Initialize variables reused when creating attributes:
IEvaluatedNetworkAttribute evalNetAttr;
INetworkAttribute2 netAttr2;
INetworkFieldEvaluator netFieldEval;
INetworkConstantEvaluator netConstEval;
INetworkScriptEvaluator netScriptEval;
// 5.0 SET DESCRIPTOR ATTRIBUTE: TURNCOST
// Create an EvaluatedNetworkAttribute object and populate its
settings.
evalNetAttr = new EvaluatedNetworkAttribute();
netAttr2 = (INetworkAttribute2)evalNetAttr;
netAttr2.setName("TurnCost");
netAttr2.setUsageType(esriNetworkAttributeUsageType.esriNAUTDescriptor
);
netAttr2.setDataType(esriNetworkAttributeDataType.esriNADTDouble);
```

```
netAttr2.setUnits(esriNetworkAttributeUnits.esriNAUUnknown);
netAttr2.setUseByDefault(false);
// Create evaluator objects and set them on the
EvaluatedNetworkAttribute object.
netFieldEval = new NetworkFieldEvaluator();
//TODO: SET EXPRSSION
netFieldEval.setExpression("[RouteNO]", "");
evalNetAttr.setEvaluatorByRef(busNetworkSource,esriNetworkEdgeDirectio
n.esriNEDAlongDigitized, (INetworkEvaluator)netFieldEval);
evalNetAttr.setEvaluatorByRef(busNetworkSource,esriNetworkEdgeDirectio
n.esriNEDAgainstDigitized, (INetworkEvaluator) netFieldEval);
// SET default attribute evalutors
netConstEval = new NetworkConstantEvaluator();
netConstEval.setConstantValue(0);
evalNetAttr.setDefaultEvaluatorByRef(esriNetworkElementType.esriNETEdg
e, (INetworkEvaluator)netConstEval);
evalNetAttr.setDefaultEvaluatorByRef(esriNetworkElementType.esriNETJun
ction, (INetworkEvaluator)netConstEval);
evalNetAttr.setDefaultEvaluatorByRef(esriNetworkElementType.esriNETTur
n, (INetworkEvaluator)netConstEval);
// Add the attribute to the array.
attributeArray.add(evalNetAttr);
// 5.1 MINITES COST ATTRIBUTE
// Create an EvaluatedNetworkAttribute object and populate its
settings.
evalNetAttr = new EvaluatedNetworkAttribute();
netAttr2 = (INetworkAttribute2)evalNetAttr;
netAttr2.setName("Minutes");
netAttr2.setUsageType(esriNetworkAttributeUsageType.esriNAUTCost);
netAttr2.setDataType(esriNetworkAttributeDataType.esriNADTDouble);
netAttr2.setUnits(esriNetworkAttributeUnits.esriNAUMinutes);
netAttr2.setUseByDefault(true);
// Create evaluator objects and set them on the
EvaluatedNetworkAttribute object.
netFieldEval = new NetworkFieldEvaluator();
//TODO: SET EXPRSSION
netFieldEval.setExpression("[IVT]", "");
evalNetAttr.setEvaluatorByRef(busNetworkSource,esriNetworkEdgeDirectio
n.esriNEDAlongDigitized, (INetworkEvaluator)netFieldEval);
evalNetAttr.setEvaluatorByRef(busNetworkSource,esriNetworkEdgeDirectio
n.esriNEDAgainstDigitized, (INetworkEvaluator) netFieldEval);
netFieldEval = new NetworkFieldEvaluator(); // remember to update the
netFieldEval for each time add new expression or constant value
netFieldEval.setExpression("1.75*[WKT]", "");
evalNetAttr.setEvaluatorByRef(walkNetworkSource,esriNetworkEdgeDirecti
on.esriNEDAlongDigitized, (INetworkEvaluator)netFieldEval);
evalNetAttr.setEvaluatorByRef(walkNetworkSource,esriNetworkEdgeDirecti
on.esriNEDAgainstDigitized, (INetworkEvaluator) netFieldEval);
netFieldEval = new NetworkFieldEvaluator();
netFieldEval.setExpression("2*[WTT]", "");
evalNetAttr.setEvaluatorByRef(wbNetworkSource,esriNetworkEdgeDirection
.esriNEDAlongDigitized, (INetworkEvaluator)netFieldEval);
netConstEval = new NetworkConstantEvaluator();
netConstEval.setConstantValue(0);
evalNetAttr.setDefaultEvaluatorByRef(esriNetworkElementType.esriNETEdg
e, (INetworkEvaluator)netConstEval);
evalNetAttr.setDefaultEvaluatorByRef(esriNetworkElementType.esriNETJun
ction, (INetworkEvaluator)netConstEval);
evalNetAttr.setEvaluatorByRef(wbNetworkSource,esriNetworkEdgeDirection
.esriNEDAgainstDigitized, (INetworkEvaluator)netConstEval);
netScriptEval = new NetworkScriptEvaluator();
String prelogic = "turntime=0\n\r" +
     "fromroute=fromEdge.AttributeValueByName (\"TurnCost\")\n\r"+
     "toroute=toEdge.AttributeValueByName ( \"TurnCost\" )\n\r" +
            "if fromroute<>toroute then\n\r" +
            "   turntime=7.5\n\r" +
            "end if\n\r";
netScriptEval.setExpression("turntime", prelogic);
evalNetAttr.setDefaultEvaluatorByRef(esriNetworkElementType.esriNETTur
n, (INetworkEvaluator)netScriptEval);
// Add the attribute to the array.
```

