BI-OBJECTIVE OPTIMIZATION OF EXCLUSIVE BUS LANE ALLOCATION AND SCHEDULING PROBLEM IN CITIES

By

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ABSTRACT

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Providing exclusive bus lanes in cities is one of the strategies to improve the performance of bus transit system. Nevertheless, proper planning of the implementation is necessary as reserving lanes on the urban transport network would reduce the roadway capacity for non-bus traffic which could exacerbate traffic congestion. This study proposed a systematic methodology to determine the exclusive bus lane allocation and scheduling for its implementation in cities. The exclusive bus lane allocation intends to find the candidate roads (links) that should have a lane reserved for buses while the scheduling intends to find the time period for the implementation. The problem is formulated as a bi-level programming model in which the upper level is a bi-objective optimization model subjected to practical constraints. The lower level is a microscopic traffic simulation model that could simulate drivers' response to the implementation as well as the bus transit system. The proposed formulation is solved with the hybrid non-sorting genetic algorithm with Paramics. An illustrative case study of Klang Valley, Malaysia is taken as the example to test the applicability of the proposed methodology. Results show that the proposed methodology is feasible to produce the best exclusive bus lane allocations and schedules. Pareto solutions are obtained which indicate that the objectives to minimize the average travel time for buses and non-bus traffic is contradicted. The acceptable solutions would thus base on the trade-off level preferred by the decision makers. The sensitivity analysis results indicate that the solutions are sensitive to the setting of the parameters, such as the minimum buses' frequency to qualify the implementation, the minimum duration of implementation, the demand level of the network, and the continuity constraint. The proposed methodology is useful for engineers to understand the impact of exclusive bus lane implementation to buses and non-bus traffic besides deciding the best policy for the exclusive bus lane allocation and schedules.

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APPROVAL SHEET

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It is hereby certified that **HO YUN LI** (ID No: **09UEB09141**) has completed this thesis entitled "BI-OBJECTIVE OPTIMIZATION OF EXCLUSIVE BUS LANE ALLOCATION AND SCHEDULING PROBLEM IN CITIES" under the supervision of Dr. KHOO HOOI LING (Supervisor) from the Department of Civil Engineering, Faculty of Engineering Science.

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DECLARATION

I hereby declare that the thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UTAR or other institutions.

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CHAPTER 1

INTRODUCTION

1.1 Background

The public transport system fulfils the basic needs of travel for the society. Those who cannot afford or choose not to own a private vehicle are relying on the public transport system to travel. There are various modes of public transport system, namely buses, rails, light rails, trams, trains, taxis and monorails systems. Each of these types has its own features and is built to serve different purpose of travel. Table 1.1 shows their features and purpose built.

The bus transit system is the oldest mode of public transport system. Its history can be traced far back to 1662 when the first omnibus system was put into operation in Paris, France (Vuchic 2007). The advantage of bus transit system compared to other system is that it requires minimum facilities to be constructed. Bus stops or bus stands are built at the roadside to provide accessibility to the services. Buses are plying on the road network to pick up and drop off passengers. It is thus flexible as the bus stops and services could be re-scheduled at any time based on the passengers' demand. Nevertheless, since the private vehicles have become more affordable and popular, the ridership of buses deteriorates. Some of the common negative perceptions of bus service by the public are low speed, long travel time, unreliable service,

Table 1.1: Various Public Transport Modes: Features and Purpose Built
(Source: Vuchic 2007)

Types	Features	Purpose
Regular bus	• Street (C) • Rubber tires • Manual • Medium-sized vehicle (30-100 spaces) or Large vehicles (>100 spaces)	• operating along fixed lines on fixed schedules • operate on all streets, arterials, and freeways • provide services covering a wide range of Level of Service, performance, costs, and impacts • represent the entire transit network or supplementary and feeder services to rail network
Light rail transit	• Medium-sized Vehicle (30-100 spaces) or Large vehicles (>100 spaces) • Manual or Semiautomatic • Part Control (B) • Electric • Steel wheels • Short trains (1-3 cars)	• advantages of guided technology: high capacity, high labor productivity (train operation), comfortable ride, distinct image, permanence • lower noise, absence of exhaust fumes, and a better safety record make LRT more compatible with pedestrian environments than buses
Train	• Full Control (A) • Steel Wheels • Manual • Large vehicle (>2000 spaces)	• Spacious vehicles with several doors on each side board passengers from high-level platforms without fare collection delays
Monorail	• Large vehicles (>100 spaces) • Electric • Rubber tires • Semiautomatic • Full control (A) • Long Trains (>3 trains)	• Rapid transit systems with a fundamentally different technology of vehicle and guideway • Operated as single regular transit lines in about a dozen cities

and less comfort. Accordingly, there is a need to improve the bus transit system in order to increase its popularity and ridership. This is simply because buses have a larger carrying capacity (if compared to the private vehicles) which can move people more effectively especially in the city centers that are usually congested. In addition, the bus transit system is a sustainable solution to the traffic congestion.

The Bus Rapid Transit (BRT) is one of the countermeasure strategies proposed to improve bus services. It is an integrated bus-based rapid transit system that utilises the advanced technologies to increase service reliability and reduce delay. One of the features of BRT is the provision of exclusive bus lane to segregate bus from the non-bus traffic. Such segregation could ensure that buses are not interrupted by the traffic condition in order to achieve a better schedule adherence and service reliability. The concept of exclusive bus lane has been used in various countries across the world. Table 1.2 shows the length of bus lanes in several cities.

Table 1.2: Bus Lane Length (LPTC 2011)

City	Bus Lane (km)
Sydney	90
Santiago	200
London	240
Singapore	155
Seoul	282
Madrid	50
Bogota	84
Hong Kong	22
Kuala Lumpur	14

Exclusive bus lane is a strategy that reserves a lane (either at the median or at the curb side) of the roadway for buses. No other vehicles are allowed to use the lane. These exclusive lanes could either be used for the whole day or only during peak periods. Usually, there will be road marking (for example, thick yellow line in Malaysia) to indicate it's a bus lane. In the case of curbside bus lane, roadside parking is not permitted when the lane is in used. Most bus lanes in Malaysia are of this type. Another type of bus lane is priority bus lane. Priority bus lane allows other vehicles to use the bus lane when it is not in use. The private vehicles does not need to leave the lane in order to accommodate the buses, but it restricts them from changing into the bus lane when there are buses traveling on the lanes (Eichler 2005). Different from the priority the bus lane, the intermittent bus lane (Zhu 2010) or the dynamic bus lane (Yang and Wang 2009) clears the private vehicles out of the bus lane when buses are approaching besides restricting traffic to enter the lanes. In the implementation of the intermittent bus lane, the status of a given section changes according to the presence or not of a bus in its spatial domain: when a bus is approaching the said section, the status of that lane is changed to bus lane, and after the bus moves out of the section, it becomes a normal lane again and is again open to traffic (Zhu 2010). Accordingly, various intelligent transport system, such as sensors technologies are required to detect the presence of buses. Variable message signs are required to disseminate advices to drivers (whether they are allowed to use the bus lane). It is found that the intermittent bus lane performs better with relative lower bus arrival frequency (Yang and Wang 2009). It is more efficient in improving the bus flow while maintaining the car flow at a higher level than the exclusive bus lane (Zhu 2010).

There are various advantages of applying the exclusive bus lane. One of the advantages is the increase of bus travel speed (Wei and Chong 2002; Shalaby 1999). Wei and Chong (2002) found that bus speed increases by 68% (from 9.6 km/hr to 15.2 km/hr) when bus lane is applied in Kunming, China. Besides, it is found that the bus travel time is reduced when the bus lane is used on site (Sakamoto et al., 2007; Patankar et al., 2007). In addition, it serves as a pull factor to increase the bus ridership (Shalaby 1999; Patankar et al., 2007). The mode shift from private vehicles to buses occur when bus lanes are implemented (Choi and Choi 1995; Sakamoto et al., 2007; Shalaby 1999).

1.1.1 Bus Transit Issues in Malaysia

The current bus services in Malaysia received a lot of complaints from the public. Some common weaknesses of the services include poor service reliability and delivery, lack of integrated and comprehensive bus planning, unpublished time tables, uncoordinated services and distinct lack of enforcement of operating rules (LPTC 2011). Currently, due to the low level of bus lane adoption in the region, buses are running in the mixed traffic condition. Accordingly, the bus services are seriously affected by the congestion in the region. Compared to private vehicles, buses are taking at least twice longer to take the passengers to the destination. This causes the buses to have poor service reliability and to adhere to schedules. Besides, competition between operators has caused the imbalance of routes density across the region. Most of the operators are focusing their resources on key corridors and the time of the day when demand is high. This has seriously affected the service quality of buses especially in the rural areas. Due to these weaknesses, buses are less popular in the region. Report shows that the mode split of public transport has fallen from 34% in the 1980's to 12% in 2008 (LPTC 2011).

It is thus urgent to look for strategies to improve the public transport, specifically the bus ridership, by mitigating the weaknesses of the system. The Land Public Transport Commission (SPAD) has recently announced the Land Public Transport Master Plan which aims to improve the public transport system for a higher public transport mode share (LPTC 2011). One of the key strategies highlighted was to increase the length of exclusive bus lane to provide priority travel for buses for better travel speed and schedule adherence (LPTC 2011). Along with other strategies, such as increasing the coverage and quality of bus stops, enforcing traffic and operator service standards, improving and reorganising the bus network, and establishing a single and better integrated ticketing platform across all operators, and improving station integration facilities for intra-modal and inter-modal transfers, it is anticipated that the bus ridership could be improved in the near future.

1.2 Challenges of Exclusive Bus Lane Implementation

Despite the advantages of implementing exclusive bus lane on the network, there are various issues relating to such implementation. By reserving a lane on the roadway, the implementation of exclusive bus lane reduces the effective capacity for non-bus traffic. In an already congested city area, the reduction of road capacity would further deteriorate the traffic congestion. In

Malaysia for example, there were many reported public complaints that exclusive bus lanes were under-utilised and were a waste of resources (Choong 2010; Yow 2011; Transit 2012). Some claimed that exclusive bus lanes had worsened the traffic congestion in the cities.

Researches were carried out which verified the public claims. Karim (2003) recorded that the travel time for the non-bus traffic on the road increases with the exclusive bus lane. Shalaby et al. (1999) showed that if the exclusive bus lane is not planned properly, it might cause negative impact on the bus performance. In addition, Shalaby and Soberman (1994) found that the effectiveness of the exclusive bus lane is low during off-peak period or whenever the traffic is low.

Accordingly, proper and careful planning is necessary to ensure the effectiveness of exclusive bus lanes. Some previous research tried to design the sets of criteria to justify the implementation of exclusive bus lanes. For example, Seo et al. (2005) suggested that exclusive bus lanes should only be implemented if roads have more than 5 bus services operating on them. Gan et al. (2002) recommended that the exclusive bus lanes are to be implemented only if it can reduce the total person travel time. Nevertheless, the studies carried out did not investigate the operational issues of the exclusive bus lane. It is thus important and necessary to carry out a study to find the optimal exclusive bus lane allocation and scheduling of its implementation. This is crucial to maximise the effectiveness of exclusive bus lanes and to minimise the negative impacts on the overall transportation network.

1.3 Study Objectives

The objectives of the study are as follows:

- To propose and develop a bi-level programming model as the methodology to determine the best link allocation and hour for the implementation of the exclusive bus lanes in the cities
- To develop a feasible solution algorithm to the proposed model
- To test and evaluate the proposed methodology and solution algorithm on a practical network by microscopic traffic simulation

1.4 Scope of Study

This study deals with the optimisation of the exclusive bus lane operation in the cities. Microscopic traffic simulation models are adopted to properly simulate the bus lane implementation on the network. The advantages of adopting microscopic traffic simulation are such as it could capture well the features of the bus transit system. Paramics is chosen as the simulation tool as it provides the Application Programming Interface functions that allow users to control the simulation model. The study area chosen is the Klang Valley region, Malaysia, which is a typical city that has various possible roads for bus lane implementation. It is thus suitable as a case study in this research.

1.5 Organisation of Thesis

Chapter 1 provides a general introduction to the exclusive bus lanes and bus transit system in the major cities in Malaysia. The importance and the need for current study are discussed. In addition, the objectives and the scope of the study are highlighted as well.

Chapter 2 is divided into 6 sections providing the necessary background of the proposed methodologies and solution algorithms adopted in the research study. First, a review on the bi-level programming model approach is presented. Then, a brief review on the evolutionary algorithms used to solve the multi-objective optimisation models is provided. Third, a review about traffic simulation models is presented. Forth, the past studies about the methodologies adopted to determine and evaluate the effectiveness of the exclusive bus lane allocation and scheduling are reviewed. Lastly, the limitations of the past studies are highlighted to support the needs for this research study.

Chapter 3 presents the proposed methodology for an optimal bus lane allocation and schedule. The bi-level programming model approach is adopted to formulate and find the best lane allocation and schedule for exclusive bus lane in the cities. The average travel time for buses and non-bus traffic is defined as the objectives of the optimisation model. The microscopic traffic simulation model, Paramics, is adopted to simulate the general traffic as well as the bus transit system. The solution algorithm is presented to solve the proposed optimisation model.

Chapter 4 illustrates the development of the traffic simulation model using Paramics. The simulation of non-bus traffic as well as the bus transit system is elaborated in detail. In addition, the collection of field data for model calibration is highlighted.

Chapter 5 shows an illustrative case study of the Klang Valley region, Malaysia. The simulation of the bus transit system and the exclusive bus lane are explained in detail in this chapter. Besides, the proposed methodology is tested and evaluated by the case study. Various scenarios are created to test the sensitivity of the parameters on the results obtained. Results are presented in the chapter together with the discussions.

Chapter 6 summarises the main findings drawn from the current study and highlights their contribution to the state-of-the-art. It also provides directions and recommendations for future research.

CHAPTER 2

LITERATURE REVIEW

This chapter reviews the previous studies which are related to the research study. It is divided into 6 sections. First, a review on the bi-level programming model is presented. The model is explained and some examples of its application in the transportation field are presented. Then, the evolutionary algorithms which are used to solve the multi-objective optimisation problems are highlighted. Justifications on why the genetic algorithms are adopted in this study are made. Third, the various types of simulation models are explained in detail. Forth, the previous studies on the methodologies adopted to determine and evaluate the exclusive bus lane allocation and scheduling are reviewed. Lastly, the limitations of the current studies are highlighted to justify the needs for this research study.

2.1 The Bi-level Programming Model Approach

The bi-level programming model is a mathematical programme that contains an optimisation problem in the constraints (Bracken and McGill 1973). It is originated from the Stackelberg Game Theory when there are situations where conflicting players are taking actions according to pre-defined sequence of play. The players who move first are called the Leader while the players who react to the leader’s decision is called the Follower. Both players tend to optimise (minimise) their own objective functions, but the actions of the

Leader will affect the choices and payoffs available to the Follower. Hence, the Follower has to observe the Leader's action and moves in a way that is personally optimal.

Many decision-making problems for the transportation system planning and management can be formulated as the Stackelberg games. Usually, the supplier of the transportation services, such as the authority, bus operator, or highway concession company is the leader while the road users or passengers are the users (Fisk 1984a). The upper level problem represents the decision making behaviour of the supplier, who wishes to determine an optimal operation plan, rates, and controls taking in users' response while the lower level problem represents the travel behaviour of the user, who makes his or her travel choice in a user optimal manner responding to these plans, rates and controls (Yin 2000a).

The earliest work which a adopted the bi-level programming model in formulating the decision making problems in transport area is by LeBlanc (1973) on network design problem. The study aimed to determine the capacity improvement of a road network, considering the investment cost and congestion reduction. The lower level of the problem is a user equilibrium condition in which the individual users' travel time is minimised. Other studies in this topic include Marcotte (1986), Leblanc and Boyce (1986), and Yang and Bell (1998).

The bi-level programming model is also adopted to find the optimal congestion pricing, such as Yang and Lam (1996), Hearn and Ramana (1998), and Larsson and Patriksson (1998). In general, the upper level of this type of model is to maximise the total revenue while the lower level is the road toll pattern. Besides, some studies adopted the bi-level programming model to estimate the origin-destination matrix, such as Florian and Chen (1995), and Meng et al. (2004). The objective is to find a demand matrix that matches the induced equilibrium flow. The upper level is thus the demand pattern while the lower level is the traffic assignment problem with user equilibrium flow.

The bi-level programming model is also used in formulating the traffic control and management problem. Meng et al. (2008) formulated the contra-flow lane configuration problem as a bi-level programming model to determine the optimum lane configuration in the cities in order to reduce the total travel time spent by drivers in the study area. The lower level is a microscopic traffic simulation model that is adopted to simulate drivers' response in avoiding traffic congestion. Meng and Khoo (2008) took the same methodology to formulate the contraflow lane scheduling problem.