```
            attributeArray.add(evalNetAttr);
            /*
             * step 8: CREATE AND BUILD THE NETWORK DATASET
             */
            // Get the feature dataset extension and create the network dataset
            based on the data element.
            IFeatureDatasetExtensionContainer fdxContainer = new
            IFeatureDatasetExtensionContainerProxy(geoDataset);
            IFeatureDatasetExtension fdExtension =
            fdxContainer.findExtension(esriDatasetType.esriDTNetworkDataset);
            IDatasetContainer2 datasetContainer2 = new
            IDatasetContainer2Proxy(fdExtension);
            IDEDataset deDataset = (IDEDataset)deNetworkDataset;
            INetworkDataset networkDataset = new
            INetworkDatasetProxy(datasetContainer2.createDataset(deDataset));
            // Once the network dataset is created, build it.
            INetworkBuild networkBuild = new INetworkBuildProxy(networkDataset);
            networkBuild.buildNetwork(deGeoDataset.getExtent());
            System.out.println("finished building this network dataset");
        } // end of try
        catch (Exception e)
        {
            e.printStackTrace();
        } //  end of catch

} // end of method
```

Step 3: calculation travel costs

```
private Double CalculateTUC(String FGDB_WORKSPACE,
                String FEATURE_DATASET,
                String NETWORK_DATASET,
                String OD_WORKSPACE,
                String INPUT_NAME_FIELD,
                String filename)
{
        double travelCost = 0;
        try
        {
            // TODO: EDIT THE OUTPUT FILE NAME
            //String fileName = "TUC.txt";
            FileWriter result = new FileWriter (filename, true);
            //open the network workspace
            IWorkspaceFactory workspaceFactory = new FileGDBWorkspaceFactory();
            IFeatureWorkspace featureWorkspace = new
            IFeatureWorkspaceProxy(workspaceFactory.openFromFile(FGDB_WORKSPACE,
            0));
             // open the OD workspace
            IFeatureWorkspace ODWorkspace = new
            IFeatureWorkspaceProxy(workspaceFactory.openFromFile(OD_WORKSPACE,  0));
             //open network dataset
            IFeatureDataset featureDataset =
            featureWorkspace.openFeatureDataset(FEATURE_DATASET);
            featureDataset = featureWorkspace.openFeatureDataset(FEATURE_DATASET);
            IFeatureDatasetExtensionContainer fdsExtCont = new
            IFeatureDatasetExtensionContainerProxy(featureDataset);
            IFeatureDatasetExtension fdsExt =
            fdsExtCont.findExtension(esriDatasetType.esriDTNetworkDataset);
            IDatasetContainer2 dsCont = new IDatasetContainer2Proxy(fdsExt);
            IDataset dataset =
            dsCont.getDatasetByName(esriDatasetType.esriDTNetworkDataset,
            NETWORK_DATASET);
            NetworkDataset networkDataset = new NetworkDataset(dataset);
            //field mapping
            INAClassFieldMap naClassFieldMap = new NAClassFieldMap();
            naClassFieldMap.setMappedField("Name", INPUT_NAME_FIELD);

            // locader setting: load stops by fields
            INAClassLoader2 naLoader = new NAClassLoader();
            naLoader.setFieldMapByRef(naClassFieldMap);
```

```
// Create the Route NALayer
INALayer naLayer = createRouteAnalysisLayer("Route", networkDataset);
INAContext naContext = naLayer.getContext();
 INAClass stopsNAClass = (INAClass)
 naContext.getNAClasses().getItemByName("Stops");
IFeatureClass routesFC = (IFeatureClass)
naContext.getNAClasses().getItemByName("Routes");
// List all the OD pairs in the OD gdb file
// Initialize the Geoprocessor
GeoProcessor geoprocessor = new GeoProcessor();
// Set the workspace to a folder containing personal geodatabases.
geoprocessor.setEnvironmentValue("workspace", OD_WORKSPACE);
IGpEnumList fcs = geoprocessor.listFeatureClasses("", "", "");
String fc= fcs.next();
 while (!"".equals(fc))
{
      // clear existing stops
      stopsNAClass.deleteAllRows();
      // open input feature class
      IFeatureClass inputStopsFClass = ODWorkspace.openFeatureClass(fc);
      // Load the Stops
      naLoader.setLocatorByRef(naContext.getLocator());
      naLoader.setNAClassByRef(stopsNAClass);

      int[] rowsInCursor = { 0 };
      int[] rowsLocated = { 0 };
      ITrackCancel cancelTracker = new CancelTracker();
      FeatureCursor cursor = new
      FeatureCursor(inputStopsFClass.search(new QueryFilter(), false));
      naLoader.load(cursor, cancelTracker, rowsInCursor, rowsLocated);
      // Solve
      INASolver naSolver = naContext.getSolver();
      naSolver.solve(naContext, new GPMessages(), cancelTracker);
      // Save the output
      IFeatureClass pFeatureClass = routesFC;
      IFeatureCursor featureCursor = pFeatureClass.search(null, true);
      IFeature pFeature = featureCursor.nextFeature();
      while (pFeature != null)
      {
            int oid = (int) pFeature.getOID();
            // TODO: edit the ouput result
            String routeNO =
            (String)pFeature.getTable().getRow(oid).getValue(2);
            double time = (double)
            pFeature.getTable().getRow(oid).getValue(6);
            travelCost += time *0.104;
            result.write(routeNO +"    "+ time*0.104 + "\t");
            result.write("\n");

            pFeature= featureCursor.nextFeature();
      } // end of while
      fc = fcs.next();
} // end of while
result.close();
System.out.println("finished calculate TUC");
} // end of try
catch (Exception e)
{
   e.printStackTrace();
}// end of catch
  return travelCost;

}// end the method
```

#####################################CodesEnd##

Appendix E Codes for Optimisation Model

According to the detailed methodology represented in Chapter 6, the optimisation model has been developed under the environment of ArcObjects for Java with following key components:

- Solution representation;
- Generate feasible neighbourhood solutions;
- Evaluate solutions by objective function;
- Search for optimal solutions by Tabu Search algorithm

Detailed methodology for each component will be displayed in this section, as well as corresponding codes.

E.1 Solution Representation

A solution S is modelled as an array table in this optimisation model, where the number of rows equals to the number of routes involved in the S, and each route is characterized by three fields: its unique route code in the candidate route set, route length, and frequency. Therefore, S is defined as

$$S = \{\{NO._{r_1}, L_{r_1}, f_{r_1}\}, \{NO._{r_2}, L_{r_2}, f_{r_2}\}, \{\dots, \dots, \dots\}, \{NO._{r_n}, L_{r_n}, f_{r_n}\}\}$$

Where

$r_1, r_2, \dots, r_n$ = there are *n* routes are involved in this solution;

$NO._{r_k}$= the route NO. of the route *k*, where $1 \le k \le n$;

L_{r_k}= route length of route *k*, where $1 \le k \le n$;

f_{r_k}= frequency of rout *k*, where $1 \le k \le n$.

E.2 Generate Feasible Neighbourhood Solutions

According to the methodology described in Chapter 5, feasible neighbourhood solutions should meet following constraints:

- Half of the bus routes in initial solution need to be replaced by new routes in candidate route set.
- Maximum fleet size constraint: guarantees that the output feasible solutions use no more vehicles than the pre-set maximum number of fleet size.

- Cross-boundary constraint: retains the service levels (measured by services frequencies) to nearby towns and cities at current levels.

Therefore, the proces of generating feasible solutions involves following steps, and corresponding codes are attached at the end of this section:

- Step 1: divide the routes in the input initial solution into two groups: one group for cross-boundary routes, another one for inter-city routes. For example, the Southampton case study was divided into 7 groups, consist of 6 groups of cross-boundary routes (Avene, Bevois Valley, Itchen Bridge, Northam, Shirly, and Western apporach) and 1 inner-city routes group.
- Step 2: randomly delete half of the initial bus routes from each group.
- Step 3: select new routes from the candidate route set to form new feasible solutions.
    - Step 3.1: for each cross-boundary group, new cross-boundary routes are randomly selected from the candidate route set until meets the cross-boundary constraint.
    - Step 3.2: for the group of inner-city routes, new inner-city routes are randomly selected from the candidate route set until meets maximum fleet size constraint.
- Step 4: merge the updated cross-boundary groups and inner-city group together to output the feasible neighbourhood solutions.

###################################CodesStart####################################