Yang and Yagar (1994) considered the optimisation of ramp metering in a freeway-surface street network system. The upper level of the problem is to determine the ramp metering rates that optimise the system total travel time. The lower level problem represents a traffic equilibrium model involving explicit ramp queuing which predicts how drivers react to the given on-ramp control pattern.

Besides, Yang and Yagar (1995) developed a bi-level programming model to optimise the traffic signal timings in the saturated road networks. The upper level problem is to determine the signal splits to optimise the system objective function, taking into account of the drivers' route choice behaviour in response to the signal split changes. The lower level problem represents the network equilibrium model involving queuing explicitly on saturated links, which predicts how drivers will react to the given signal control pattern. Other studies adopting the bi-level programming model for traffic signal optimisation include Chiou (1999) and Fisk (1984b).

Some other transport (private vehicle) related studies that adopted the bi-level programming model are Meng et al. (2000) for the land-use and transportation problems; Tam and Lam (2000) for car ownership problem; Zhang (1994) for calibrating parameters in the combined models of urban travel choices; Leurent (1998) for the bi-criterion traffic equilibrium problem; and Feng and Wen (2005) for allocating vehicle flow during emergency. More detailed and comprehensive survey studies about the usage of bi-level programming model in transport area could be found from Migdalas (1995).

Recently, there is an increasing number of studies in public transit that adopted the bi-level programming model to formulate the transit network design and operational problems. Zha and Wang (2010) formulated the public transit network design problem using the bi-level programming model. The aim of the model is to minimise the investment cost while taking into consideration the passengers' route choice behaviour. Zhao et al. (2012) formulated the capacity of bus transit network, in which the upper level is the maximum flow problem with the level of service, passenger demand pattern, line and stop capacity constraints. The lower level model is a passenger route choice model. dell'Olio et al. (2006) proposed a bi-level programming model to optimise the location of bus stops and bus frequencies in the congested local public transport networks. The upper level aimed to minimise the overall cost of the system (i.e. the cost of service provision and bus stop construction), while the lower level is a transit equilibrium model.

Mesbah et al. (2008) proposed a new methodology for optimising the transit road space priority at the network level. The aim of the proposed approach is to find the optimum combination of exclusive lanes in an existing operational transport network. Mode share is assumed variables and an assignment is performed for both private and transit traffic. The network road space allocation problem is formulated using bi-level programming model. The sum of travel time for all users is included in the upper level. With the introduction of an exclusive bus lane, a mode shift is expected and consequently a reassignment would require to be carried out for the network. Therefore, a model split between transit and passenger cars as well as an assignment model is formulated in this study at the lower level. In other words, the objective function at the upper level is subject to constraints of the modal split and the assignment results.

Chen et al. (2008) formulated the bi-level programming model to optimise the urban rail transit network layout. The upper level is a multi-objective function which is aimed to minimise the total travel time, total length of transit line, and total transfer time. The lower level is a capacity-constrained traffic assignment model that describes passenger flow assignment on the rail transit network. Samantha and Jha (2006) optimise the locations of stations along the rail transit lines. At the upper level, the number and location of the intermediate stations are determined by minimising the sum of user, operator, and location costs. At the lower level, the potential ridership generated from the major cities is estimated by dividing the study area in an optimum number of zones, in order to maximise the usage by potential riders.

Other transit related studies that adopted bi-level programming model in the formulation are the optimisation of the headway of public transit line (Zhang and Li, 2010); optimisation of dynamic transit schedule planning problem (Ren and Gao 2006); the effect of public transit information system on passengers' route choice (Liu 2006); and optimisation of transit fare (Zhou and Lam 2001).

It could be seen that most of the studies mentioned above formulated the problem (the upper level) as a single-objective optimisation model. However, Yin (2000b) stressed that many of the decision making problems of transport planning and management are naturally multiple objectives because the supplier, or the regulating agency always has several aims and social concerns. As such, the upper level could be formulated as a multi-objective optimisation problem, for example, Samantha and Jha (2006), and Chen et al. (2008). Some of the transport related studies involving multi-objective optimisation (not necessary bi-level programming models) are: Chang et al. (2000), Flynn and Ratick (1988), Mauttone and Urquhart (2009), Tilahun and Ong (2012), and Wang et al. (2009). Such models might be difficult to be adopted in practice as some of them might not be able to solve using the theoretical approach. Fortunately, the near optimal solutions could be found using the heuristics algorithms.

The nature of the exclusive bus lane allocation and scheduling problem follow the Stackelberg Game in which the upper level is the authority who determine the best allocation and schedules, while the lower level is the users who will respond by choosing the shortest routes to avoid congestion. Accordingly, the bi-level programming model could be adopted in this study.

In addition, there are at least 2 objectives that the authority needs to consider, i.e. the travel time of buses and non-bus traffic, because there are two types of users on the network. As such, a bi-objective bi-level programming model is feasible to model the problem.

2.2 The Evolutionary Algorithms

The evolutionary algorithm stands for a class of stochastic optimisation methods that simulate the process of natural evolution. Many evolutionary methodologies have been proposed in the literature, mainly genetic algorithms (GA), evolutionary programming, and evolution strategies (Back et al., 1997). The methodology operates on a set of candidate solutions and involves two important principles, namely selection and variation (Zitler et al., 2003). Selection is a procedure that mimics the competition for reproduction and resources among living beings, while the variation imitates the natural capability of creating new living beings by means of a recombination and mutation (Zitler et al., 2003).

The evolutionary algorithms are most appropriate for solving multi-objective optimisation problems because they can provide many Pareto optimal solutions in parallel via a population of solution in a single run. Besides, their capability to perform a search in the large and complex search spaces has made them feasible to solve the multi-objective optimisation problems (Elaoud et al., 2007). The first multi-objective genetic algorithm was proposed by Schaffer (1985). Subsequently, more than thirteen multiobjective GAs have been developed (Coello 2002), including the niched Pareto genetic algorithm

(NPGA) (Horn et al., 1994), the random weight-based genetic algorithm (RWGA) (Murata and Ishibuchi 2005), the non-dominated sorting genetic algorithm (NSGA) (Srinivas and Deb 1995) and the fast non-dominated sorting genetic algorithm (NSGA-II) (Deb et al., 2002). Generally, these multi-objective GAs differ based on their fitness assignment procedures, elitism choice strategies and population diversity mechanisms.

The non-dominated sorting genetic algorithms-II (NSGA-II) was developed by Deb et al. (2002), which is an improved version of the NSGA (Srinivanas and Deb 1995). The main features of the NSGA-II are fast nondominated sorting approach and diversity mechanism. Compare to other algorithms, NSGA-II has the following advantages: (1) computational efficient with $O\left(MN^2\right)$ computational complexity, (2) incorporated with the elitism mechanism to preserve good solutions, and (3) diversity mechanism is based on density estimation which is guided by the crowded-comparison operators.

Many of the transport problems formulated as the bi-level programming models have adopted the evolutionary algorithms as the solution algorithm. As highlighted by Yin (2000a), the bi-level programming models are difficult to solve because the evaluation of the upper level objective function requires the solution of the lower level optimisation problem. In addition, the lower level is a nonconvex programming problem which causes the global optimum difficult to find. Accordingly, the evolutionary algorithms could be adopted to find the near-optimal solutions by iteratively enumerate all the possible solutions and at the end choose the best solutions. Examples of the studies which adopted the evolutionary algorithms as the solution algorithms are Meng et al. (2008), Meng and Khoo (2008), Zha and Wang (2010), Zhao et al. (2012), Samatha and Jha (2006), and Zhang and Li (2010).

2.3 Traffic Simulation Models: Tools for Evaluation

Traffic simulation is the process of designing a computer model to represent the real system. The purposes of simulation are to predict the system behaviour under various conditions, such as to ask “what-if” questions to facilitate decision making, to evaluate transportation plans before they are built, and to test new scenarios or strategies. Traffic simulation models are important when the mathematical models are inappropriate to represent the system which is too complex. Besides, it is also applicable when the graphical or animated output is desirable. The following sub-section will illustrate the types of simulation models and the important issues in simulation.

2.3.1 Types of Simulation Models

There are many types of classification for traffic simulation models. It can be categorised according to the facilities modelled such as intersections, arterials, urban networks, freeways, and freeway corridor. It can also be classified according to the dynamic modelling system which is either continuous or discrete. The classification method adopted in this proposal is according to the level of detail in which it represents the system, namely macro-scopic, micro-scopic and meso-scopic. The description of the nature of these models will be supplemented with the elaboration of two commercial software models developed for this purpose.

Macro-scopic simulation models assume that the aggregate behaviour of drivers depends on the traffic conditions in the drivers' direct environment. Traffic is modelled analog to fluids or gases in which its behaviour is governed by sets of differential equations. Continuum models such as Lighthill-Whitham-Richards (LWR) model (1955) and Payne model (1971) are employed to derive the evolution of traffic condition i.e. speed, density and flow over time and space. No individual vehicle or individual driver behaviour is modelled in detail.

METACOR (Elloumi et al, 1994) simulates and describes the propagation of vehicle flow in the freeway corridor (freeway and the parallel streets). It can model multi-origin, multi-destination freeway networks with arbitrary topology and geometric characteristics. The road is divided into cells, for which at discrete interval time the flow, speed and density are calculated based on flow conservation equation and a dynamic speed-density relationship. It is appropriate to model large road networks since the interactions of the entities in the system can be modelled explicitly.

Another macro-scopic simulation model, TRANSYT (TRAffic Network StudY Tool) is used for modelling urban street network. It is a deterministic, single-time period simulation model that incorporates with the optimisation model used to obtain optimal signal timing. It is designed to model traffic behaviour and produce fixed-time signal plans that minimise vehicle delay and stops the urban network of coordinated traffic signals. Signal offsets and the allocation of green times can be optimised by taking into consideration different classes of vehicle modelled and bus priority.

Different from macro-scopic simulation model, the micro-scopic simulation model describes traffic at the level of individual vehicles and their interaction with each other and the road infrastructure. This behaviour is captured by a set of rules which determine when a vehicle accelerates, change lane, and choosing the route. The car following models enable drivers in the model to determine the accelerating and breaking patterns that result from the lead vehicle. Lane changing model govern the driver's decision to perform the mandatory change to avoid obstacle or discretionary lane change to achieve his desired speed while gap acceptance model determine whether the lane change is executable or not. Furthermore, traffic control and management devices can be simulated in detail. Traffic signal, variable message signs, ramp metering and the detectors can be emulated. Because of these features, the micro-scopic model has emerged as an important tool to simulate and model various ITS strategies in traffic management (Boxill and Yu 2000).

To simulate the traffic assignment using the micro-scopic simulation model, the traffic demand needs to be modelled. Generally speaking, the demand can be represented in two ways. One is by specifying the OD matrix from the origin zone to the destination zone while another method is through specifying the turning percentages of traffic at each intersection. The time varying demand is more suitable to be modelled using the former method in which different OD matrix can be modelled independently for each time period. Most of the simulation software is able to do the dynamic traffic assignment, except several models such as FLEXSY (Middelham et al., 1994), FRESIM (Jacobson 1992) and others. Nevertheless, the assignment approach adopted is different for different simulation packages.

VISSIM is the leading micro-scopic simulation programme for multi-modal traffic flow modelling. It is developed by PTV in Germany back in 1992. It could model various transport modes such as urban and highway traffic, including vehicle (cars, buses, trucks), public transport (trams, buses), cyclists, pedestrians and rickshaws with a high level of details. The vehicle behaviour model is based on the Wiedemann car-following model. It assumes that a driver can be in one of the four driving modes, i.e. free driving, approaching, following and braking. For each mode, the acceleration is described as a result of speed, speed difference, distance and the individual characteristics of driver and vehicle.

MITSIM (Qi 1997) can perform dynamic traffic assignment. Vehicles in MITSIM choose paths according to the route choice models. Each OD pair or individual vehicle can be assigned a set of predetermined paths. Paths can be pre-defined or generated on-line. When vehicles enter the network, they choose a path from their choice set based on the probabilities given by the route choice models. The data used in making route choice decisions include vehicle type (guided and unguided vehicles may use different travel information), time-dependent link or path travel times, types of the paths, regulation of intersection turning movements, and so on. By default, a logic based route choice model is used, but can be easily customised to other user defined route choice models.

The meso-scopic model falls between micro-scopic and macro-scopic model. It describes traffic characteristics at a high level of detail but their behaviour and interactions are described at a lower level of detail. It models individual vehicles or platoon of vehicles but does not model the interaction between them. There is no car following model to describe how the vehicles follow their lead vehicle. Instead, it employs headway distribution model to describe the headway between individual of vehicles. The vehicles can be modelled as individual vehicles or as a cluster of vehicles. The size of a cluster (the number of vehicle in a cluster) and the velocity of a cluster are of dominant importance. The size of the cluster is dynamic in which it can grow or decay according to the traffic condition. The individual driver's behaviour within a cluster is not modelled. Hence, the cluster is homogenous in this sense.

The velocity of the vehicles in the model is modelled using the gas-kinetic continuum model, which is macro-scopical. The speed of the vehicles is defined by the speed-density relationship of the link. If the link has a higher density, a lower speed will be assigned for the vehicles. Lane changing of the vehicles is not modelled. At nodes, the 'additional delay' for packets is calculated based on signal timing plans, average give way delays and others. The capacities at the node servers follow from the saturation flows and their variance is calculated. Signal controlled intersection can be modelled by replacing the queue servers with gates that open and close according to the signal timing.

Most of the simulation-based DTA use the meso-scopic model. DYNASMART (Jayakrishnan et al., 1994) is capable to solve the optimal system and user equilibrium solutions for OD demand with fixed departure times using iterative algorithm. It calculates optimal travel path based on the simulated travel times and simulates the movements and routing decisions by individual drivers equipped with in-vehicle information system. The model assumes that a complete priori knowledge of OD demands is known. Because of this capability, DYNASMART is widely adopted for the evaluation of the Advanced Traveller Information System (ATIS) strategy.

Another well-known meso-scopic model that can perform the dynamic traffic assignment is DynaMIT (Ben-Akiva 1996). It is developed to estimate and predict real time current and future traffic conditions. It consists of a demand and a supply simulator that interacts to generate user equilibrium route guidance under the rolling horizon framework. The demand simulator simulates the time-varying OD demand flows and dis-aggregates route choice. It models in detail the time dependent OD demand flows, route and departure time choices, as well as the en-route changes of route choices in response to information. The supply simulator simulates the movements of the vehicles over the network. The vehicles are grouped into cells which move over the links with a speed determined by current density on the link. The model reproduces queue-forming, dissipation and propagation over links and nodes on a lane-by-lane basis, which enable the lane blockage due to incident being simulated. A wide range of traffic controls such as traffic signals, Variable Message Signs (VMS), ramp metering and incidents and user responses can be emulated.

2.3.2 Paramics

PARAMICS (PARAllel MICroscopic Simulation) (Quadstone Pte Ltd 2008) incorporates an intelligent route choice model. It allows the specification of the origin-destination (OD) matrix and the OD profile to simulate the time dependent traffic demand. The driver-vehicle unit (DVU) in the model is divided into two categories: familiar and unfamiliar drivers. When the DVU is released from its origin zone, it is routed through the network based on the computation of the general cost function at every decision node. Hence, each DVU does not have a set of pre-determined complete set of route associated with it when it is released. The next turning/ route choice is determined by two links before the DVU arrive at the decision node. PARAMICS is able to simulate static, stochastic and dynamic route choice. For the static assignment, the free flow travel time of the link is used in the calculation of the general cost function. To perform the stochastic assignment, some percentage of random noise is introduced to the model. If the dynamic feedback tab is toggled, the dynamic assignment can be performed. However, only familiar drivers will be influenced in which at every interval time specified, the route tree of the familiar driver will be updated based on the average link travel time.

PARAMICS is not a black-box model where users simply employ it to carry out analysis. It provides additional functions that allow users to interact with the core models of PARAMICS. The functionality of the model could be enhanced by Application Programming Interface (API). Extra commands can be set into PARAMICS to extend the existing functions provided by the model. This is done through Dynamic Link Library (DLL) created using C-programming. There are four types of functions available for the users, namely getting functions, extending functions, override functions and setting functions. Getting functions allow users to collect information from PARAMICS, for example, the simulation time; extending functions allow users to extend the function of the model. For example, after the simulation starts, users can extend its function by asking PARAMICS to read some file. Override functions allow users to override the original setting or logic of the model. For example, users can embed their own car following the model in PARAMICS. For setting functions, users can set value to the parameters in the model. For instance, driver reaction time can be set. This has offered great flexibility for the users to do research using the tool. Due to its additional features, PARAMICS is adopted as the traffic simulation tool in this study.

2.3.3 Important Features: Calibration, Verification, Validation

Traffic simulation models are like a black box to the users if the users do not understand the underlying concept behind the model. This is due to the complex nature of the traffic simulation models and the derivation of the associate mathematical properties is impossible. Calibration, verification and validation are very important steps in any traffic simulation models in order to ensure that the system is represented correctly and the outcome from the models are reliable.

Hellinga (1996) had defined the terminology of calibration, verification and validation. Model calibration is defined as the process by which the model user establishes input parameter values in order to reflect the local traffic conditions being modelled while model validation is defined to be the process of determining if the model logic proposed by the model developer is correctly represented by the computer code. Verification simply ascertains that the outputs from the computer code are consistent with the model logic. Model validation is defined to be the process of determining to what extent the model underlying theory and logic reflects reality. We as the users of the simulation model play a crucial role in the calibration and validation process. We need to perform these two steps to ensure the reliability and credibility of our models.

Although traffic simulation models have emerged as an important tool in traffic control and management area nowadays, the issue of calibration and validation still tangle the researchers. To date, there are no manual or special guidelines that can be adopted by the researcher when dealing with these issues. There are many on-going procedure proposed by the researchers regarding this issue. Nevertheless, most of the calibration and validation effort is concentrated on the micro-scopic model. This is simply because the micro-scopic simulation model is more complex and it is widely used in the modelling especially in research pertaining to the Intelligent Transportation System (ITS) management.

Many types of methodology are proposed in literature. Many of the researches proposed the systematic step-based and flow chart-based procedure in the calibration and validation process. Hourdakis et al. (2003) proposed a general and complete three step calibration procedure i.e. volume-based, speed-based and objective based calibration. Richard et al. (2003) also proposed a three step procedure which consisted of capacity and network calibration as the first step, route choice as second and system performance as the third step. Chu et al. (2006) proposed a four step systematic procedure i.e. driving behaviour (network), route choice, OD estimation calibration and model fine tuning.

The optimisation technique has also being employed to ease the calibration process. Cheu et al. (1998) adopted Genetic Algorithm (GA) to do the calibration on an expressway in Singapore using FRESIM model. Subsequently, Lee et al. (2004) adopted the same approach but using PARAMICS as the simulation model. Park et al. (2006) combined the GA algorithm in his proposed systematic flow chart procedure to accelerate the calibration process. The other methods used are the statistical method (Merritt, 2003) and failure detection method (Wan et al., 2006).

Besides methodology, one fundamental issue is about the most important components of the simulation models that need calibration. Generally speaking, it can be classified into two categories namely network based and demand based. Basic network geometry such as the accuracy of mapping of the network compared to the real network needs calibration effort. This is extremely important for micro-scopic simulation model. The location of the traffic signal, the stop line, the road kerb point, the VMS location etc may influence the drivers' behaviour. In addition, parameters that govern the driver's behaviour such as target mean headway and mean reaction time also need calibration. The second component is the OD demand and the route choice model. In reality, these types of information are very difficult to obtain.

Most of the calibration and validation effort is concentrated on the first component that is the network calibration. Gardes et al. (2001) calibrated the network and the model general configuration such as time step per second using PARAMICS for a freeway corridor. Lee et al. (2004) calibrated the mean target headway and mean reaction time for a freeway in the US using PARAMICS. For the route choice model calibration, Jayakrishnan et al. (2001) calibrated the PARAMICS route choice model using a hybrid model with DYNASMART while Mahut et al. (2004) calibrated the route choice model for a road network using method of successive average. Recently, Chu et al. (2006) recognised the importance of the OD matrix calibration in the validation procedure. He calibrated the OD matrix for a freeway corridor using PARAMICS. Ma et al. (2006) also proposed a five step procedure for micro-simulation calibration differencing the driving behaviour, the departure time choice and the route choice model by using GA.

Calibration parameters and performance measures are another issue in the calibration and validation process. From the existing literature, it is observed that, the calibration parameters chosen for freeway calibration usually are volume, flow and speed while for the arterial road segment with intersection; maximum queue length, queue time and travel time are chosen. Nevertheless, the performance measure chosen in evaluation is inconsistent. Richard et al. (2003) used mean square error, Brockfeld et al. (2005) adopted Theil's U statistic, Cheu et al. (1998), Lee et al. (2004) used average relative error, Mahut et al. (2004) adopted chi square statistic (GEH) and Kim & Rilett (2003) used mean absolute error ratio.

In summary, it is seen that there are many inconsistencies in the calibration and validation issue such as the methodology used and the performance measure adopted. One more question remains open and unsolved is how accurate do we expect the simulation model to represent the real situation. How do one judge whether his calibration effort is adequate? Is an average relative error of 10% sufficient for a reliable result or we need to have the relative error as small as 0.1%? On the other hand, the accuracy and appropriateness of field data collection will also influence the calibration process. If this is the case, if a large error occur in the calibration parameter, which should we believe the simulation model or the field data? Hence, it is expected that there will be more research on this issue in the coming years.

2.4 Evaluation of Exclusive Bus Lane Using Simulation Models

Traffic simulation models are adopted by researchers to evaluate the impact of exclusive bus lane on the transport network. Tu et al. (2009) investigated the advantages of exclusive bus lanes by comparing the travel time of general traffic between ordinary lane case and exclusive bus lane case by using PARAMICS. Three scenarios are simulated, namely exclusive bus lane, bus priority lane and ordinary lane scenarios. It was found that the physical characteristics of a vehicle (length, velocity, acceleration, deceleration, etc) are important to influence the effectiveness of bus lane especially at curve slope. Besides, it is found that the bus' priorities at bus stops will cause vehicles on the main stream to slow down leading to local congestion. Exclusive bus lane is found to improve the bus performance while the non-bus traffic could perform better if the lane remains as an ordinary lane.

Chen et al. (2010) adopted a microscopic traffic simulation approach to analyse the impact on capacity for the weaving sections when the exclusive bus lanes are installed on the urban expressways. Three typical configurations of the exclusive bus lane in Beijing are identified, including median bus lane with off-on-ramp, curb-side bus lane with on-off-ramp and curb-side bus lane with off-on-ramp. VISSIM is adopted as the evaluation tool. Four factors are studied, i.e. weaving section length, headway, mainline volume, and off-ramp and on-ramp volumes for non-bus traffic. The performance of the exclusive bus lane is investigated under various scenarios such as expressways' configurations, high volume bus routes, almost saturated mainline traffic, and heavy traffic on the on/off ramps. It was found that the headway is more sensitive than weaving section length for median bus lane and vice versa for curb-side bus lane. It also shows that the weaving section length is more sensitive for the on-off-ramp than for the off-on-ramp scenario for the curb bus lane.

Tranhuu et al. (2007) studied the impact of motorcycles for priority bus lane. The meso-scopic simulation model, SATURN, was used to compare the different bus lane schemes in mixed traffic environment. Two levels of testing are carried out. The first level identified the specific areas that have different transport features and problems. In the second level, the cross city bus lane designs are tested to analyse whether the proposed combinations of bus lanes are working well. In addition, different layouts of bus lane are examined to find out how internal running way factors affects the efficiency of bus priority schemes. The study collected detailed data from 82 junctions and 1108 links in Hanoi, Vietnam. It was found that the violation by motorcycles has an important impact on the bus lane schemes. There is no significant speed improvement on bus lanes if other traffic measures are not simultaneously used to enforce the usage of bus lanes.

Shalaby (1999) studied the impacts of reserved bus lanes implemented in an urban arterial in downtown Toronto. Changes in the performance of buses and other non-bus traffic in the same arterial were treated equally. The data such as turning movement counts, midsection speeds, and vehicle occupancies are collected. TRANSYT-7F model was used to simulate the bus transit system and non-bus traffic for cases before and after the exclusive bus lane implementation. Two strategies, namely the junction turning movement and permitting taxis to use the exclusive bus lane, are simulated and investigated. Results showed that the performance of the average bus improved when the exclusive bus lane is implemented while the performance of the non-bus traffic deteriorated. The simulations also showed that modifications to left turn movements would have a minor impact on both bus and adjacent traffic performance. Nevertheless, the removal of taxis from the reserved lanes would cause more damage to the general traffic than the benefits obtained by the buses.

Patankar et al. (2007) analysed the impact on traffic quality and commuter mobility by implementing the exclusive bus lanes under Indian traffic situation. A 6.4 km long mixed traffic corridor in Delhi was chosen to study the impact of exclusive bus lane in which the AIMSUN software was acquired as the simulation model. The measures of effectiveness chosen are traffic flow, speed, travel time, delay time, stop time, and fuel consumption. The findings show that the exclusive bus lane plays a significant role in mitigating traffic congestion and pollution problems.

Yang and Wang (2009) proposed a new innovative dynamic bus lane system that could mitigate the existing weaknesses of the exclusive bus lane. Using the simulation model developed with Paramics, they compared the effectiveness of the proposed system to the exclusive bus lane in terms of operation and safety. The results showed that the proposed dynamic bus lane has lesser impact on the general traffic and could minimise the conflict risks in a relative lower magnitude compared to the exclusive bus lane.

2.5 Analytical Methodology for Exclusive Bus Lane Allocation

Apart from the studies which focused on evaluating the effectiveness of the exclusive bus lane, there are some existing studies investigating the best design for the exclusive bus lanes. Besides, there are studies looking at developing a criteria and a set of guidelines in justifying the implementation of the exclusive bus lanes.

Seo et al. (2005) proposed a methodology to determine the necessity of having exclusive bus lane in the arterial network. Using the simulation model of Seoul transport network developed with NETSIM, a before-and-after analysis of the exclusive bus lane was proposed. It was suggested that the bus lane should only be reserved when the average travel time for the road sections could be improved by doing so. As a result, the exclusive bus lane should be installed when the total general traffic and bus volume is above certain points.

Gan et al. (2002) described an effort to develop the operational performance and decision models that can be used to justify and design bus lanes on arterial streets. The model considers the average person travel time under two treatments: with and without the exclusive bus lane. The micro-scopic traffic simulation model, CORSIM, was selected as the modelling tool because the complex interactions among the variables of interest (such as bus lane, bus bay, bus stop location, signal offset, and etc) cannot be modelled mathematically. Besides, it was not feasible to collect field data that would provide a sufficient sample size for calibrating empirical models. An average speed is chosen as the measure of effectiveness (MOE) to determine the quality of traffic flow on the arterial streets. The average speed of buses and non-bus traffic is recorded when each of the value of the variables are changed. Impact analysis using statistical approach is then carried out to find the best combination of the variables. The objective is then to minimise the travel time of all road users of bus and non-bus traffic by comparing the person travel times (PTT) associated with the different design alternatives.

Miandoabchi et al. (2011) formulated the exclusive bus lane allocation problem as a bi-modal discrete urban road design problem. In their model, 4 decision variables are defined, i.e. the addition of lanes to the existing streets, new street constructions, convert 2-way road to 1-way road, and allocation some lanes for exclusive bus lane. The objectives are to maximise consumer surplus and demand share for buses, while taking care of the response of travelers by a combined modal split/assignment. A hybrid of genetic algorithm and simulated annealing, a hybrid of particle swarm optimisation and simulated annealing, and a hybrid of harmony search and simulated annealing are proposed to solve the problem.

Mesbah et al. (2008) proposed a new methodology for optimising transit road space priority at the network level. The aim of the proposed approach is to find the optimum combination of exclusive lanes in an existing operational transport network. Mode share is assumed variables and an assignment is performed for both private and transit traffic. The network road space allocation problem is formulated using the bi-level programming model. The sum of travel time for all users is included in the upper level. With the introduction of an exclusive bus lane, a mode shift is expected and consequently a reassignment would require to be carried out for the network. Therefore, a modal split between transit and passenger cars as well as an assignment model is formulated in this study at the lower level. In other words, the objective function at the upper level is subject to constraints of the modal split and the assignment results.

Li and Ju (2009) investigated the travellers' reactions to the exclusive bus lane allocation in mode choices, departure time choices, and path choices. They formulated the problem using Variational Inequality (VI) formulation. They used a multi-mode point queue model to reflect the interactions of cars and buses in the cases of with and without the exclusive bus lane. Besides, they adopted the multi-mode dynamic traffic assignment (DTA) to model travellers' reactions to the network changes. Results reported that at demand 3000 persons to 4000 persons, bus passengers will benefit from the exclusive bus lane, while car drivers experience more delay. If mode shift happens, this will cause the bus lane to be non-congested while reducing delay on general purpose lanes.

2.6 Limitations on Existing Studies

There are a few limitations of the existing studies. First, most (all) of the studies investigate the best (optimum) allocation of bus lane on the transport network. None of them are concerned about the bus lane schedules. Nevertheless, bus lane scheduling has been in practice for some time. In addition, research (Zhu 2010; Yang and Wang 2009) has shown that the exclusive bus lane could have a higher effectiveness (to avoid under-utilisation) if it could be opened intermittently to the non-traffic when there is no bus. As such, the delay on the general traffic could be reduced. Proper determination of bus lane schedule (rather than real time opening and closing of the bus lane, such as dynamic bus lane proposed by Yang and Wang (2009)) could have the drivers better informed and reduce their confusion.

Second, in terms of bus lane allocation, parts of the solution provided by Miandoabchi et al. (2011) considered adding new lanes to existing streets and constructing of new streets. However, in a developed city with land scarcity problem, the proposed solutions might not be practical. Besides, changing of 2-way streets into 1-way streets might cause the re-design of the existing bus routes. In such a case, more stakeholders will be involved and it will pose difficulty in communication and practice.

Third, the travel time functions adopted for traffic flow modelling are static functions (Miandoabchi et al., 2011; Mesbah et al., 2008) or point queue model (Li and Ju 2009). These models could not represent the traffic flow realistically as they could not model the queue spill-back situation during traffic congestion. This could affect the accuracy of delay estimation.

Forth, the bus transit system has not been modelled in detail. Mesbah et al. (2008) used Spiess and Florian (1989) transit assignment model in which the bus capacity and schedule are not captured. Li and Ju (2009) treated the bus transit system like other general traffic by defining the system using general traffic equations, such as link exit functions. Miandoabchi et al. (2011) took the same approach as Li and Ju (2009), but static functions are derived. The bus transit system is different from the general traffic as it has its own characteristics, such as frequent stop at bus stops. Modelling the bus transit system as the non-bus traffic would reduce the results accuracy. In addition, there is a need to capture the merging of buses with the general traffic at the end of the exclusive bus lane. Current models used could not model this properly.

Fifth, most of the studies adopted the small size network to test their methodology. Mesbah et al. (2008) used a simple 6-node and 7-link network, Li and Ju (2009) tested on a network with 13 nodes, 17 links, and 2 OD pairs, while Miandoabchi et al. (2011) used a network with 8 nodes and 13 links. Testing on the small size network in some extent could not guarantee for its applicability on the larger size network.

The methodology proposed in this research study could tackle the above-mentioned limitations. The proposed methodology used the micro-scopic traffic simulation model as the modelling tool which could model the bus transit network in detail. Most of the bus elements, such as bus stops, bus bay, dwell time, bus schedules, and capacity are considered simultaneously in the same model. In addition, the buses and non-bus traffic flow could be propagated more realistically according to the micro-scopic behaviour of drivers, such as car following, lane changing and gap acceptance at intersections. Besides, the research aims to find the best lane allocation and scheduling for exclusive bus lane simultaneously under a framework. An evaluation to the proposed methodology is carried out using a real network of Klang Valley in Malaysia. This could show the applicability of the proposed method on large scale and practical networks.

CHAPTER 3

THE BI-LEVEL PROGRAMMING MODEL AND SOLUTION ALGORITHM

This chapter illustrates the formulation of the bi-level bi-objective optimization model for the exclusive bus lane allocation and scheduling problem. The problem formulation, objective functions, decision variables, and constraints are presented. In addition, the hybrid Non-sorting Genetic Algorithm (NSGA)-Paramics is presented as the solution algorithm to the proposed formulation.

3.1 Problem Formulation

Let $G=(N,A)$ denote a connected and directed transportation network in which $N=\{1,2,\ldots,u,\ldots\}$ is the set of nodes and $A=\{(u,v)\mid u,v\in N\}$ is the set of links. The network $G=(N,A)$ has two sub-networks, i.e. non-bus traffic (such as passenger cars and trucks) sub-network, $G_a=(N_a,A_a)$ and bus transit system sub-network, $G_b=(N_b,A_b)$.

For the non-bus traffic sub-network, $G_a=(N_a,A_a)$, $N_a=\{1,2,...,e,...\}$ represents the set of nodes and $A_a=\{(e,f)\mid e,f\in N_a\}$ represents the set of links where the non-bus traffic are travelling on. Note that $N_a\subseteq N$ and $A_a\subseteq A$. Each directed link $(e,f)\in A_a$ composes several lanes that are numbered from the curbside to the median along the direction from node e to

f by integer $m=1,.....l_{ef}$ where l_{ef} is the total number of lanes of the link (e,f). The sets of origins and destinations for non-bus traffic are denoted by R_a and S_a, respectively where $R_a, S_a \subseteq N_a$. For an O-D pair $r_a s_a$ (for which $r_a \in R_a$ and $s_a \in S_a$), there is a time-dependent traffic demand denoted by $q_{r_a s_a}(\tau)$ where τ represents a time instant.