```
Methods to generate cross-boundary routes of feasible solutions
private double[][] getCrossBoundaryNeighbors(double MaxFrequency,
double[]frequencyList, double [][] inputInitialSolution,
double[][]inputCandidateRouteSet)
{// the Keep Section
    int keeproutesnumber = Math.round(inputInitialSolution.length/2);
    double [][] KeepSection = RandomSearchbyRouteNO(keeproutesnumber,
    inputInitialSolution);
     // meet the frequency constraint
     //TODO: edit the max. needed frequency
    double needAddFrequency = MaxFrequency - calculateFrequency(KeepSection);
     // the New Add section
     //System.out.println("this is the new add Section");
    double [][] NewAddSection = RandomSearchbyFrequency(needAddFrequency,
    inputCandidateRouteSet, frequencyList);
     // the new out-boundary sub-solution
     double [][] NBSOutput_dirty = append(KeepSection, NewAddSection);
     // combine the dulplicates
     double [][]NBSOutput= removeDuplicates(NBSOutput_dirty);
     return NBSOutput;

     }// end of method

private double[][] RandomSearchbyFrequency(double MaxiFreqency, double[][]
InputArrayTable, double[]frequencyList)
{     // define the output array table and row number
      //TODO: edit the size of output array table
      //fields: routeNO/ route Length/ frequency
      double[][] OutputArrayTable = new double [][3];
      int row =0; // the row number of the OutputArrayTable
```

```
        // define a chooseonce list
        ArrayList<Integer> chooseoncelist = new
        ArrayList<Integer>(InputArrayTable.length); // create a choose once list
        double currentFrequency = 0;
        // randomly choose the initial solution
        while (currentFrequency < MaxiFreqency) // the maxi. fleet size constraint
        {
              double remainFrequency = MaxiFreqency - currentFrequency;
              int index = new Random().nextInt(InputArrayTable.length);
              // each candidate routes only can be selected once
              if (!chooseoncelist.contains(index))
              {
                    int frequencyIndex = new Random().nextInt(frequencyList.length);
                    double randomChooseFrequency = frequencyList[frequencyIndex
                          if (randomChooseFrequency<=remainFrequency)
                          {
                                currentFrequency += randomChooseFrequency;
                                // save the current solution to 2D arraylist
                                OutputArrayTable[row][0] = InputArrayTable[index][0];
                                OutputArrayTable[row][1] = InputArrayTable[index][1];
                                OutputArrayTable[row][2] = randomChooseFrequency;
                                row++;
                                chooseoncelist.add(index);
                          }
                    }
              }
        return clearoutput;
}// end of method
```

Methods to generate inner-city routes of feasible solutions

```
private double[][] getNormalNeighbors (double MaxFleetSize, double []
frequencyList, double [][] crossBoundarySolution, double [][]
inputInitialSolution, double[][] inputCandidateRouteSet)
{
        // the Keep Section
        int keeproutesnumber = Math.round(inputInitialSolution.length/2);
        double [][] KeepSection = RandomSearchbyRouteNO(keeproutesnumber,
        inputInitialSolution);
        // meet the max. fleet size  constraint
        double remainFleetNO = MaxFleetSize -
        calculateFleetSize(crossBoundarySolution) - calculateFleetSize(KeepSection);
        // the New Add section
        double [][] NewAddSection =
        RandomSearchbyFleetSize(remainFleetNO,inputCandidateRouteSet, frequencyList);
        double [][] NBSNormal_dirty = append(KeepSection, NewAddSection);
        // combine the dulplicates
        double [][]NBSNormal= removeDuplicates(NBSNormal_dirty);
        return NBSNormal;
}// end of method