For the bus sub-network, $G_b=(N_b, A_b)$, $N_b=\{1,2,...,g,...\}$ represents the set of bus stations and $A_b=\{(g,h) \mid g,h \in N_b\}$ represents the set of links where buses are moving on. Note that $N_b \subseteq N$ and $A_b \subseteq A$. Unlike non-bus traffic, buses are released from and destined to bus terminals. The sets of origin and destination terminals are denoted by R_b and S_b respectively, and $R_b, S_b \subseteq N_b$. For an O-D pair $r_b s_b$, $r_b \in R_b$ and $s_b \in S_b$, there is an associated transit demand denoted as $d_{r_b s_b}$. There are some shared links/common links between the non-bus traffic network and bus transit network, i.e. $A_a \cap A_b \neq \phi$. Some of the bus stations are located at the intersections, in which $N_a \cap N_b \neq \phi$, while some are at the midblock of links A_m, in which $A_m \subseteq A_a \cap A_b$.

Let A_1 be the set of links in the study area such as Central Business District (CBD), i.e. $A_1 \subseteq A$. Let A_2 be the set of candidate links identified for the implementation of the exclusive bus lane. They could be chosen based on some guidelines, such as the volume of buses traveling on those links, or by engineering judgment. Practically, only those links that have at least one bus service running on them are eligible to be considered as the candidate links.

Accordingly, $A_2 \subseteq A_a \cap A_b$ indicates that the candidate links are selected from the set of shared/common links which are used by buses and non-bus traffic.

Furthermore, the candidate links can be partitioned into K groups, i.e. $A_2 = A_2^1 \cup A_2^2 \cup ..... \cup A_2^K$. The grouping is carried out to ensure continuity and consistency of the exclusive bus lane implementation. This is crucial to avoid drivers' confusion and for safety consideration. For example, links are grouped based on their geometrical layout and sequence. Several continuous road segments/links could be grouped together to have the exclusive bus lane implemented and are assigned the same schedule. This ensures the continuity and avoids sudden truncation of the exclusive bus lane that could evoke confusion. The rule to determine the grouping of links could be based on the authority's guidelines or by engineers' judgment. It is important to note that there is no common links across different groups. Each of the links in A_2 belongs to one and only one group.

Given also a time period denoted by $\left[0,T\right]$ when the exclusive bus lane operation is considered. The time period is discretized into homogeneous interval when each t represents a n -minute interval, namely, $t \in \left\{1,2,\cdots,{}^{T}\!/_{n}\right\}$.

3.2 The Bi-level Programming Model

The bi-level programming model is adopted to formulate the exclusive bus lane allocation and scheduling problem. It is chosen because the nature of the problems fulfils the Stackelberg game theory. The upper level is a bi-objective optimization model which aims to minimize the average travel time of non-bus traffic and buses in the study area. The lower level is a microscopic traffic simulation model that is used to simulate the movement of private vehicles and buses.

3.2.1 Upper Level: Bi-objective Optimization Model

The exclusive bus lane allocation and scheduling problems addressed two major issues, i.e. the lane allocation and scheduling problems. Accordingly, three decision variables can be defined for the problem, as shown follows:

$$z_{ij} = \left\{ \begin{array}{l} 1, \text{ if a lane on link } (i, j) \text{ is chosen as exclusive bus lane} \\ 0, \text{ otherwise} \end{array} \right\}, \quad (i, j) \in A_2$$

x_{ij} : start time of the bus-only lane for link $(i, j) \in A_2$

y_{ij} : end time of the bus-only lane for link $(i, j) \in A_2$

For the sake of presentation, let $\mathbf{x}, \mathbf{y}, \mathbf{z}$ represent the row vectors of the start and end time and the binary decision variable for exclusive bus lane allocation and scheduling problem for all candidate links respectively, namely, $\mathbf{x} = \left(x_{ij}, (i, j) \in A_2\right)$, $\mathbf{y} = \left(y_{ij}, (i, j) \in A_2\right)$, and $\mathbf{z} = \left(z_{ij}^k, (i, j) \in A_2, k = 1, 2, \cdots, l_{ij}\right)$.

There are some constraints that need to be considered for practical implementation for traffic safety purposes. First, the candidate links must have at least 2 lanes to avoid alteration of the overall network layout which can confuse the drivers. The constraint can be formulated as follow:

$$l_{ij} - z_{ij} > 0 \tag{3.1}$$

where l_{ij} is the total number of lane for link (i, j).

Second, for cost-benefit consideration, the exclusive bus lane should only be provided if there is high density of buses using the road. This could be measured by the frequency of buses arriving on the link. The constraint is expressed as:

$$\left(f_{ij} - f_{\min}\right) z_{ij} \geq 0 \tag{3.2}$$

in which $f_{\min}$ is the minimum frequency of buses travel along the link.

Third, it is also important to consider continuity of the exclusive bus lane. In some situation, a segment of road might consist of a few links. It is thus important to ensure that the implementation of the exclusive bus lane is continued for the entire road segment. Accordingly, the candidate links are categorized into groups based on their geometry linkage. Define a total of M links $\left\{(i, j_1), (j_1, j_2), (j_2, j_3), (j_3, j_4), \cdots, (j_{m-1}, j_m)\right\}$ that belong to the same group k, the constraint can be expressed as follow:

$$z_{j_1 j_2} = z_{j_2 j_3} = z_{j_3 j_4} = \cdots = z_{j_{m-1} j_m}, \ \left(j_g\, j_{g+1}\right) \in A_2^k \tag{3.3}$$

Forth, there must be a minimum, $\breve{T}_{ij}$, and maximum, $\overset{\frown}{T}_{ij}$ duration for the exclusive bus lane implementation. The constraint is expressed by:

$$\breve{T}_{ij} \leq y_{ij} - x_{ij} \leq \overset{\frown}{T}_{ij}, \ \left(i, j\right) \in A_2 \tag{3.4}$$

Note that: $0 \leq \breve{T}_{ij}$ and $\overset{\frown}{T}_{ij} \leq T$ in which T is the total time period considered.

Fifth, for the same road segment, the exclusive bus lane schedule must be the same in order to avoid drivers' confusion. Similarly, the candidate links are categorized into group k, A_2^k. The constraints are expressed as follow:

$$x_{j_1 j_2} = x_{j_2 j_3} = x_{j_3 j_4} = \cdots = x_{j_{m-1} j_m}, \ \left(j_g\, j_{g+1}\right) \in A_2^k \tag{3.5}$$

$$y_{j_1 j_2} = y_{j_2 j_3} = y_{j_3 j_4} = \cdots = y_{j_{m-1} j_m}, \quad (j_g j_{g+1}) \in A_2^k \tag{3.6}$$

The objectives of the exclusive bus lane allocation and scheduling problems are to minimize the average travel time spent by non-bus traffic and buses in the study area. The time when a vehicle enters and exits the boundary of the study area, A_1, it is recorded. The time difference between the entering and exit of the vehicle is defined as its travel time in the study area. The following equations express the average travel time for general traffic and buses respectively.

$$\min\ F_1(\mathbf{x},\mathbf{y},\mathbf{z}) = \frac{\sum_{n=1}^{N(\mathbf{x},\mathbf{y},\mathbf{z},T,A_1)} \left(t_n^{exit} - t_n^{enter}\right)}{N(\mathbf{x},\mathbf{y},\mathbf{z},T,A_1)} \tag{3.7}$$

$$\min\ F_2(\mathbf{x},\mathbf{y},\mathbf{z}) = \frac{\sum_{n=1}^{N_b(\mathbf{x},\mathbf{y},\mathbf{z},T,A_1)} \left(t_{nb}^{exit} - t_{nb}^{enter}\right)}{N_b(\mathbf{x},\mathbf{y},\mathbf{z},T,A_1)} \tag{3.8}$$

where $N(\mathbf{x},\mathbf{y},\mathbf{z},T,A_1)$ and $N_b(\mathbf{x},\mathbf{y},\mathbf{z},T,A_1)$ are the total amount of non-bus traffic (in terms of number of vehicle) and buses traveling in the study area, A_1 during time period T. According to the literature (Shalaby 1999 and Sakamoto et al., 2007), both objective functions shown in eqns. (3.7) and (3.8) could be contradicted with each other. This is logic because if one lane of the road is reserved as the exclusive bus lane, the road capacity for non-bus traffic would be reduced. Hence, their travel time will be increased.

3.2.2 Lower Level: Microscopic Traffic Simulation Model

The lower level of the model is to measure how drivers of non-bus traffic react when the exclusive bus lane is activated. According to Wardrop's principle (1952) of user equilibrium, drivers will tend to change route in order to minimize their travel time. The drivers' reaction could be simulated using the microscopic traffic simulation model. In addition, the simulation of the bus transit network could be carried out. The advantages of using microscopic traffic simulation model are that the bus movement can be simulated more precisely and in details. Most of the essential bus transit features could be simulated, such as bus schedule, frequency, dwell time, occupancy, and fleet size. More importantly, how buses merge back into the traffic stream could be captured using the microscopic traffic simulation model as well. Figure 3.1 shows the inputs, outputs, and the simulation steps for the simulation model.

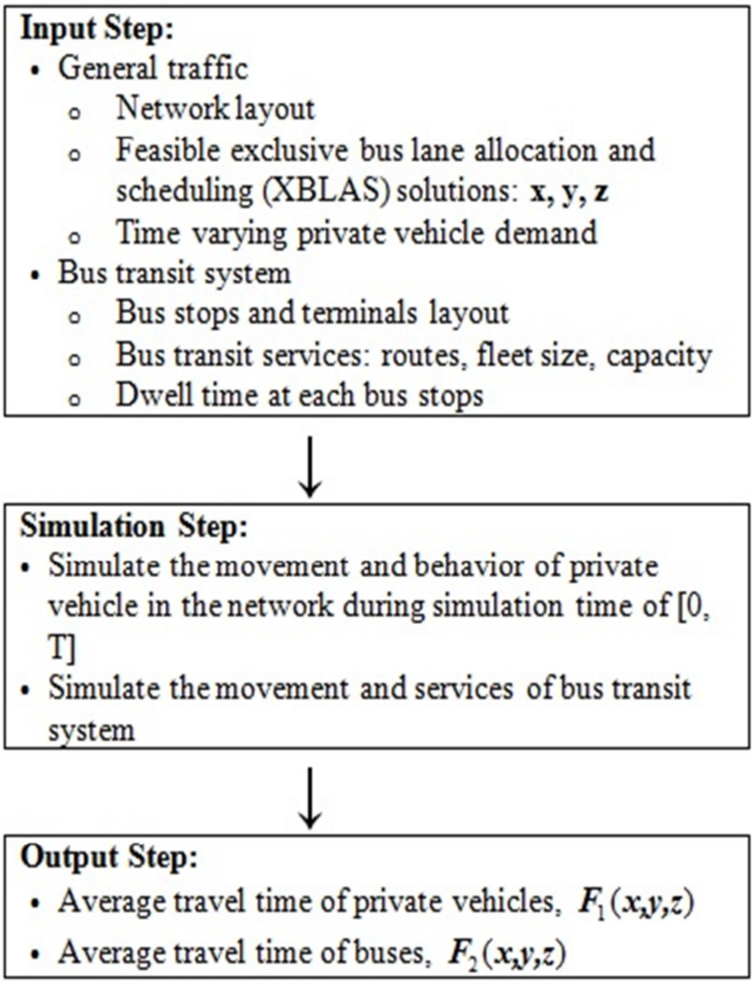


Figure 3.1: The lower level: microscopic traffic simulation model

In summary, the bi-level programming model for the exclusive bus lane allocation and scheduling problem is shown as follow:

Upper level:

$$\min \begin{pmatrix} F_1(\mathbf{x},\mathbf{y},\mathbf{z}) \\ F_2(\mathbf{x},\mathbf{y},\mathbf{z}) \end{pmatrix} \tag{3.9}$$

subject to:

$$l_{ij} - z_{ij} > 0 \tag{3.10}$$

$$\left(f_{ij} - f_{\min}\right) z_{ij} \geq 0 \tag{3.11}$$

$$z_{j_1 j_2} = z_{j_2 j_3} = z_{j_3 j_4} = \cdots = z_{j_{m-1} j_m}, \ \left(j_g j_{g+1}\right) \in A_2^k \tag{3.12}$$

$$\breve{T}_{ij} \leq y_{ij} - x_{ij} \leq \widehat{T}_{ij}, \ (i, j) \in A_2 \tag{3.13}$$

$$x_{j_1 j_2} = x_{j_2 j_3} = x_{j_3 j_4} = \cdots = x_{j_{m-1} j_m}, \ \left(j_g j_{g+1}\right) \in A_2^k \tag{3.14}$$

$$y_{j_1 j_2} = y_{j_2 j_3} = y_{j_3 j_4} = \cdots = y_{j_{m-1} j_m}, \ \left(j_g j_{g+1}\right) \in A_2^k \tag{3.15}$$

Lower level:

The lower level is shown in Figure 3.1.

The bi-objective minimization model (3.9)-(3.15), in general, does not possess a universal optimal solution due to trade-offs between both objectives. In fact, the scalar concept of "optimality" cannot be directly applied for a bi-objective optimization model. However, the Pareto-optimality can be adopted to characterize a solution of a bi-objective optimization model (Deb, 2001). A feasible exclusive bus allocation and scheduling solution satisfying the Pareto-optimality condition for the bi-objective optimization shown is referred to as the Pareto-optimal solutions, which is illustrated in the later section.

3.3 Pareto Solutions

Pareto solutions are usually obtained for multi-objective (bi-objective) optimization models as the search spaces are not ordered. They are the non-dominated solutions in which the objective values could not be improved without deteriorating the other objective values in the vector of decision variables. The set of non-dominated solutions obtained is termed as the Pareto optimal set. The plot of the objective functions whose non-dominated vectors are in the Pareto optimal set is called the Pareto front.

Let Γ be the set of all feasible exclusive bus lane allocation and scheduling solutions for the bi-objective minimization model (3.9)-(3.15), namely,

$$\Gamma = \left\{ (\mathbf{x}, \mathbf{y}, \mathbf{z}) = \left(x_{ij}, y_{ij}, z_{ij} \right),\ (i, j) \in A_2 \right\} \tag{3.16}$$

Any two feasible solutions are comparable in terms of the Pareto-dominance relation defined by the bi-objective functions shown in eqn. (3.9):

Definition 1: (Pareto-dominance) The feasible exclusive bus lane schedule $(\mathbf{x_1}, \mathbf{y_1})$ is said to dominate another feasible exclusive bus lane schedule $(\mathbf{x_2}, \mathbf{y_2})$ if and only if $\mathbf{F^1} = \left(F_1^1 (x_1, y_1, z_1), F_2^1 (x_1, y_1, z_1) \right)$ is partially less than $\mathbf{F^2} = \left(F_1^2 (x_2, y_2, z_2), F_2^2 (x_2, y_2, z_2) \right)$, i.e.

$$F_i^1 \le F_i^2 \quad \forall i \in \{1, 2\} \tag{3.17}$$

and there is at least one solution such that

$$F_i^1 < F_i^2 \qquad \forall i \in \{1, 2\} \tag{3.18}$$

In view of the bi-objective functions, the Pareto-dominance is a partial mathematical ordering relation between two exclusive bus lane allocation and scheduling solutions. Based on the Pareto-dominance relation, the Pareto-optimality condition for the bi-objective minimization model (3.9)- (3.15) can be defined as follows (Steuer 1986):

Definition 2: (Pareto-optimality) Let $(\mathbf{x},\mathbf{y},\mathbf{z})\in\Gamma$ be a feasible exclusive bus lane allocation and scheduling solution:

(i) The feasible exclusive bus lane allocation and scheduling solution $(\mathbf{x},\mathbf{y},\mathbf{z})$ is said to be *nondominated* regarding a subset $\Gamma'\subseteq\Gamma$ if and only if there is no solution in Γ' which dominates $(\mathbf{x},\mathbf{y},\mathbf{z})$.

(ii) The feasible exclusive bus lane allocation and scheduling $(\mathbf{x},\mathbf{y},\mathbf{z})$ is called a Pareto-optimal exclusive bus lane allocation and scheduling solution if and only if $(\mathbf{x},\mathbf{y},\mathbf{z})$ is nondominated regarding the whole set Γ.

In general, the Pareto-optimal exclusive bus lane allocation and scheduling solution is not unique and it cannot be improved with respect to any objective without worsening at least one other objective. Let Γ^* denote a set of all Pareto-optimal exclusive bus lane allocation and scheduling solutions, and the corresponding vectors of the objective function values, denoted by $\left\{\left(F_1(\mathbf{x},\mathbf{y},\mathbf{z}),F_2(\mathbf{x},\mathbf{y},\mathbf{z})\right)\middle|(\mathbf{x},\mathbf{y},\mathbf{z})\in\Gamma^*\right\}$, is called Pareto-front.

3.4 Solution Algorithm

The bi-objective optimization model shown in eqn. (3.9)-(3.15) is an NP-hard problem. The objective functions value could not be obtained analytically, but they are obtained by implementing the simulation model from the lower level. As such, the bi-objective optimization model can only be solved using meta-heuristic algorithms. In this study, the non-dominated sorting genetic algorithm (NSGA-II) (Deb et al., 2002) is adopted to solve the problems. It is chosen due to a few reasons:

(1) It is incorporated with the elitism choice strategies in which elite solutions could be kept and bring forward to the last generation. This would improve the convergence speed and the quality of the solutions.
(2) It is incorporated with the population diversity mechanisms to prevent the crowding of solutions.
(3) It is an efficient and well-tested algorithm (Konak et al., 2006).

NSGA-II operates with a collection of chromosomes, called a population. A chromosome corresponds to a unique solution of the problem of interest in the solution space by a chromosome decoding scheme. As for the bi-objective minimization model, the exclusive bus lane allocation decision variables, $\{z_{ij},\ (i,j)\in A_2\}$ is coded as binary strings, while the scheduling decision variables, $\{(x_{ij},y_{ij}),\ (i,j)\in A_2\}$ are coded as integer strings. A chromosome decoding scheme is then designed to decode the strings in order to obtain feasible exclusive bus lane allocation and scheduling solutions. It is important to make sure that the solutions obtained are feasible in which they fulfil all the constraints (3.10)-(3.15). A chromosome repairing procedure is thus designed to repair the chromosomes that do not fulfil the constraints. The feasible solutions are then implemented at the lower level- Paramics (the microscopic simulation model). Paramics allows such implementation through its Application Programming Interface (API) functions available. The average non-bus traffic and buses travel time is then computed and adopted by the upper level as the objective function values. The NSGA II embedded with Paramics adopted to solve the exclusive bus lane allocation and scheduling optimization model is described below.

NSGA-II embedding with Paramics

Step 1: (Initialization) Randomly create a parent population P_0 of size L in the dynamic ramp metering rate solution space. Set the number of generations $\omega = 0$.

Step 2: (Generate an initial offspring population) Randomly select chromosome from population P_0 to perform crossover and mutation to generate offspring population B_0 of size L.

Step 3: (Stopping criterion checking) If a stopping criterion is satisfied, stop and return to P_ω. Otherwise, go to Step 4.

Step 4: Set $H_\omega = P_\omega \cup B_\omega$.

Step 5: (Chromosome repairing procedure) Check each of the chromosome to ensure that the solutions are feasible. Chromosomes that violate constraints (3.10)-(3.15) are repaired.

Step 6: (Call Paramics) Decode each chromosome in set H_ω into the exclusive bus lane allocation and scheduling solution and then call Paramics to run. The commensurate objective function values are computed according to eqns. (3.7) and (3.8).

Step 7: (Allocate fitness value) Apply the fast non-dominate sorting algorithm (Deb et al., 2002) to identify all the non-dominated fronts in set H_{ω}, denoted by $\bar{H}_1, \bar{H}_2, \cdots, \bar{H}_{M_{\omega}}$ where M_{ω} is a positive integer, in terms of the bi-objective function values evaluated in Step 4.

Step 8: (Maintain elitist chromosomes) (i) Let set $P_{\omega+1} = \phi$ (ii) For fronts $m = 1$ to M_{ω} do the following steps:

Step 8.1: (Crowding distance assignment) Calculate the crowding distance of each chromosome in the non-dominated front $\bar{H}_m$, defined by Deb et al. (2002).

Step 8.2: (Create parent population for next generation) Create $P_{\omega+1}$ as follows:

Case 1: If $|P_{\omega+1}| + |H_m| \leq L$, then set $P_{\omega+1} = P_{\omega+1} \cup f_g$

Case 2: If $|P_{\omega+1}| + |H_m| > L$, then add the least crowded $L - |P_{\omega+1}|$ solutions from H_m to set $P_{\omega+1}$.

Step 9: (Crossover) Set $B_{\omega+1} = \phi$ and generate an offspring population $B_{\omega+1}$ of size L as follows:

Step 9.1: (Parent selection with diversity mechanism). Use binary tournament selection method (Goldberg, 1989) based on the crowding distance to select parents from $P_{\omega+1}$.

Step 9.2: Use a crossover operator to generate offspring to add them to set $B_{\omega+1}$.

Step 10: (Mutation) Mutate each chromosome in set $B_{\omega+1}$ with a predefined mutation rate. Let the number of generations $\omega=\omega+1$ and go to Step 3.

CHAPTER 4

THE DEVELOPMENT OF MICROSCOPIC TRAFFIC SIMULATION MODEL USING PARAMICS

In this chapter, the development of the microscopic traffic simulation model as the lower level of the bi-level programming model is elaborated. There are two types of network developed in this study as defined in Chapter 3, i.e. base network (G) and bus transit network (G_b). The development of both networks is illustrated in detail. In addition, the simulation of the exclusive bus lane and the scheduling is also explaine.

4.1 Development of the Base Network

Paramics allows for quick model building from scratch by importing the overlay as the background. An overlay is the map or snapshots of maps that provide the positions of roads and junctions as the background for network building. In this study, we used snapshots of Google Map as the overlay of our model. The nodes and links are then plotted on the overlay in which the scale of the simulation model takes after the overlay's scale. Paramics allows the adjustment of the overlay location by the x-axis, y-axis and z-axis. It can support various types of file, such as BMP, JPG, PNG, TIF and others as the overlay.

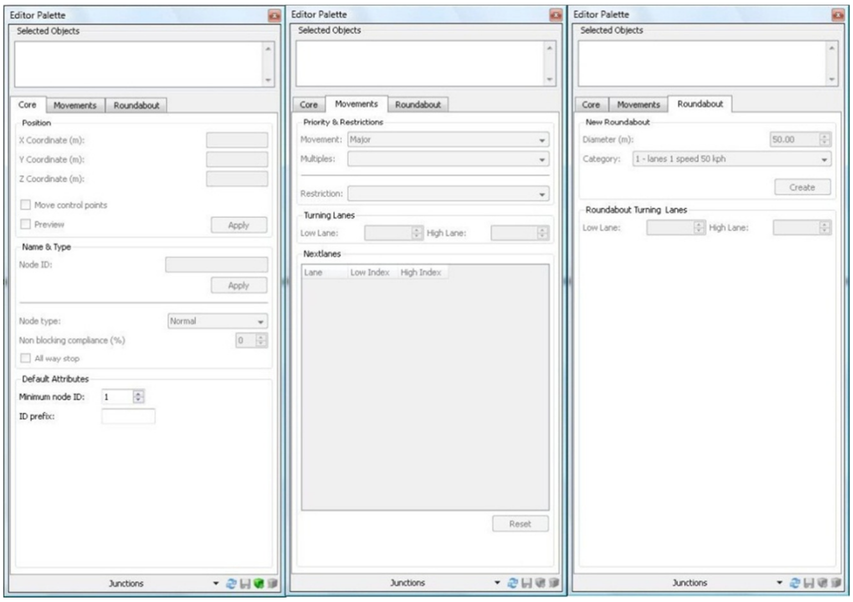
The development of the network starts by using the *New Network Wizard* provided by Paramics. It is a fast and efficient way to create a new network involving a sequence of dialogues in which the user provides the basic configuration details of the network. The physical network is built up of nodes and links. Nodes were place at the location which represents a physical change in the characteristics of the road layout. Two types of nodes are defined, i.e. junction nodes and connecting nodes. Junction nodes represent the physical junctions on the road network, such as T-junctions, four-leg junctions and roundabouts. Elevated interchanges and ramps could be modelled as well by inputting the z-coordinates of the nodes. Connecting nodes are those connectors for links development to represent roadways. For example, they could be added where there is a new lane added or simply to model the bend of the road. Nodes could be built in Paramics through the *Junction Editor*. The characteristics of the nodes, such as the movement priorities, next lanes, and roundabout elements could be specified using this editor. It is divided into three tabs, namely *Core*, *Movement*, and *Roundabout* tabs, each allowing access to different function of the editor actions.

The *Core* tab (Figure 4.1-left) allows users to perform the basic actions of nodes development, such as adding, deleting, or moving the changing the x-,y-, and z- coordinates of the nodes, adding the name of the nodes, and others. Junction priorities could be specified using the *Movement* tab (Figure 4.1-middle). The order of the movement priority at junctions is: major, medium, minor and barred. Major indicates that traffic has the priority over others to move. If two conflicting movements are both given major priority the vehicles will tend to drive through each other. Medium indicates that traffic has to give way to the major movement but has priority over minor and barred movements. Traffic with a medium priority at an intersection will allow it to stop if needed.

Minor represents traffic has the lowest priority in movement. Traffic with minor priority has the intention to stop at the junctions and will perform the "rolling stop" if there are no conflicts. Barred movement indicates that traffic is barred from performing the specified movement at the junctions. This function could be used in modelling the red phase of a traffic signal at the junctions. Paramics represent each of the movement using colours arrows, i.e. green is for major, yellow is for medium, white is for minor, and red is for barred movements as shown in Figure 4.2. The *next lanes* function allows the user to indicate the target lane after the next junction.

The junction could be converted as a roundabout using the *Roundabout* tab (Figure 4.1-right). The lane allocation of vehicles when approaching or circulating the roundabout could be modelled using this function. The junction could be converted into signalised junction as well. Using the *Signal Control* tab, the cycle time, phases, and timing could be input. In addition, the users need to assign the junction priorities, i.e. to indicate the major, medium, minor, and barred movements. Both fixed and actuated traffic signal could be simulated.

Links are built by connecting two vicinity nodes. They represent the physical roads on the network. There are several types of roads, such as minor or major arterial, urban or rural highways, and ramps. The detailed information about the links (roads), such as speed limit, number of lanes, width, and link types could be specified in Paramics. The development of the network could be carried out by using the *Link Editor* Palette function.



Node type: Normal
Non blocking compliance (%) 0
Minimum node ID: 1

Movement: Major

Diameter (m): 50.00
Category: 1 - lanes 1 speed 50 kph

Figure 4.1: ***Junction Editor*** **Palette**

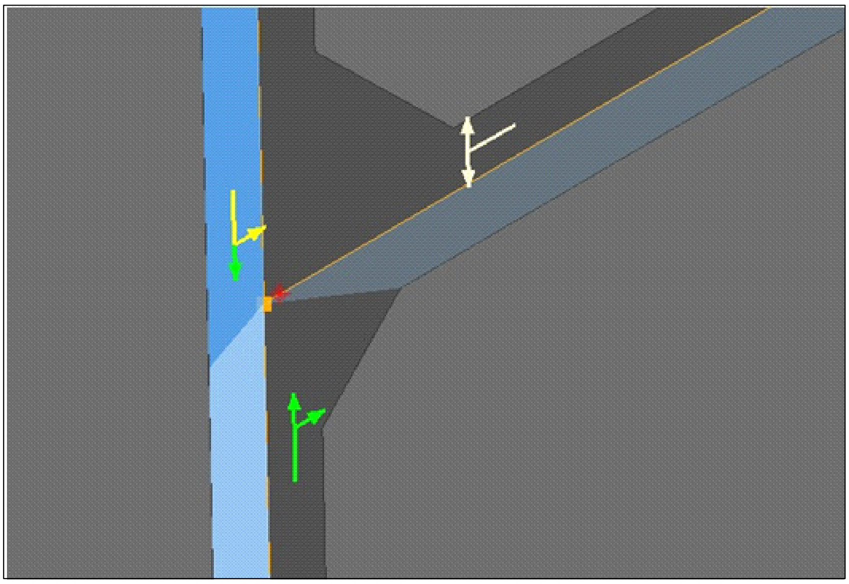
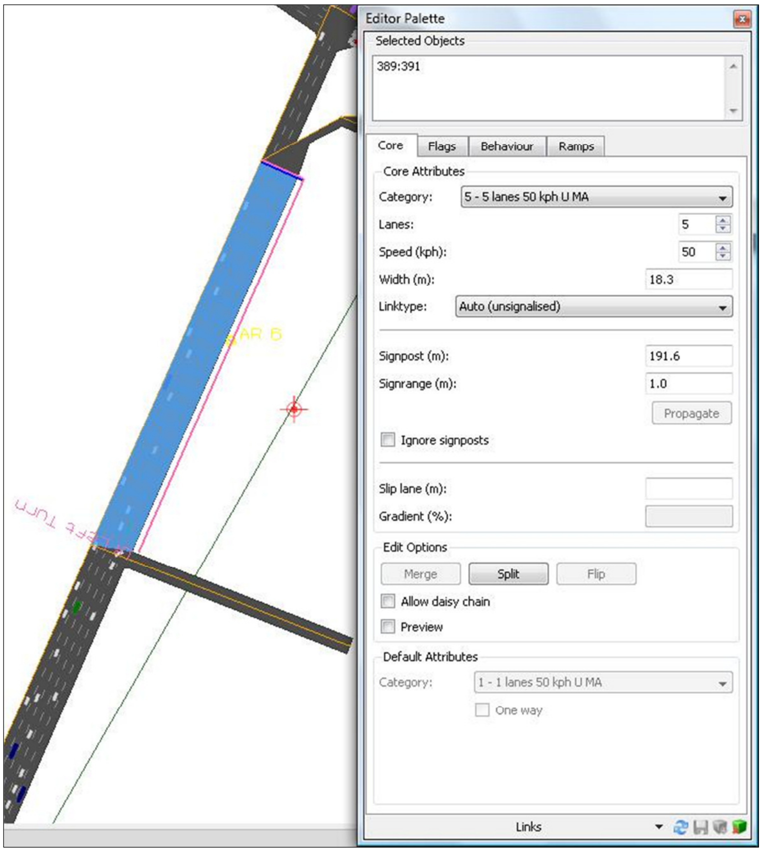


Figure 4.2: Movement priority specifications at a junction

Zones (i.e. Traffic Analysis Zones) are necessary in the model to facilitate the loading of traffic demand on the network. In Paramics, a Zone is a set of points defining the boundary of a region used to categorise the origins and destinations of the traffic in the model. Each Zone has a unique ID which is used with the demand file to specify the travel demand among zones in the model. The number of points and the position of each of the points can be edited by using the functions available in the *Zone Editor* palette as shown in Figure 4.4. The size of the zones and the choice of links covered could be modified as well. It is important to note that a link has to be selected first before the zones can be built. In addition, the length of the zone must be covered at least half of the link's length. Zones could be converted to car parks as well.



Selected Objects: 389:391

Category: 5 - 5 lanes 50 kph U MA

Lanes: 5

Speed (kph): 50

Width (m): 18.3

Linktype: Auto (unsignalised)

Signpost (m): 191.6

Signrange (m): 1.0

☐ Ignore signposts

Slip lane (m):

Gradient (%):

☐ Allow daisy chain

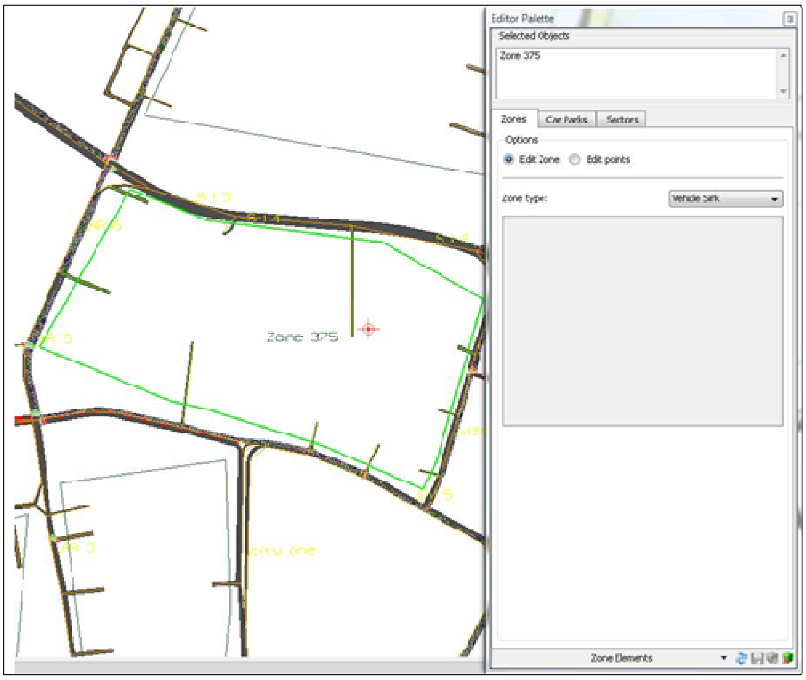
☐ Preview

Category: 1 - 1 lanes 50 kph U MA

☐ One way

Figure 4.3: Link Editor Palette

To generate traffic on the network, it is necessary to input the travel demand and their releases. The *Travel Demands Editor* is used to configure how vehicles are released into the network. The origin-destination (OD) demand matrix is an input in the simulation model to specify the number of vehicles travelling from the origin zones to the destination zones. By using the *Profile* function, the release rates of the vehicles for each OD could be specified. This is because the function allows the simulation time to be split into smaller time slices and periods according to the user specification. As such, the departure time choice of drivers could be simulated.