private double[][] RandomSearchbyFleetSize(double MaxiFleetSize, double[][]
InputArrayTable, double[]frequencyList)
{// define the output array table and row number
        //TODO: edit the size of output array table
        double[][] OutputArrayTable = new double [500][3]; //fields: routeNO/ route
Length/ frequency
        int row =0; // the row number of the OutputArrayTable
        // define a chooseonce list
        ArrayList<Integer> chooseoncelist = new
        ArrayList<Integer>(InputArrayTable.length); // create a choose once list
        double currentFleetSize = 0;
        // randomly choose the initial solution
        while (currentFleetSize < MaxiFleetSize) // the maxi. fleet size constraint
        {
              double remainFleetSize = MaxiFleetSize - currentFleetSize;
              int index = new Random().nextInt(InputArrayTable.length);
              // each candidate routes only can be selected once
              if (!chooseoncelist.contains(index))
              {
                    int frequencyIndex = new Random().nextInt(frequencyList.length);
```

```
                double randomChooseFrequency = frequencyList[frequencyIndex];
                double randomChooseFleetSize =
                Math.round(InputArrayTable[index][1]*randomChooseFrequency
                /9293.235);
                if (randomChooseFleetSize<=remainFleetSize)
                {
                      currentFleetSize += randomChooseFleetSize;
                      // save the current solution to 2D arraylist
                      OutputArrayTable[row][0] = InputArrayTable[index][0];
                      OutputArrayTable[row][1] = InputArrayTable[index][1];
                      OutputArrayTable[row][2] = randomChooseFrequency;
                      row++;
                      chooseoncelist.add(index);
                }
          }
     }

     return clearoutput;
}// end of method
```

##################################CodesEnd####################################

E.3 Solution Evaluation

Each feasible solution needs to be evaluated by the objective function (TSC), consists of three components: TOC, TEC and TUC. Once the proposed solution network is generated, the associated candidate bus routes and related frequencies are determined, allowing the TOC and TEC to be calculated based on vehicle mileage. The TUC for the solution network are calculated by summing the travel cost for each OD pair, weighted based on the destination types served by each route. Because of complex real-world size solution network and large size of potential OD pairs, calculation of TUC is a vital component in the solution evaluation procedure, and costs majority of the calculation time. Using the ArcObjects for Java, the whole calculation process could run automatically, and the calculation speed will improve a lot compared with other available software packages. The codes of modelling travel costs calculation has been developed for the accessibility model (see Appendix D), and can be directly adopted here for solution evaluation.

E.4 Tabu Search Algorithm

According to the methodology described in section 6.4.4, the Tabu Search algorithm was applied in searching optimal solutions, and codes below were developed under the environment of ArcObjects for Java.

##################################CodesStart####################################

```
Method for Tabu Search
public TabuSearch(Solution initialSolution)
{
     Solution bestSolution = initialSolution;
     Solution currentSolution = initialSolution;

     Integer currentIteration = 0;
     while (!stopCondition.mustStop(++currentIteration, bestSolution))
     {
```

```
            List<Solution> candidateNeighbors = currentSolution.getNeighbors();
            List<Solution> solutionsInTabu =
            IteratorUtils.toList(tabuList.iterator());
            Solution bestNeighborFound =
            solutionLocator.findBestNeighbor(candidateNeighbors, solutionsInTabu);

            if (bestNeighborFound.getValue() < bestSolution.getValue())
            {
                  bestSolution = bestNeighborFound;
            }

            tabuList.add(currentSolution);
            currentSolution = bestNeighborFound;
            tabuList.updateSize(currentIteration, bestSolution);
      }

      return bestSolution;
}
```

Method for Tabu List

```
public final class TabuList implements TabuList
{
      private CircularFifoQueue<Solution> tabuList;

      public StaticTabuList(Integer size) {
            this.tabuList = new CircularFifoQueue<Solution>(size);
      }
      @Override
      public void add(Solution solution) {
            tabuList.add(solution);
      }
      @Override
      public Boolean contains(Solution solution) {
            return tabuList.contains(solution);
      }
      @Override
      public Iterator<Solution> iterator() {
            return tabuList.iterator();
      }

}
```

Method for Stop Condition (= maximum number of iterations)

```
public class IterationsStopCondition implements StopCondition
{
      private final Integer maxIterations;
      public IterationsStopCondition(Integer maxIterations)
      {
            this.maxIterations = maxIterations;
      }
      /**
       * Check if the current iteration is gte than the given
       */
      @Override
      public Boolean mustStop(Integer currentIteration, Solution bestSolutionFound)
      {
            return currentIteration >= maxIterations;
      }
}
```

####################################CodesEnd#######################################

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