● Edit Zone ○ Edit points

Zone type: Vehicle Sink

Figure 4.4: Zones Editor Palette

4.2 Model Verification and Calibration

Model verification and calibration is carried out to ensure that the simulation model developed is accurate. The following sub-sections explain in detail the work carried out for verification and calibration of the model.

4.2.1 Model Verification

Verification is an important step to ensure that the simulation model developed is performing reasonably. For example, vehicles have to stop when the traffic light is red. After the model is developed according to the procedure highlighted in previous section, it is checked thoroughly by visual inspection to ensure that the model is built properly. There are several issues arising from poor modeling techniques and are explained as follows.

It is observed that there are poor connections between road edges when two links are joined at a node as shown in Figure 4.5. This happens when there is a connection between the straight link and curve link. It would affect the stop line points and the entry points of the links. As a consequence, vehicles might not stay in the lane and move forward correctly. This deficiency could be fixed by reposition of the kerb points (using the *Control Point* palette) that define the edge of the roads. The kerb points have to be adjusted for a few times until satisfactory connections are obtained.

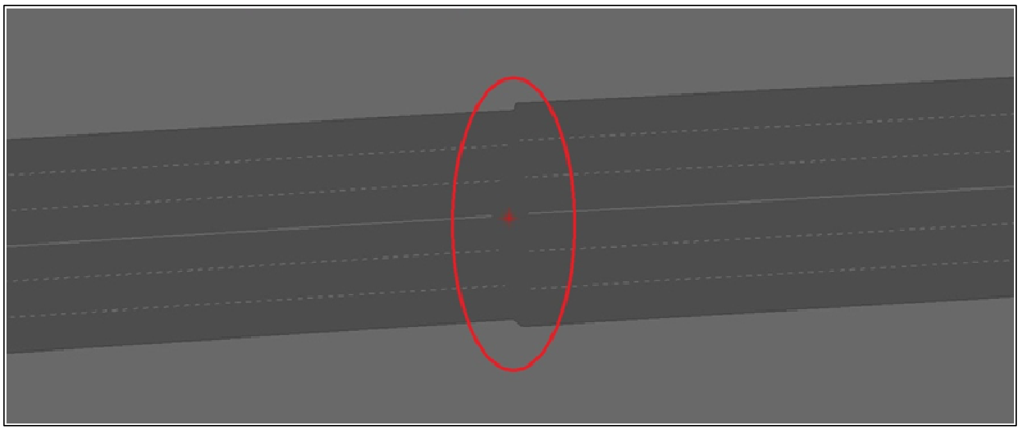


Figure 4.5: Poor Connection of Edges

It is observed that in some occasions, vehicles overlap with each other during the simulation run as shown in Figure 4.6. The overlapping usually happens when vehicles are waiting at the traffic signal, or at the start and at the end of the interchange. The main reason of such deficiency is due to wrong coding of the link types. At the traffic signal the minor/major movement has to be coded properly. At the interchanges, the feeder links have to be coded as on-ramps rather than as arterial streets. Accordingly, the priority of the ramp-highway system could be coded properly.

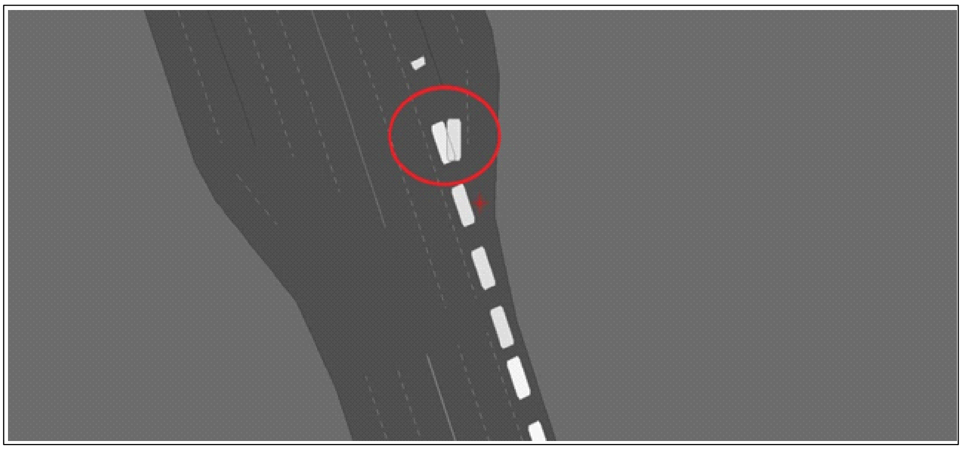


Figure 4.6: Overlap of vehicles

Another deficiency of the network coding is observed in which unusual gaps are observed when vehicles are queuing in the model as shown in Figure 4.7. This would reduce the effective capacity of the road because vehicles are not utilising the road spaces fully. Besides, unusual gaps could be a source of traffic congestion in the model since stopped vehicles before the gaps could create bottlenecks to the traffic flow. This situation could be mitigated by reducing the number of short links (links with length shorter than 50 m) and proper coding of lane choice in the model. Lane choice allows users to specify the target lanes of vehicles when moving across links. In addition, the positions of the stop lines are checked to ensure that they are coded properly at the end of the links. In Paramics, stop lines could affect the behaviour of vehicles entering, existing, and traversing on the links. If they are not coded properly, vehicles might stop and queue unreasonably.

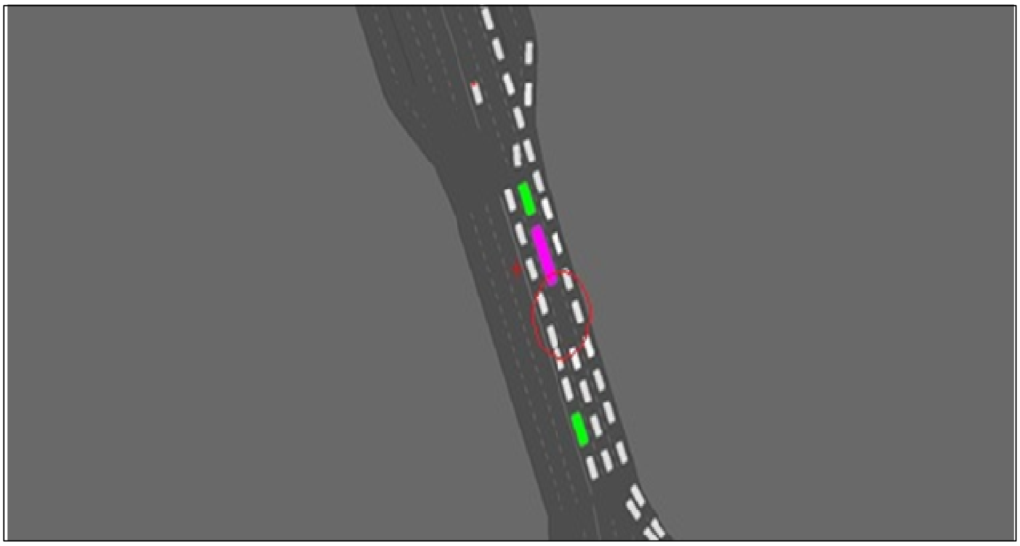


Figure 4.7: Unusual gaps between vehicles

It is observed that during the simulation runs, some vehicles disappear when they arrive at intersections and re-appear at the subsequent links. This is due to improper assignment of movement priority at intersections. Accordingly, all the turning movements and priorities are checked to ensure that they are properly coded. Besides, unreasonable turns are barred.

4.2.2 Model Validation

Validation is a process to determine the values of the input data and parameters. The models have to be properly validated for a meaningful output. The inputs that require proper calibration are road types, speed limit, number of lanes for each road, signalised junctions, and geometry layout of the roads. On-site recording is carried out to gather proper information with the help of a team of student assistants. The video is then played back in the laboratory for data collection and recording.

4.3 Simulation of Driver Responses

According to Wardrop's First Principle (1952), drivers aim to minimise their travel time. During congestion, drivers are expected to re-route to alternative routes for faster travel. Paramics simulate drivers' responses by 3 types of assignment method, i.e. all-or-nothing, stochastic, and dynamic feedback assignment. All-or-nothing assignment allows drivers to choose the shortest path without consideration of roadway condition. As such, drivers might not respond to the congestion at real time. Stochastic assignment introduces some variability into the assignment. Accordingly, some drivers might choose longer route due to lack of knowledge about the overall transport system. The dynamic feedback assignment, which is used in this study, updates drivers' route cost table of every specified interval. As such, drivers could respond to traffic congestion at real time and divert to alternative routes.

The setting of the dynamic feedback period could be carried out at the *Configuration* tab under the *Core Network Attributes* function. At the beginning of each feedback period, drivers' route cost tables are updated by calculating the travel time (cost) required from their current positions to the destination nodes. The optimal paths are then determined based on these updated route cost tables. Accordingly, drivers could respond to the real time traffic congestion by choosing alternative routes to avoid bottlenecks.

4.4 Development of the Bus Transit Network

In this sub-section, the development of bus transit network is elaborated in detail. In addition, the input data required for bus transit development is highlighted as well.

4.4.1 Bus Transit Network Development

Paramics allows modelling of bus transit system using the *Public Transport* palette. There are four important features associated to the simulation of bus transit system, namely *Stops*, *Routes*, *Associated Stops*, and *Timetable*. *Stops* allow the development of bus stop locations on the road network. Using the feature, one can indicate the orientation of bus stops, i.e. whether they are situated on the kerb lane or median lane. Besides, the stopping zone of the bus stops can be defined as well. The first and the last stop indicated by the bus route will automatically be defined as the terminals of the buses.

Routes allow the indication of bus services on the network. The route index and the service name could be specified. In addition, the information about bus fleet could be indicated as well. This includes the type of vehicle assigned for the specific routes. By defining the vehicle types to the bus services, the capacity of buses could be simulated. The departure schedule could be indicated in detail by specifying the exact release time of the bus services. For each release, the initial occupancy of the buses could be indicated as well.

Associated Stops allow the simulation of bus activities at bus stops in detail. There are 3 options to define or compute the buses dwell time at stops, namely specific time, mean and deviation of the dwell time distribution, and passenger rates. The specific time function indicates the deterministic buses stopping time at the stops. Besides, stochastic dwell time can be simulated by associating proper distributions to the services. This can be carried out by indicating its mean time and deviation of the distribution. Besides, the dwell time can also be determined internally by Paramics by specifying the passenger rates at the stops. This will depend on the passengers' arrival and alighting rate and the average pay time per passenger which are user inputs. One can also indicate the minimum stop time of the buses at the stop and to indicate whether the buses should stop at the stops mandatorily. *Timetable* allows the user to specify an overlay time for the services which is the earliest time that buses are allowed to leave the stops. Figure 4.8 shows the *Public Transport* palette.

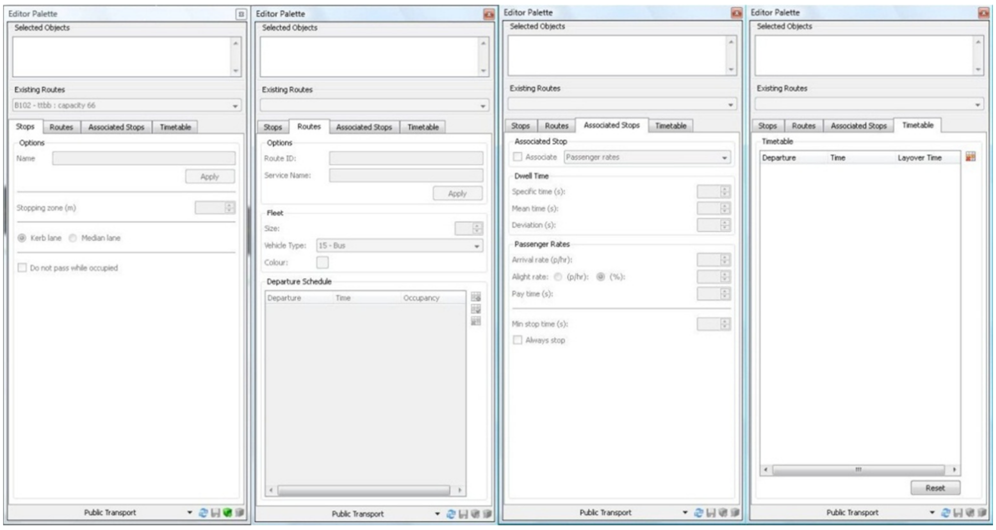

Existing Routes: B102 - ttbb : capacity 66
Vehicle Type: 15 - Bus
Associate: Passenger rates

Figure 4.8 *Public Transport* Palette

4.4.2 Calibration of bus transit model

Most of the input data required for the simulation of bus transit system in this study is collected from the bus operator, i.e. Prasarana (2011). The information collected is the bus routes, types of buses, buses capacity, and service routes frequency. The bus stop locations are collected from the local authority (DBKL 2010). The dwell time functions are collected from site since there are no available data.

The bus stops in the study area are categorised into 3 categories based on the number of buses they serve, i.e. low, medium, high density. Bus stops that serve lesser than 8 routes are classified as low density bus stops, while bus stops that serves 9-18 routes are classified as medium density bus stops, and bus stops serving 19-26 routes are classified as high density bus stops. For each bus stop category, a team of students is sent to the site to measure and collect the dwell time of buses at the stops. Statistical analysis is then carried out to compute the mean and standard deviation of dwell time for each bus stops category.

4.5 Simulation of the Exclusive Bus Lane and Scheduling

The exclusive bus lane is simulated using the *Restrictions* function available in the Paramics Modeler. Under the *Network Core Attributes*, a restriction is set to bar all the vehicles except buses from using the links/lanes in the network. It is then assigned on the links that have the exclusive bus lane implementation. In Modeler, it is not allowed to set the schedule of the implementation. Once the *Restriction* is assigned to the link, it will be activated when the simulation is started.

The Dynamic Link Library (DLL) plugin is required to simulate the scheduling of the exclusive bus lane implementation. The plugin carries the instruction to activate the implementation which was written using the Paramics Programmer. It can activate the *Restriction* according to the schedules. The plugin is called by inserting a command file, i.e. *Programming.txt* in the network folder.

Figure 4.9 shows the step-by-step simulation of the exclusive bus lane and scheduling. After the simulation starts, the DLL will check whether current time is equivalent to the designated schedule (i.e. the start time or end time) of the implementation at every time step. If it is one of the designated schedules, the DLL will then check to implement the *Restriction* (i.e. exclusive bus lane) on the designated links. This is carried out in every time step until all the schedules are implemented.

The commands used in developing the DLL are such as follows:

- The *Extension* function, i.e. qpx_NET_timeStep(), is used to extend the functionality of the model at every time step. All the instructions to check and implement the exclusive bus lane is written within this function. It is equivalent to the *Main* function in C-programming.
- The current simulation time is queried using the *Getting* function, i.e. qpg_CFG_simulationTime() function. It is necessary to check whether the current simulation time is equivalent to the schedule for implementation. This query is carried out at every time step.

- The activation (deactivation) of the exclusive bus lane implementation is carried out by the *Setting* function, i.e. qps_LNK_restriction (link, lane, on/off). It allows the restriction to be applied on the designated links and lanes. In this study, the left most lanes are chosen as the candidate lanes for implementation.

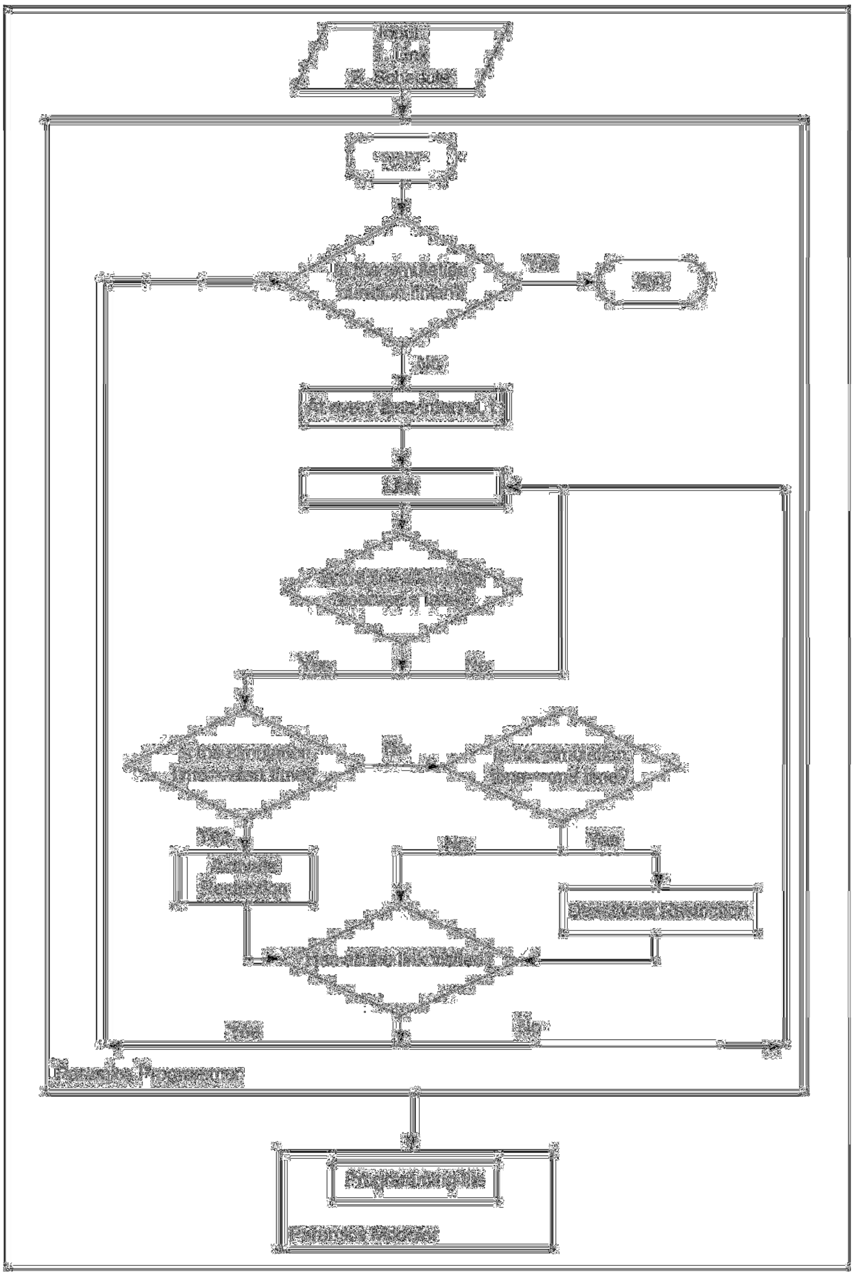


Figure 4.9: Simulation Logic for Exclusive Bus Lane Simulation in Paramics

CHAPTER 5

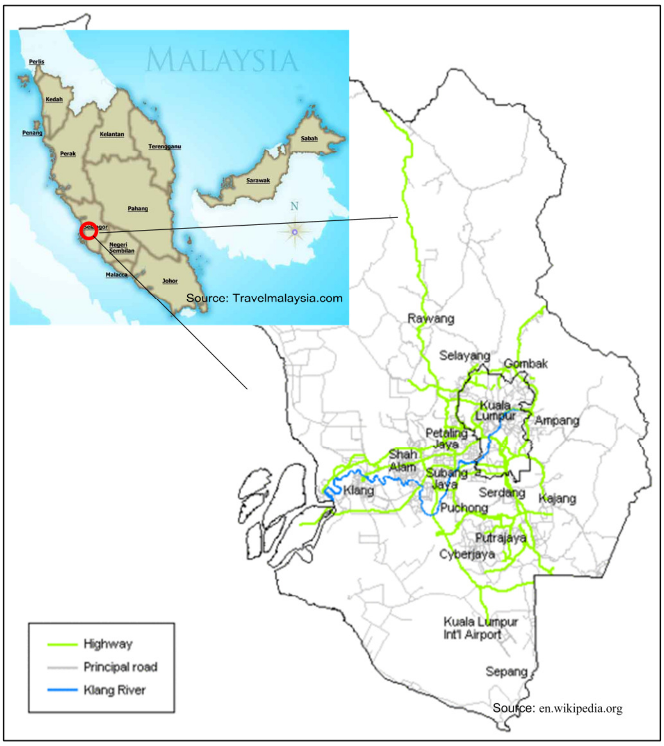
AN ILLUSTRATIVE CASE STUDY FOR EVALUATION

In this chapter, the proposed methodology is evaluated using an illustrative case study of Klang Valley, Malaysia. The network is constructed in Paramics according to the procedure elaborated in Chapter 4. Sensitivity analysis is carried out to test the impact of varying the parameters' values to the results obtained.

5.1 The Study Area

The study area adopted as the illustrative case study is the Klang Valley region, Malaysia. The region is about 2834 square kilometer. It comprises Kuala Lumpur (the capital of Malaysia) and its neighboring sub-urban cities and towns. Figure 5.1 shows the location of Klang Valley and its sub-urban cities. Over the years, the region has archived strong economic growth compared to other states in the country. This has attracted migration from other states over the past few years, causing the population to increase from 4 million in 2004 to 6 million in 2007. Along with the growth in economy and increase in population size, private vehicle population has also increased by about 50% from 2.21 million of vehicles in 1996 to 5.5 million in 2008. Among these vehicles, about 55% of them are private cars, 35% motorcycles, 0.37% buses, 0.59% taxis, 5% trucks and 4% other types of vehicle (Department of

Transport Malaysia 2010). Use of private transport also increases and the modal split of private vehicles to public transport has increased from 75%:25% in 1985 to 84%:16% in 2006. There were 2.2 million of private vehicles moving into the city daily in 2006 (The Star 2006), and this amount has increased to 3.7 million recently (Tai 2010). Among these vehicles, 70% of them are single occupancy vehicles. The excessive influx of private vehicles into the region has caused a reduction of travel speeds in the region to a critical level (Kiggundu, 2009) as well as adverse impact on energy consumption and the environment.



Source: Travelmalaysia.com

Source: en.wikipedia.org

Figure 5.1: Klang Valley Region

In terms of public transport system, bus transit system is the oldest public transport system in the region. Currently, there are a total of 239 routes plying on the streets in the region. The route services are provided by 13 different bus concession companies in the region. RapidKL (www.prasarana.com.my) is the main operator which provides 67% of the routes. It is a government owned company which was established in 2004 during the public transport reformation exercise. The bus routes operated under RapidKL are divided into 4 service types, i.e. Trunk services, Local services, City services, and Express services. The Trunk services funnel the passengers from the sub-urban areas into the city hubs; the Local services carry passengers from the residential areas to the main routes, while the City services pick up passengers at the city hubs and send them to their final destination in the city center. The Express service is a non-stop ride from key points around the Klang Valley straight into the city. In February 2010, the Bus Express Transit (BET) was introduced to provide faster service by utilizing the under capacity highways to transport passengers from sub-urban into city centre during morning and afternoon peak hours.

Zonal fare system is adopted by the bus companies. Single zone charges are applied when a passenger travels within a given zone regardless the distance of his/her journey. Fare for two zones is charged when a passenger travels from one zone to the other. The zonal fare rate varies across different concession companies subjected to the statutory maximum determined by the authority. However, RapidKL adopts the zonal system only for its Trunk services. For other services, such as Local and City services, the charges are fixed. Table 5.1 shows the fare table. A smart card system, ‘Touch’n Go’, is available to ease passengers for fare payment. Nevertheless, the system is only available for RapidKL services. Other companies still use the cash fare system.

Table 5.1: Fare structure

Zone	Fare		
	RapidKL (Trunk)	Selangor	Others
1 Zone	RM 1.00	RM 0.70	RM 1.00
2 Zone	RM 1.90	RM 1.20	RM 1.90
3 Zone	RM 2.50	RM 1.60	RM 2.50
4 Zone	RM 3.00	RM 2.00	RM 3.00

In terms of facilities, the bus stops coverage is less extensive. There are only 61% of people in the region that could access to the services within 400 meters (LPTC, 2011). In terms of bus lane provision, there is a total of 14.8 km of bus lane existed in the region (LPTC, 2011). The implementation of bus lanes started since 1997. They are marked with continuous yellow lines with the words "Buses and Taxis Only" at the left most lane (curbside) of the road. It is the exclusive bus lane in which no other vehicle, except buses and taxis, is allowed to use the lanes. Road signs are mounted at the starting points of the bus lanes to notify drivers. The operation of the bus lane has fixed schedule in which it starts at 6 am and end at 8 pm on weekdays.

5.2 The Paramics Network Model

The network of Klang Valley is coded in Paramics with a total of 16726 nodes, 38274 links, and 424 zones as shown in Figure 5.2. The study area is circled in the figure which is the Kuala Lumpur city centre. The calibration procedure highlighted in Chapter 4 is implemented on the network in this area. The network in other areas is not calibrated but it serves to provide alternative routes for vehicles to reroute. A total of 1075 links in the study area are identified as the candidate links in which $A_1 = A_2$ in this case. The origin-destination (OD) demand is assumed based on the historical data from the authority. The OD demand matrix is a 45 x 45 matrix. The demand is loaded into the network in the first hour during the simulation. The average traffic flow in the study area is designed to be about 1000 vehicle per hour. The total number of trips in the study area is 13,1340 vehicles. The time period considered for the implementation of exclusive bus lane is from 6 am to 12 noon, divided into 15-minute intervals, when considered for the exclusive bus lane scheduling.

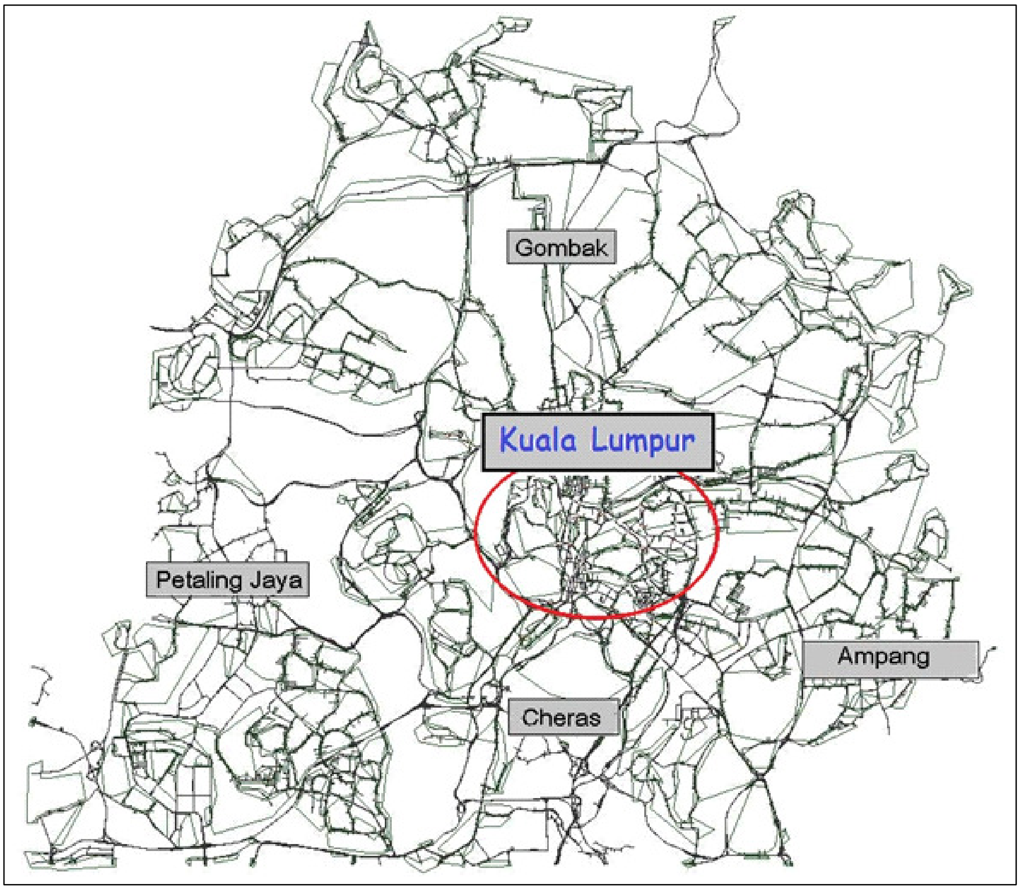


Figure 5.2: Klang Valley Network and the Study Area

A total of 10 bus routes plying through the study area (i.e. Kuala Lumpur City Centre) which are operated by Prasarana (Prasarana 2011) are simulated. The bus routes are listed in Table 5.2 and are shown graphically in Figure 5.3. The locations of bus stops are obtained from the local authority (DBKL 2010). The bus services information, such as the service frequency, types of buses used, and bus capacity, is obtained from Prasarana (Prasarana 2010). The dwell time data is collected on site via video recording on the passengers' and buses movement at the bus stops. The video footages are played back in the lab to compute the dwell time at bus stops based on the bus density classification as shown in Table 5.3.

Table 5.2: Bus Routes Coded in Paramics

Route No.	Origin-Destination	Service headway (minutes)	Length of bus routes (km)
B101	Titiwangsa-KL Sentral	20	14.2
B102	Titiwangsa-Bukit Bintang	10	14.4
B103	Titiwangsa-Bukit Bintang	15	16.7
B105	KLCC-Mid Valley	10	19.1
B110	Bukit Bintang-Mid Valley	10	15.9
B111	Maluri-Chow Kit	10	15.2
B112	Maluri-KL Sentral	30	21.8
B113	Maluri-Pasar Seni	10	16.5
B114	Maluri-Titiwangsa	15	22.8
B115	Pasar Seni-Kompleks Kerajaan Jalan Duta	60	18.4

Table 5.3: Bus Stops Dwell Time Input

Bus stops level	Range of buses density	Number of bus stops in the model	Mean (seconds)	Standard deviation (seconds)
Low	0-8	153	22	20
Medium	9-18	27	32	39

High	19-26	14	28	23

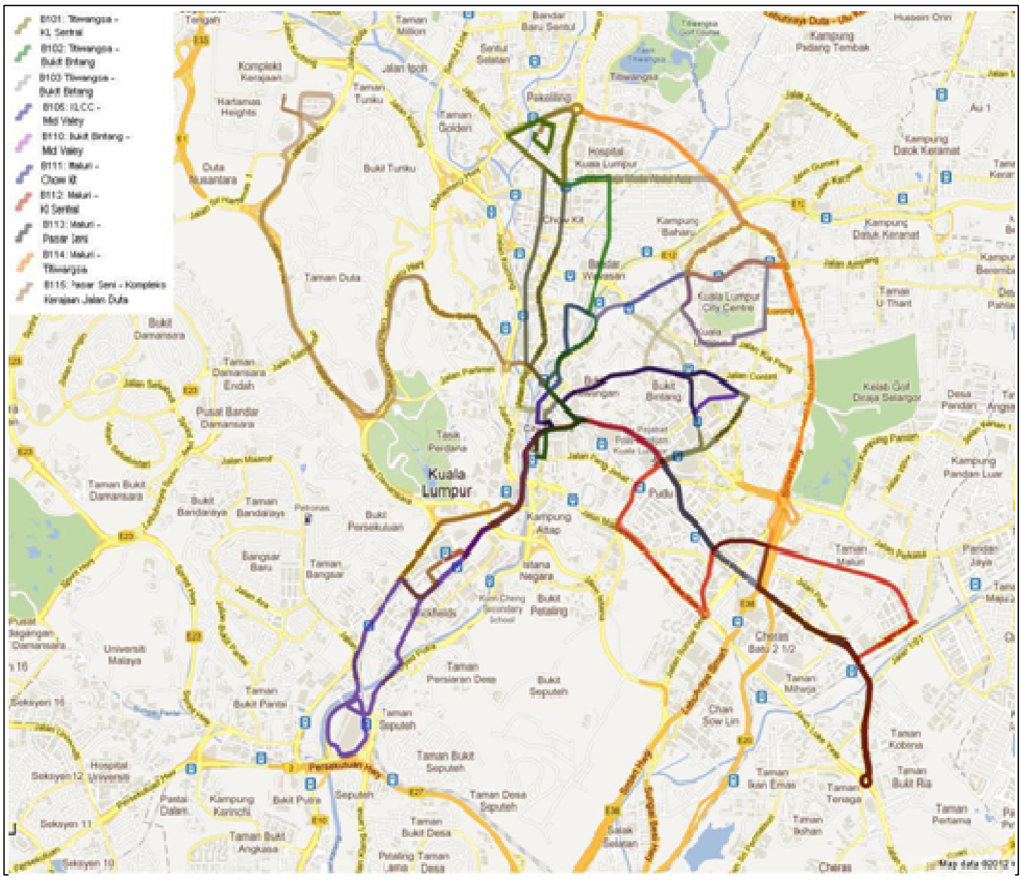


Figure 5.3: Bus Routes In the Study Area

5.3 Benchmark and Other Scenarios

The benchmark scenario is created to test the applicability of the proposed methodology. The values used for the parameters are shown in Table 5.5. Various scenarios are created to understand the influence of alternating the values of these parameters on the results. A total of 8 scenarios are created. Scenario 1 differs from benchmark scenario by imposing the continuity constraint, i.e. eqns. (3.12), (3.14)-(3.15) of the optimization model. Scenario 2 has the population size of 30. Scenarios 3 and 4 study the impact of the minimum duration on the results by setting the value to 1 hour and 3 hours respectively. Scenario 5 and 6 study the impact of minimum frequency by setting the value to 30 (below average) and 115 (above average) respectively. Scenarios 7 and 8 study the impact of varying level of demand. Table 5.5 shows the summary of the scenarios.

Table 5.4: The Parameter Values for Benchmark Scenario

Population Size	20
Maximum generation	10
Minimum frequency, $f_{\min}$ (eqn. (3.2))	46
Minimum duration for exclusive bus lane	2 hours
Probability of crossover	0.3
Probability of mutation	0.03

Table 5.5: Various Scenarios and Their Values

<table>
<tr><th>Scenario</th><th>Continuity eqn?</th><th>Population size</th><th>Minimum frequency</th><th>Minimum duration</th><th>Demand level</th></tr>
<tr><td>1</td><td>Yes</td><td colspan="4">Same as benchmark scenario</td></tr>
<tr><td>2</td><td rowspan="7">Same as benchmark scenario</td><td>30</td><td></td><td rowspan="3">Same as benchmark scenario</td><td rowspan="5">Same as benchmark scenario</td></tr>
<tr><td>3</td><td rowspan="6">Same as benchmark scenario</td><td>30</td></tr>
<tr><td>4</td><td>115</td></tr>
<tr><td>5</td><td rowspan="4">Same as benchmark scenario</td><td>1 hour</td></tr>
<tr><td>6</td><td>3 hours</td></tr>
<tr><td>7</td><td rowspan="2">Same as benchmark scenario</td><td>10%</td></tr>
<tr><td>8</td><td>50%</td></tr>
</table>

5.4 Results

This section presents the results obtained for the benchmark and other scenarios.

5.4.1 Benchmark Scenario

Figure 5.4 shows the objective function values obtained for the exclusive bus lane and scheduling problem for the benchmark scenario. The red line in the figure indicates Pareto solutions (front 1) for the exclusive bus lane and scheduling problems. It is observed that that the average travel time for bus transit system could not be further improved without worsening the average travel time of general traffic. Accordingly, these solutions are equally good. The choice of the solution to be adopted will be based on the system's manager aims and level of acceptable trade-off.

The best solution for non-bus traffic is 31.42 minutes (with bus transit system is 52.83 minutes), while the best solutions for bus transit system is 47.33 minutes (with the average travel time for non-bus traffic is 38.09 minutes). This shows that there is a trade-off of 17% increment in the average travel time for non-bus traffic for an 11% improvement of the average travel time for bus transit system. The solutions obtained commensurate to these optimal objective function values are the lane allocation and schedule for the exclusive bus lanes shown in Table 5.6. The solutions suggest that 818 links (out of 1075 candidate links) to be reserved a lane (the left most lane) for exclusive bus lanes. Besides, the scheduling results show that the popular time period for the exclusive bus lane implementation is during 7 am – 8 am, followed by 6 am – 7 am, and 8 am – 9 am. This shows that more lanes should be reserved for the exclusive bus lane during morning peak period, while the number of lanes reserved reduces towards the non-peak periods. There is no lane reserved during 11 am – 12 noon. This is due to the modeling constraint in which the application should be activated with a minimum duration of 2 hours.

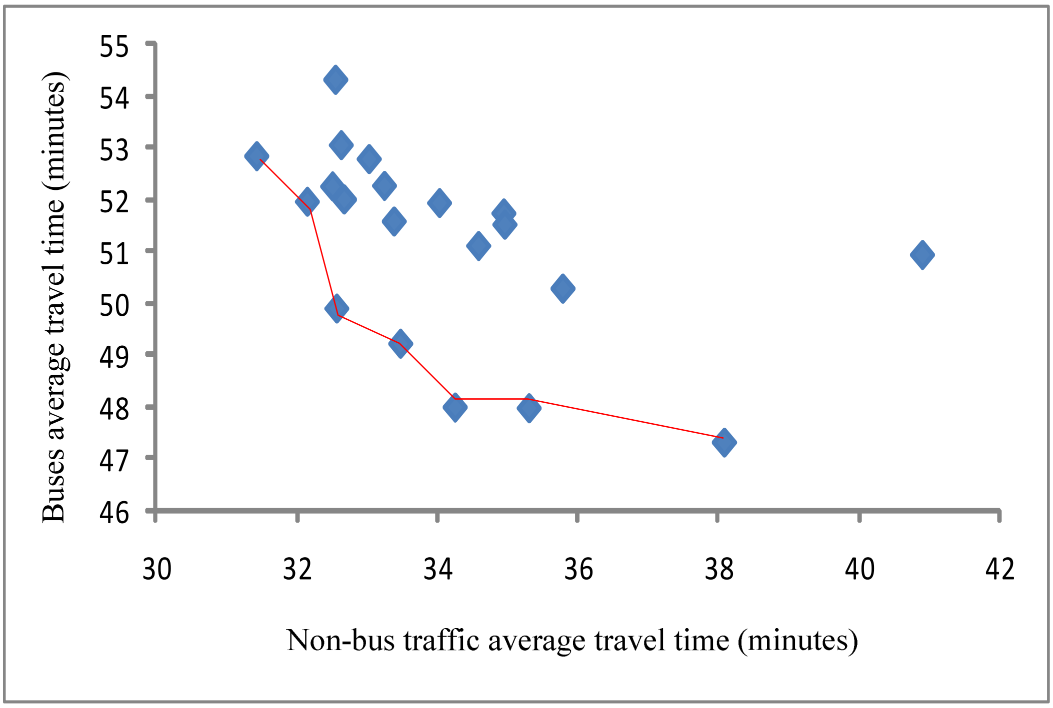


Figure 5.4: Pareto solutions for Benchmark Scenario

5.4.2 Other Scenarios

The Pareto solutions for scenario 1 shows that generally the average travel time for both buses and general traffic increases by imposing the continuity constraint on the optimization model. The best solution for bus transit system (57 minutes) has an increase of 21% compared to the benchmark scenario but not for the non-bus average travel time. This is because if more exclusive bus lanes are reserved on the network (in order to ensure continuity), the effective road capacity is reduced. Queue might developed at the road stretches that do not have bus lanes which cause buses to suffer more delay compared to non-bus traffic. The non-bus traffic could divert to avoid traffic congestion. The solutions show that there is a trade-off of 12% increment of the non-bus traffic's average travel time in order to obtain a 22% improvement of the bus transit system's average travel time. This shows that the cost-benefit ratio for scenario 1 is higher than the benchmark scenario. The optimal solution shows that there is a total of 786 links proposed to be reserved for the exclusive bus lanes. The scheduling trend obtained for Scenario 1 is similar to the benchmark scenario. Most of the links are reserved for exclusive bus lanes during 7 am – 8 am indicating that this period of time is the peak hour period for buses.

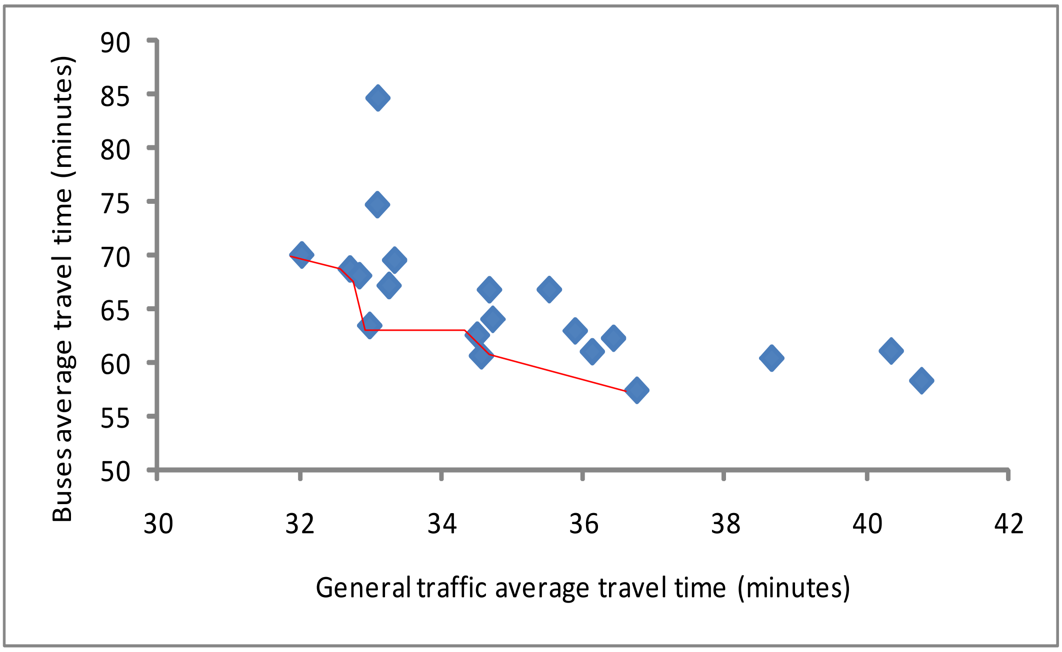


Figure 5.5: Pareto Solutions for Scenario 1

Table 5.6: The Optimal Solutions for Benchmark and Other Scenarios

Item	Benchmark scenario	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8
Lane Allocation *									
Number of exclusive bus lane links	822	786	890	816	808	863	572	786	806
Scheduling *									
6am–7am	408	312	463	325	481	448	271	387	384
7am–8am	485	576	506	550	403	496	346	485	478
8am– 9am	242	275	250	309	137	234	175	245	239
9am–10am	79	76	74	161	11	73	56	88	61
10am–11am	6	1	4	61	0	1	5	2	2
11am–12pm	0	0	0	6	0	0	0	0	0
Objective function values									
*Bus (general traffic) average travel time/minutes	47.3 (38.1)	57.4 (36.8)	46.7 (32.2)	52.1 (35.7)	46.3 (39.3)	46.3 (39.3)	50.2 (37.1)	44.4(15.3)	44.8 (17.9)
#Non-bus traffic (bus) average travel time/minutes	31.4 (52.8)	32.0 (70.0)	30.7 (51.8)	30.6 (62.0)	30.3 (52.4)	30.2 (52.4)	29.6 (60.3)	14.9(45.1)	17.5 (45.5)

Remarks: * indicate the best solution in terms of bus transit average travel time
#indicate the best solution in terms of non-bus traffic average travel time

The results of scenario 2 show that by increasing the number of population size, it could not further improve the number of Pareto solutions. For benchmark scenario, there are 7 front-1 solutions (out of 20), while for scenario 2 there is only 5 front-1 solutions (out of 30). The best solution for buses is 47 minutes while the best for general traffic is 39.7 minutes which fall between the ranges of values obtained for benchmark scenario.

Scenario 3 and scenario 4 tested the influence of setting the minimum duration for the exclusive bus lane implementation. It is observed that the buses average travel time for scenario 3 is 52 minutes (the best solution), which is higher than the benchmark and scenario 4 (46 minutes). This shows that the effectiveness of the exclusive bus lane reduces if the duration of application is too short. Comparing the exclusive bus lane schedules of the benchmark scenario and scenario 4, it is observed that the period of 6 am- 9 am is important to have the exclusive bus lane on the network, while the period 10 am-12 pm is less important for the application.

Scenario 5 and Scenario 6 evaluate the impact of varying the minimum frequency of buses to be qualified for implementing the exclusive bus lane on the network. It could be seen from Table 5.5 that if the minimum frequency increases, the number of links/roads to have the exclusive bus lane implemented reduced. Accordingly, the bus transit system suffers from longer delay compared to benchmark scenario and scenario 5.

Scenario 7 and 8 evaluate the impact of varying the network demand level to the solutions obtained. They have only 10% and 50% respectively of the benchmark scenario's demand. Thus, the average travel time for buses and non-bus traffic is 6% and 80% lower compared to the benchmark scenario. The reduction for buses is small because buses are operated on fixed route. Besides, there is no change of bus release schedules in these scenarios. The reduction for the non-bus traffic is great because lesser vehicles are loaded on the network in which delay due to congestion is minimal.

5.4.2 Non-exclusive Bus Lane Scenario

The non-exclusive bus lane scenario shows that the non-bus traffic has the average travel time of 15 minutes while the buses' average travel time is 47 minutes. Comparing this result to the benchmark and other scenarios presented in Table 5.6, it is found that Scenario 4 and 5 are performing better compared to the non-exclusive bus lane scenario. It is shown that the buses could have 2% of average travel time savings, but the performance of non-bus traffic is deteriorated by 50%. Comparing to the benchmark scenario, it shows little improvement while comparing to Scenario 1, 2, and 3 shows a deteriorating performance. Both buses and non-bus traffic performance is deteriorated with the implementation of exclusive bus lane in these scenario. This shows that there is a need to carry out proper planning before the exclusive bus lane implementation. In this case, either Scenario 4 or 5 is favored for practical implementation.

5.5 Comments on the Results

The results show that the proposed methodology and solution algorithm is feasible in determining the near optimal for the exclusive bus lane allocation and scheduling problem. A set of Pareto solutions is obtained, which indicates that both objective functions for minimization of the average travel time for buses and non-bus traffic is contradicted in nature. From the Pareto solutions, it can be seen clearly the trade-offs between favouring either one of the solutions. For example, the additional delay encounter by the non-bus traffic could be computed if the exclusive bus lanes are implemented on the network. This allows the engineers to choose the best solution that fulfil their objective. It is thus useful for the engineers during the planning stage.

CHAPTER 6

CONCLUSIONS

6.1 Summary

This study proposed a methodology to systematically determine the allocation and scheduling of the exclusive bus lane on the urban transportation network. The allocation and scheduling of the exclusive bus lane is formulated using the bi-level programming model. The upper level is a bi-objective non-linear optimization model that aims to minimize the average travel time of buses and non-bus traffic simultaneously. The decision variables are exclusive bus lane allocation and schedules. Several constraints for practical implementations are considered. The lower level is a microscopic traffic simulation model that simulates the non-bus traffic and bus transit system. The drivers' response to avoid traffic congestion due to the implementation of the exclusive bus lane is simulated with the *dynamic feedback* function in Paramics. Besides, the bus transit system is simulated in detailed where many of the crucial features, such as bus stops, bus routes, fleet size, capacity, and operational schedule is simulated. The proposed methodology is solved with a hybrid Non-sorting Genetic Algorithm (NSGA II) with Paramics. Chromosome repairing procedure is embedded in the algorithm to ensure that the constraints are fulfilled.

The proposed methodology is evaluated with an illustrative case study of Klang Valley region, Malaysia. The network of the study area is calibrated with the field data collected from the site. Secondary data is collected from the local authority and bus operator as the inputs to the simulation model. A benchmark scenario is defined to test the applicability of the proposed methodology. Results show that Pareto solutions are obtained which indicate that both objectives to minimize the average travel time are contradicted. The value of one objective could not be improved without deteriorating the other objective. A set of Pareto solutions is obtained and the preferred solutions should be chosen based on the acceptable trade-offs between the objectives. Sensitivity analysis is carried out to test the impact of varying the parameters' value to the solutions. It is observed that the solutions are sensitive to the parameters setting, such as minimum duration, minimum frequency, demand level, and the consideration of continuity constraint. Nevertheless, the solutions are not sensitive to the population size. Higher number of population size does not guarantee more feasible solutions obtained.

The proposed methodology is feasible to produce the best solution for the exclusive bus lane and scheduling. It allows the engineers to evaluate the impact on bus transit system and the non-bus traffic for each of the solution chosen. Thus, engineers could choose the best solutions that in line with their objectives or guidelines.

6.2 Limitations

The limitation of the proposed methodology is that it needs substantial time to process the results. The computational time is depended on the population size, the number of generation (iteration) performed, and the simulation speed. The simulation speed is depended on the size of the network and the number of vehicles present on the network. The bigger the network is, the longer the simulation model needs. In this study, a simulation run required about 60 minutes on an Intel i7 975 with 8 GB RAM work station. The methodology could be enhanced if parallel programming method is adopted. Due to this limitation, the proposed methodology is only appropriate during the planning stage.

6.3 Future Work

There are a few suggestions for the future work listed as follows:

- The model calibration and validation could be extended for the whole network.
- Other types of bus routes, such as Bus Express routes, could be simulated in order to determine the corridor that needs to have the exclusive bus lane for better bus performance.
- Other types of multi-objective optimization algorithm could be employed as the comparisons to NSGA II in terms of computational efficiency.
- Parallel programming could be adopted to improve the computational time.
- A transit assignment model could be adopted as the lower level in order to account for transit route choice in response to the exclusive bus lane implementation.

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